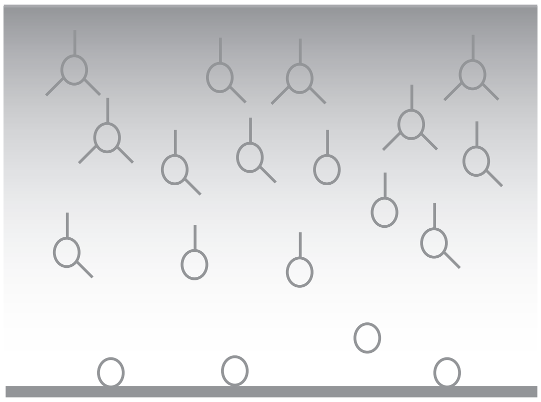
ICMOVPE-XII



The Twelfth
International Conference on
METAL ORGANIC VAPOR PHASE EPITAXY

AT-MEETING PROGRAM

May 30-June 4, 2004
Westin Maui Hotel • Lahaina, Maui, Hawaii

TMS

SCHEDULE OF EVENTS

Sunday, May 30, 2004

Registration	3:00 pm-9:00 pm
Welcoming Reception -	7:00 pm-10:00 pm
sponsored by EMF Ltd.	

Monday, May 31, 2004

Registration	7:30 am-3:00 pm
Continental Breakfast	7:30 am-8:30 am
Opening Remarks	8:45 am-9:00 am
Plenary Session	9:00 am-10:20 am
Coffee Break	10:20 am-11:00 am
Sessions	11:00 am-12:20 pm
ICMOVPE Exhibit	1:00 pm-5:00 pm
Lunch	12:30 pm-2:00 pm
Sponsored by Veeco Compound Semiconductor	
Poster Session	2:00 pm-3:30 pm
Free Afternoon	

Tuesday, June 1, 2004

Registration	7:30 am-5:00 pm
Continental Breakfast	7:30 am-8:30 am
ICMOVPE Exhibit	10:00 am-3:30 pm
Plenary Session	8:20 am-9:40 am
Sessions	9:50 am-10:50 am
Coffee Break	10:50 am-11:30 am
Session	11:30 am-12:30 pm
On Your Own Lunch	12:30 pm-2:00 pm
Plenary Session	2:00 pm-2:40 pm
Coffee Break	2:40 pm-3:20 pm
Sessions	4:00 pm-5:20 pm
Poster Session/Reception -	6:00pm-8:00pm
Sponsored by Nippon Sanso Corporation	

Wednesday, June 2, 2004

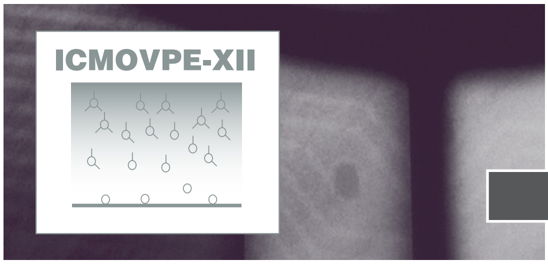
Registration	7:30 am-4:00 pm
Continental Breakfast	7:30 am-8:30 am
ICMOVPE Exhibit	10:00 am-2:00 pm
Plenary Session	8:20 am-9:40 am
Sessions	9:50 am-10:50 am
Coffee Break	10:50 am-11:30 am
Session	11:30 am-12:30 pm
On Your Own Lunch	12:30 pm-2:00 pm
Plenary Session	2:00 pm-2:40 pm
Coffee Break	2:40 pm-3:20 pm
Poster Sessions	2:40 pm-4:00 pm

Thursday, June 3, 2004

Registration	7:30 am-5:00 pm
Continental Breakfast	7:30 am-8:30 am
Plenary Session	8:20 am-9:40 am
Sessions	9:50 am-10:50 am
Coffee Break	10:50 am-11:30 am
Session	11:30 am-12:30 pm
On Your Own Lunch	12:30 pm-2:00 pm
Plenary Session	2:00 pm-2:40 pm
Coffee Break	2:40 pm-3:20 pm
Sessions	3:20 pm-4:40 pm
Poster Session	4:40 pm-6:00 pm
Conference Banquet Reception -	6:30 pm-7:30 pm
sponsored by Akzo Nobel High Purity Metalorganics	
Conference Banquet	7:30 pm-10:00 pm
Sponsored by AIXTRON AG	

Friday, June 4, 2004

Registration	7:30 am-12:00 pm
Continental Breakfast	7:30 am-8:30 am
Plenary Session	8:20 am-9:00 am
Sessions	9:10 am-10:30 am
Coffee Break	10:30 am-11:10 am
Session	11:10 am-12:10 pm
Final Remarks	12:10 pm-12:30 pm



Twelfth International Conference on Metal Organic Vapor Phase Epitaxy (ICMOVPE-XII)

May 30-June 4, 2004 • Lahaina, Maui, Hawaii

TMS

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ADDITIONAL PROCEEDINGS MAY BE PURCHASED	Fee	Number	Total
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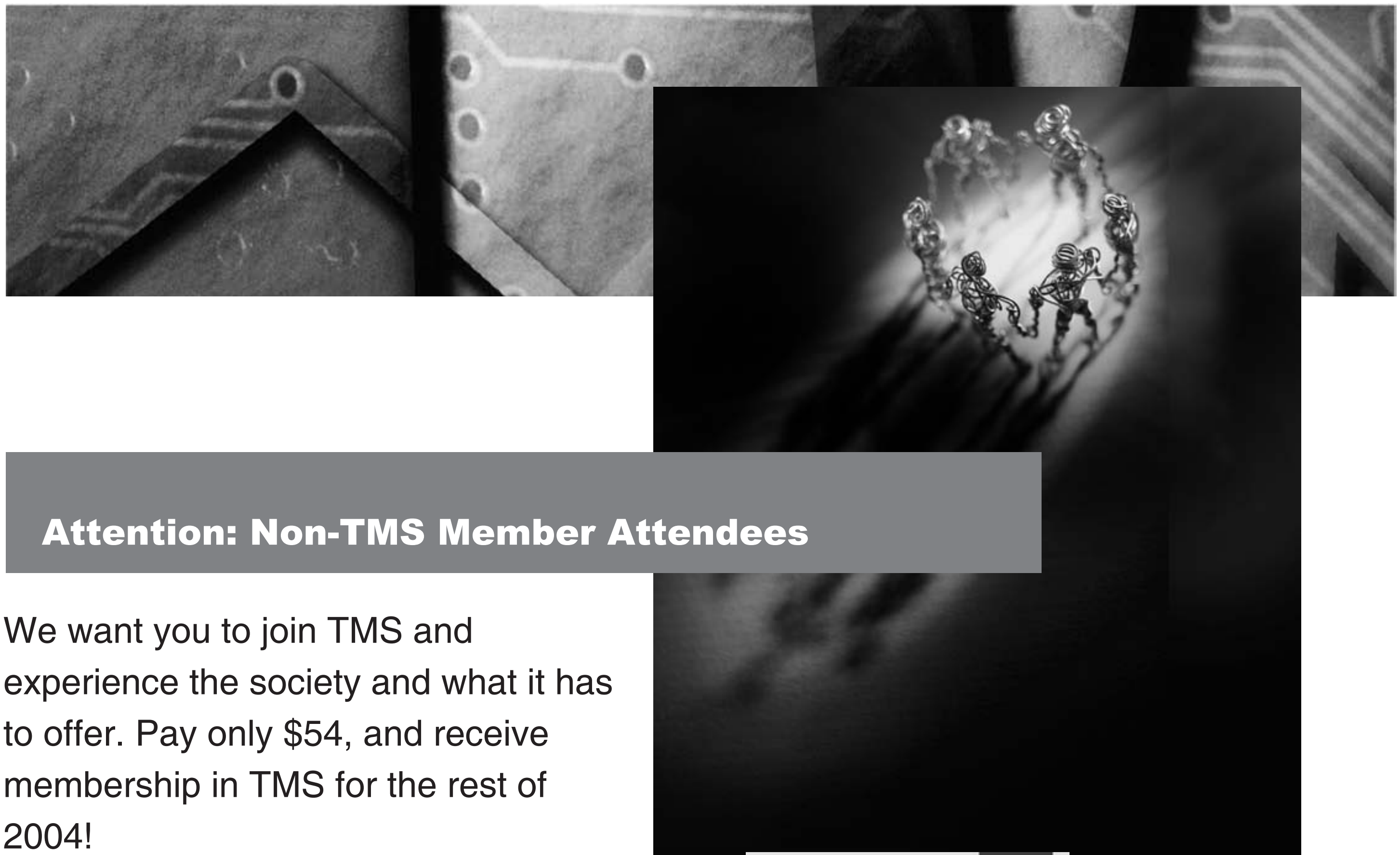

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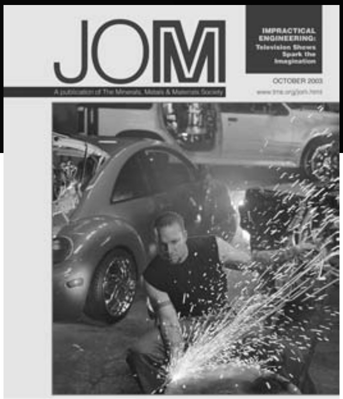

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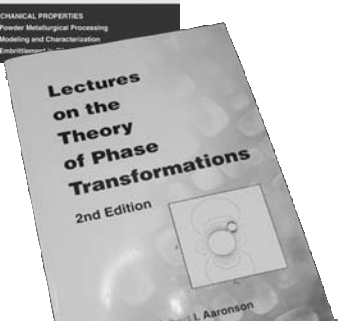

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ICMOVPE

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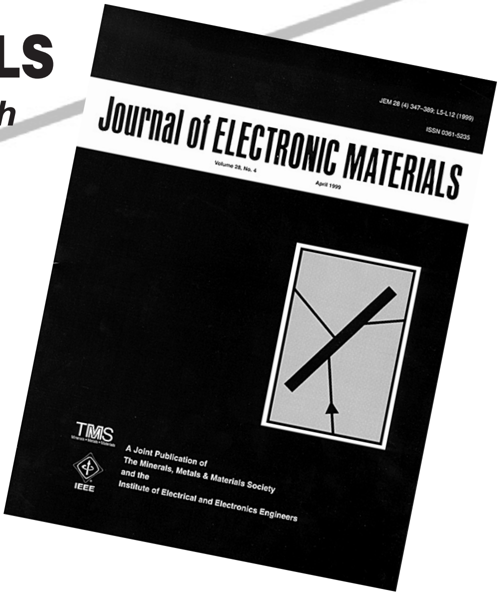

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The Twelfth International Conference on Metal Organic Vapor Phase Epitaxy (ICMOVPE XII)

May 31 – June 4, 2004

		Kihei	Kula	Lahaina
MONDAY	**AM**	**Plenary** 8:30 AM – 10:20 AM **Nitride Devices I** 11:00 AM – 12:20 PM	**Long Wavelength** 11:00 AM – 12:20 PM	
	PM			**Wide Gap Nitrides Poster Session** 2:00 PM – 3:30 PM
TUESDAY	**AM**	**Plenary** 8:20AM – 9:40 AM **Nitride Devices II** 9:50 AM – 10:50 AM **Basic Growth I** 11:30 AM – 12:30 PM	**Dots I** 9:50 AM – 10:50 AM **Dots II** 11:30 AM – 12:30 PM	
	PM	**Plenary** 2:00 PM – 2:40 PM **Novel Materials I** 4:00 PM – 5:20 PM	**Devices I** 4:00 PM – 5:20 PM	**Quantum Structures Poster Session** 6:00 PM – 8:00 PM
WEDNESDAY	**AM**	**Plenary** 8:20 – 9:40 AM **Basic Growth II** 9:50 – 10:50 AM **Nitrides Growth I** 11:30 AM – 12:30 PM	**Nanostructures I** 9:50 AM – 10:50 AM **Nanostructures II** 11:30 AM – 12:30 PM	
	PM	**Plenary** 2:00 PM – 2:40 PM		**Industry/Safety Poster Session** 2:40 PM - 4:00 PM
THURSDAY	**AM**	**Plenary** 8:20 – 9:40 AM **Nitrides Growth II** 9:50 – 10:50 AM **Nitrides Growth III** 11:30 – 12:30	**Dots III** 9:50 AM – 10:50 AM **SAE** 11:30 AM – 12:30 PM	
	PM	**Plenary** 2:00 – 2:40 PM **Dilute Nitrides I** 3:20 – 4:20 PM	**Devices II** 3:20 PM – 4:20 PM	**Growth Issues Poster Session** 4:40 PM to 6:00 PM
FRIDAY	**AM**	**Plenary** 8:20 AM – 9:00 AM **Nitrides Growth IV** 9:10 AM – 10:10 AM **Novel Materials II** 11:10 AM – 12:10 PM	**Characterization I** 9:10 AM – 10:10 AM **Characterization II** 11:10 AM – 12:10 PM	
	PM	**Closing Ceremony** 12:10 PM - 12:30 PM		

ICMOVPE XII
TECHNICAL PROGRAM

Monday AM - May 31, 2004

Plenary Session

Monday AM — Room: Kihei
May 31, 2004 — Location: Westin Maui Hotel

Session Chairs: S. Denbaars, University of California, Santa Barbara, CA 93106 USA; S. Keller, University of California, Santa Barbara, CA 93106 USA

8:45 AM Opening Remarks

9:00 AM Invited
MOVPE for Solid State Lighting: *M. George Craford*[1]; [1]Lumileds Lighting, 370 W. Trimble Rd., M/S 91UE, San Jose, CA 95131 USA

LEDs have been commercially available since the 1960's, but until the early 1990's MOVPE was not utilized for commercial LED production. With the emergence of the AlInGcP and AlInGaN technologies MOVPE has become the dominant technology for high performance LED production. The performance improvements of the past decade have enabled the use of LEDs in a variety of colored and white lighting applications. Colored LEDs have already become the technology of choice for traffic signals, much of interior and exterior vehicle lighting, signage of various types often as a replacement for neon, and other areas. LEDs are expected to become the dominant technology for most colored lighting applications and LEDs are beginning to penetrate white lighting markets such as flashlights and localized task lighting. With further improvement LEDs have the potential to become an important technology for large area general illumination. White LED products already have performance of 30 lumens/watt which is 2x better than incandescents. LEDs have the potential to achieve a performance of over 150 lumens/watt which would be roughly 2x better than fluorescents. White LEDs with outputs of more than 100 lumens are already available commercially, and higher power devices can be expected. LEDs can be used as point sources, or can be used with light guides of various types to provide distributed illumination. Backlighting for LCD displays is one example of an emerging application of this type. LEDs are expected to save energy, be environmentally friendly, and provide a variety of other features, including long lifetime, compact size, and programmable color control, which enable design options for new approaches to lighting. This presentation will cover an overview of LED technology, the current applications, and a comparison of LEDs with conventional lighting technologies. Developments that will need to occur for LEDs to be viable for large area general illumination will also be discussed, as well as the impact this could have on MOVPE technology.

9:40 AM Invited
Progress in Growth and Optical Properties of GaN-Based Quantum Dots: *Yasuhiko Arakawa*[1]; [1]University of Tokyo, RACST &IIS, 4-6-1-Komaba, Meguro-ku, Tokyo 153-8505 Japan

Since the first proposal of the quantum dots (QDs) for the three dimensional quantum confinement of carriers in 1982 by Arakawa et al.[1], much effort has been devoted to investigation of fabrication and physics of the QDs as well as device applications. There have been also lots of research on the QDs for wide bandgap semiconductors. In particular, GaN-based QDs are of great importance for highly efficient and low threshold UV light emitters. In this paper, we disucss the progress in the growth and optical properties of GaN-based QDs with emphasis on high-quality GaN-based QDs with the Stranski-Krastnaow growth mode[2-4]. Future prospect of the GaN-QDs is also discussed including possible application to single photon light sources and quantum computing devices technologies. Self-assembled GaN-QDs were grown by MOCVD on AlN epitaxial layers on 6H-SiC substrates. One of a unique growth condition for the QDs is that the V/III ratio is as low as 20. After the growth of the GaN QDs, a thin cap-layer of AlN was grown. Observation of two peaks from QDs and a wetting layer in photoluminescence spectrum is one of clear evidences that the growth is dominated by Stranski-Krastanow growth mode. Growth of vertically aligned GaN QDs and GaN QDs on AlGaN layers are discussed. A time resolved measurement shows an extremely long radiative lifetime up to 1 msec[3]. Such a long radiative decay time is due to smaller oscillator strength induced by the Quantum Confined Stark effect through a strong polarization effect in the GaN/AlN QD heterostructures. The result demonstrates that high quality of the GaN QDs which are free from nonradiative recombination process. We also investigated single dot spectroscopy of the GaN QDs in a masked sample. The integrated photoluminescence intensity as a function of excitation power showed quadratic dependence of the biexcitons. The binding energy defined by 2Ex-Exx is a negative value of which the magnitude was about 30 meV. This negative binding energy is attributed to the effect of strong built in electric field inside the QD[4]. The author would lie to thank K.Hoshino, S. Kako, S. Ishida, T. Saito, and M. Nishioka for their contribution. This work is supported by IT program, MEXT. References: [1]Y. Arakawa and H. Sakaki, Appl. Phys. Lett., vol. 40, pp. 939-941(1982). [2]M. Miyamura, K. Tachibana, and Y. Arakawa, Appl. Phys. Lett., 80, 3987 (2002). [3]S. Kako, M. Miyamura, K. Tachibana, K. Hoshino, and Y, Arakawa, Appl. Phys. Lett., 83, 984 (2003). [4]S. Kako, K. Hoshino, S. Hoshino, and Y, Arakawa, in preparation.

10:20 AM Break

Nitride Devices I

Monday AM — Room: Kihei
May 31, 2004 — Location: Westin Maui Hotel

Session Chairs: K. M. Lau, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon Hong Kong; A. A. Allerman, Sandia National Laboratories, Albuquerque, NM 87185 USA

11:00 AM
Wet Photoelectrochemical Etching for Gallium Nitride-Based Electronic and Optical Device Application: *Yan Gao*[1]; Ilan Ben-Yaacov[2]; Tetsuo Fujii[3]; Rajat Sharma[1]; Kenji Fujito[3]; Michael Craven[1]; James Speck[1]; Steven P. DenBaars[1]; Shuji Nakamura[1]; Umesh Mishra[2]; Evelyn L. Hu[2]; [1]University of California, Matls. Dept., Santa Barbara, CA 93106 USA; [2]University of California, Elect. & Computer Engrg. Dept., Santa Barbara, CA 93106 USA; [3]NICP/ERATO JST, UCSB Grp.

Wet Photoelectrochemical (PEC) etching is attractive for GaN-based device fabrication due to low damage and etching selectivity. The bandgap-dependent etch selectivity has allowed us to form 600Å thick In0.03Ga0.97N current apertures in a novel Current Apertured Vertical Field Effect Transistor (CAVET) that can provide lower DC-RF dispersion. Light-controlled crystallographic etching of N-face GaN has been used to texture the surface of a Light Emitting Diode (LED) structure, enhancing light extraction by a factor of 2 to 3 times. This paper will discuss the change in etch rate, selectivity and morphology as a function of illumination intensity, electrolyte composition and other etch parameters. In addition, recent studies on a-plane GaN grown by Lateral Epitaxial Overgrowth (LEO) has revealed the possibility of rapid, crystallographic etching of GaN surfaces other than (0001) or (000-1) face, with atomically smooth surfaces.

11:20 AM
Laser Diode of 350.9 nm Grown on Low-Dislocation-Density AlGaN by MOVPE: *Kazuyoshi Iida*[1]; Takeshi Kawashima[1]; Atsushi Miyazaki[1]; Hideki Kasugai[1]; Syunsuke Mishima[1]; Yasuto Miyake[1]; Akira Honshio[1]; Motoaki Iwaya[1]; Satoshi Kamiyama[1]; Hiroshi Amano[1]; Isamu Akasaki[1]; [1]Meijo University, Faculty of Sci. & Tech., 1-501 Shiogamaguchi, Tempaku-ku, Nagoya, Aichi 468-8502 Japan

Laser diodes (LDs) in the UV region are promising in such applications as super high-density optical storage, medical devices and laser processing. In this paper, we demonstrated a GaN/AlGaN multi-quantum-well (MQW) LD grown on a low-dislocation-density AlGaN. After depositing a low temperature (LT) buffer layer on a sapphire substrate, a 3-?Ým- thick GaN layer was grown. Periodic grooves along the direction were fabricated by RIE. After depositing an LT-AlN interlayer, a 3.5-?Ým-thick Al0.18Ga0.82N layer and an UV-LD structure having a GaN/

AlGaN MQW active layer were grown. The combination of an LT-AlN interlayer and lateral seeding epitaxy realized crack-free and low-dislocation-density AlGaN on the grooves. The ridge waveguide was fabricated on the groove region. The lasing wavelength was 350.9 nm under pulsed current injection at room temperature, which is the shortest wavelength ever reported.

11:40 AM

Improvement of Quantum Well Interfaces in GaN-Based Laser-Diodes: Stephan Figge[1]; *Detlef Hommel*[1]; Sven Einfeldt[1]; Tim Böttcher[1]; Jens Dennemarck[1]; [1]University of Bremen, Inst. of Solid State Physics, Otto-Hahn-Allee, Bremen 28359 Germany

GaN-based laser diodes emitting arround 400 nm under pulsed current injection were fabricated by metalorganic vapor phase epitaxy (MOVPE) on c-plane sapphire. Extensive studies were performed on the growth of the active region consisting of multiple InGaN/GaN quantum wells (QW). The evaluation of high resolution transmission electron microscopy (HRTEM) images reveals that the composition profile across the wells is far from being step-like and is influenced by the segregation of Indium. To obtain more abrupt InGaN/GaN interfaces, the pretreatment of the GaN surface by either predeposition of trimethylindium (TMI) or silane before InGaN growth and etching the InGaN surface by hydrogen before overgrowth with GaN were investigated. All the pretreatments were found to enhance the photoluminescence (PL) efficiency at room temperature. However, this is not neccesarily accompanied by an improvemed spatial homogeniety of the local cathodoluminescence (CL) spectra and the electroluminescence (EL) efficiency of devices which will be discussed in detail.

12:00 PM

Comparison of Dilute Nitride Growth on a Single- and 8x4-Inch Multiwafer MOVPE System for Solar Cell Applications: *Frank Dimroth*[1]; Carsten Baur[1]; Andreas W. Bett[1]; Kerstin Volz[2]; Wolfgang Stolz[2]; [1]Fraunhofer ISE, SWT, Heidenhofstrasse 2, Freiburg 79110 Germany; [2]Philipps-University Marburg, Matl. Scis. Ctr., Marburg 35032 Germany

The dilute nitrides like (GaIn)(NAs) or Ga(NAsSb) are attractive materials for future photovoltaic cells with 4 to 6 active junctions. Unfortunately, these compounds suffer from a low minority carrier diffusion length. This can be partially compensated by choosing suitable device structures. First (GaIn)(NAs) solar cells with a bandgap of 1.0 eV have been grown on an AIX200 single wafer MOVPE reactor. The cells achieved excellent short-circuit current densities up to 10 mA/cm2, measured under AM0 spectral conditions filtered with GaAs. Already at the present stage of development this value is sufficient for the application in 5 or 6 junction photovoltaic cells. Major challenges for the process transfer to a 8x4-inch AIX2600-G3 production reactor are the reduced growth rate and the parasitic coating of reactor walls. This paper will discuss differences in the growth of dilute nitrides on a single and multiwafer MOVPE system. Results of (GaIn)(NAs) growth using the metalorganic sources TEGa or TMGa and TBAs or AsH3 together with TMIn and UDMHy will be presented and discussed in detail.

Long Wavelength

Monday AM　　Room: Kula
May 31, 2004　　Location: Westin Maui Hotel

Session Chairs: W. Stolz, Philipps-University, Marburg D-35032 Germany; R. Bhat, Corning, Red Bank, NJ 07701 USA

11:00 AM

Effects of Gas Switching Sequences on the Structure of GaAs/GaAsSb Superlattices Grown by MOVPE: *Brian E. Hawkins*[1]; Anish A. Khandekar[1]; Jeng Ya Yeh[2]; Luke J. Mawst[2]; Thomas F. Kuech[1]; [1]University of Wisconsin, Dept. of Chem. & Bio. Engrg., 1415 Engineering Dr., Madison, WI 53706 USA; [2]University of Wisconsin, Dept. of Elect. & Computer Engrg., 1415 Engrg. Dr., Madison, WI 53706 USA

The interfacial structure of GaAs/GaAsSb superlattices was modified through changes in the gas switching sequence. Trimethyl gallium, trimethyl antimony, and arsine were used as the precursors. The growth of GaAs layers was conducted at a V/III ratio of 40 while GaAsSb layers were grown at a V/III ratio of 2.3 and Sb/V ratio of 0.67, conditions that yield 40%Sb in bulk films. TMSb introduction during the switching sequence prior to GaAsSb growth was required for obtaining abrupt interfaces and the desired Sb incorporation in the subsequent GaAsSb layer. X-ray diffraction curves of films grown using various switching sequences show that while arsine exposure is needed in the switching sequence subsequent to GaAsSb growth, an excess of arsine exposure can cause a degradation of the interface quality. Formation of an Sb segregation layer and possible arsenic-for-antimony exchange processes appear to lead to interfacial grading and low Sb incorporation in thin GaAsSb layers.

11:20 AM

Growth Monitoring of GaAsSb:C/InP Heterostructures with Reflectance Anisotropy Spectroscopy: *Frank Brunner*[1]; Stefan Weeke[2]; Martin Zorn[1]; Markus Weyers[1]; [1]Ferdinand-Braun-Institut für Höchstfrequenztechnik, Matls. Tech. Dept., Albert-Einstein-Str. 11, Berlin 12489 Germany; [2]Technische Universität Berlin, Institut fuer Festkoerperphysik, Hardenbergstr. 36, Berlin 10623 Germany

Reflectance anisotropy spectroscopy (RAS) has been used to study and optimize the MOVPE growth process of the GaAsSb:C/InP base-emitter heterojunction in InP-DHBTs. The work focusses on antimony segregation and memory effects which may affect device characteristics like base current ideality factor and turn-on voltage. The RAS spectra of GaAsSb:C at growth temperature shows a broad positive feature around 3.8 eV, which is attributed to a stable Sb surface layer. At this energy, time-resolved RAS measurements monitor the Sb surface coverage with high sensitivity enabling a detailed investigation of group V exchange reactions. RAS transients of thin GaAsSb:C/InP superlattice structures employing different gas switching procedures and growth temperatures are compared. Observed changes in the RAS signal during growth are correlated with compositional differences measured by high-resolution X-ray diffraction. This allows for optimization of the arsine purge time after GaAsSb growth with regard to reduced Sb carry-over in the InP emitter layer.

11:40 AM

Investigation of Bi Induced Ordering Change in GaAsSb Grown by MOVPE: *Weiyang Jiang*[1]; Jinqiang Liu[1]; MyoungGi So[1]; Tatavarti Rao[1]; Karen Kavanagh[1]; Simon Watkins[1]; [1]Simon Fraser University, Dept. of Physics, 8888 Univ. Dr., Burnaby, BC V5A 1S6 Canada

GaAsSb is a very promising material for high-speed HBTs. Alloys with Cu-Pt, Cu-Au, and chalcopyrite ordering have been seen by several groups in samples grown by MBE or MOVPE. Recently we have observed a novel 6-fold ordering along [110] in this material. In this work, we report that Bi can be used as a surfactant to change ordering structures in the GaAsSb material system. Weak 6-fold ordering is observed in the absence of Bi, while strong Cu-Au/chalcopyrite ordering occurs with only 1% Bi/Ga in the vapor phase. This trend is opposite to the case of InGaP, where Bi surfactant suppresses Cu-Pt ordering. Clearly, a completely different ordering mechanism is present in GaAsSb. HRTEM images and corresponding diffraction patterns clearly show the coexistence of ordered and disordered atom arrangements. The effects of this ordering on the optical and transport properties will also be reported.

12:00 PM

RAS and UHV Study of MOVPE Grown GaAsSb on InP(100) and InP/GaAsSb Heterointerfaces: *Zadig Kollonitsch*[1]; K. Möller[1]; S. Neumann[2]; F.-J. Tegude[2]; M. Neges[1]; F. Willig[1]; T. Hannappel[1]; [1]Hahn-Meitner-Institut, SE4, Glienicker Strasse 100, D-14109 Berlin Germany; [2]Universität Duisburg/Essen, Halbleitertechnik/Halbleitertechnologie, Lotharstr. 55, D-47057 Duisburg Germany

GaAs$_x$Sb$_{1-x}$ layers were grown on InP(100) substrates in an AIX200 MOVPE reactor. During and after growth GaAsSb surfaces were observed in-situ with reflectance anisotropy/difference spectroscopy (RAS/RDS). The RA spectrum during growth and that of the TESb-stabilized surface were similar. The RA spectrum changed under stabilisation with TBAs to a more stable As-rich surface. After growth As- and Sb-rich GaAsSb(100) samples were transfered to UHV without contamination and characterized with photoelectron spectroscopy and LEED. As-rich GaAsSb surfaces showed a c(4×4) reconstruction, whereas Sb-rich GaAsSb showed a (1×3)-like reconstruction. In-situ monitoring of subsequent InP growth on GaAsSb is discussed with respect to interface abruptness. The measured RA spectra are similar to spectra of As and Sb overlayers on InP(100) [1]. LEED showed typical P-rich InP(100) (2×1) pattern after 90-100 Angstroem of InP growth. [1] C.X. Wang, O.J. Pitts, S.P. Watkins, J. Crystal Growth 248 (2003) 259.

Monday PM - May 31, 2004

Wide Gap Nitrides Poster Session - 2:00 to 3:30 PM

Monday PM Room: Lahaina
May 31, 2004 Location: Westin Maui Hotel

Session Chair: Robert M. Biefeld, Sandia National Laboratories, Albuquerque, NM 87185-0601 USA

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(1) In-Situ Determination of Growth-Rate and Concentration of Ternary MOCVD Nitrides Via Multiple Wave-Length Ellipsometry: *Alberta Bonanni*[1]; Klaus Schmidegg[1]; Helmut Sitter[1]; [1]Johannes Kepler University, Inst. für Halbleiter- und Festkörperphysik, Altenbergerstr. 69, Altenbergerstr. 69, Linz A-4040 Austria

One of the crucial requirements for the fabrication of nitride-based multi-structures for opto-electronic applications is the determination of ternary compounds composition. For this study, multiple-wave length (MWL) ellipsometry in the visible-ultra-violet range has been performed during the metalorganic chemical vapour deposition of hexagonal GaN and its ternary alloys on sapphire substrates. We applied an algorithm based on the virtual interface approximation to the MWL data and by minimizing the variance of the composition in the growth-rate versus concentration data space, we achieved the simultaneous and real-time determination of growth-rate and composition of AlGaN. Furthermore, MWL measurements of the optical constants as a function of time at the early stages of GaN growth on sapphire provided insights into the onset of the overgrowth mechanisms and confirmed, e.g., the expected partial desorption of the initial GaN nucleation layer in a standard deposition process.

(2) GaN Heteroepitaxy on Si(100): F. Schulze[1]; *A. Dadgar*[1]; J. Blaesing[1]; P. Veit[1]; T. Riemann[1]; A. Diez[1]; J. Christen[1]; A. Krost[1]; [1]Otto-von-Guericke-Universitaet Magdeburg, FNW/IEP, Universitaetsplatz 2, Magdeburg 39106 Germany

GaN growth of Si is interesting from the viewpoint of cost reduction and integration of optoelectronic devices with the well established Si technology. The latter requires the growth of GaN on Si(100) which, in contrast to Si(111) does not support a suited atomic arrangement of surface atoms for the growth of a hexagonal crystal. The lack of a suited atomic arrangement promotes polycristalline growth of GaN; thus there are only few reports on the growth of GaN on Si(100) in literature. We systematically investigated the growth of GaN using different Al(Ga)N buffer layers and layer sequences. Depending on the type of buffer layers we can grown GaN with preferred (10-12) or (0001) orientations. Using off-oriented substrates we can further improve the preferred orientation in the case of the (10-12) orientation.

(3) Antimony as a Surfactant During the Growth of GaN-Based GaNAs Alloys by Metal Organic Vapor Phase Epitaxy: *Akitaka Kimura*[1]; Zhiyan Liu[2]; Thomas F. Kuech[2]; [1]NEC Corporation, Sys. Devices Rsch. Labs., 9-1, Seiran 2-chome, Otsu-shi, Shiga 520-0833 Japan; [2]University of Wisconsin, Dept. Chem. & Bio. Engrg., 1415 Engineering Dr., Madison, WI 53706 USA

Surfactants can change both the morphology and chemistry of the growth surface. The impact of Sb addition during the growth for GaN-based GaNAs alloys, through the addition of triethyl antimony (TESb), was investigated. Both the absolute growth rate and As content of the film decreased with TESb mole fraction. Atomic force microscopy observations revealed that a low amount of Sb did not significantly change the surface morphology, a high TESb mole fraction led to a step-bunched surface with atomically-flat terraces. No Sb incorporation was detected in the films by electron probe microanalysis. However, surface segregated Sb was detected by X-ray photoelectron spectroscopy, which suggests that Sb atoms are surface segregated. Sb addition to the growth environment does alter the growth of GaNAs kinetically and/or thermodynamically-based processes. The Sb addition may be used to control the GaNAs growth and surface structure, particularly in the formation of thin quantum structures.

(4) A Radical Chain Mechanism for the Formation of Gas Phase Agglomerates During the MOVPE of GaN: *Davide Moscatelli*[1]; Carlo Cavallotti[1]; [1]Politecnico di Milano, Dept. Chimica, Materiali e Ingegneria Chimica, via Mancinelli, 7, Milano I-20131 Italy

The formation of agglomerates in the gas phase during the MOVPE of GaN is known to be detrimental to the film quality. Unfortunately, despite its importance, the gas phase chemistry active during the GaN MOVPE is not yet fully understood. Here we used quantum chemistry to investigate the reaction pathways that might lead to the gas phase formation of agglomerates. We found that a gas phase radical chain mechanism started from radicals desorbed from the growing surface can determine the fast formation of a significant amount of cyclic gas phase GaN molecules, such as (GaCH3NH)3 and (GaHNH)3, which we consider as precursor to the formation of larger molecules. To test its performance, the reaction mechanism here developed was embedded in a FEM 2D model of a typical MOVPE GaN reactor and used to simulate the formation of gas phase particles during the growth process.

(5) Strain Effects of Low-Temperature AlN Interlayers for Growth of Crack-Free AlGaN and AlN/GaN Multilayers: *Clifford McAleese*[1]; Menno J. Kappers[1]; Colin J. Humphreys[1]; [1]University of Cambridge, Dept. of Matls. Sci. & Metall., Pembroke St., Cambridge CB2 3QZ UK

The effects of thickness and growth conditions of low-temperature AlN interlayers on the strain state of MOVPE-grown AlGaN epilayers on GaN/sapphire templates have been investigated. For epitaxial Al(Ga)N growth on GaN, the tensile stress arising from the lattice mismatch results in a critical thickness for crack formation of little more than a few tens of nm. Use of low-temperature AlN interlayers, with thicknesses varied here between 10 and 50 nm, allows thick crack-free $Al_xGa_{1-x}N$ films (x=0.5) to be obtained. The AlGaN composition and strain state have been determined using HR-XRD, showing that the AlN interlayers cause compressive strain in the AlGaN layer, thereby preventing cracking. Furthermore, the compressive strain was found to increase with interlayer thickness. By use of thicker AlN, the number of interlayers required in AlN/GaN superlattice structures has been reduced, and the growth of crack-free AlN/GaN multilayers with individual layer thicknesses exceeding 50 nm has been achieved.

(6) Temperature-Dependent Photoluminescence Studies of the Degree of Localization Induced by Quantum-Dot Like States in InGaN SQW LEDs Grown by MOCVD on (0001) Sapphire: D. I. Florescu[1]; *J. C. Ramer*[1]; V. N. Merai[1]; A. Parekh[1]; D. Lu[1]; D. S. Lee[1]; E. A. Armour[1]; [1]Veeco TurboDisc, 394 Elizabeth Ave., Somerset, NJ 08873 USA

We investigate the temperature-dependent PL of InGaN/GaN SQW LEDs and its correlation with the degree of localization induced by QD like states in these structures. By varying the growth parameters and based on AFM and 300K PL findings, a high density of QD like states was achieved. More specifically, AFM scans reveal 5-25 nm diameter “bumps” with a density in the range of $2\text{-}7\text{x}10^9\text{cm}^2$. At the same time, the 300K PL signal shows at least a 10x intensity increase compared to similar structures without the “bumps”. Temperature-dependent PL spectra display the anomalous “S-shaped” behavior of the PL energy peak for the structures where the QD like states are present. Concurrently, a change in the temperature range of the PL emission that outlines the “S-shape” is observed for samples with different “bump” density and sizes. A strong correlation of the “S-shape” lower inflection point with the degree of localization induced by the presence of QD like states is proposed. Applying these principles, a thermally robust 465 nm SQW LED with an unpackaged chip-level output power in the 5.5-6.0 mW range and forward voltage <3.2V at 20 mA was achieved.

(7) Characterization of GaN Grown on Patterned Si(111) Substrate: *D. Wang*[1]; Y. Dikme[2]; J. Shuo[1]; P. van Gemmern[2]; Y. C. Lin[2]; K. J. Chen[1]; K. M. Lau[1]; M. Heuken[3]; [1]Hong Kong University of Science and Technology, Dept. of Elect. & Elect. Engrg., Clear Water Bay, Kowloon, Hong Kong China; [2]RWTH Aachen, Inst. fuer Theoretische Elektrotechnik, Kopernikusstrasse 16, Aachen Germany; [3]RWTH Aachen, Inst. für Halbleitertechnik, Templergraben 55 and AIXTRON AG, Kackertstr. 15-17, Aachen D-52074 Germany

GaN films were grown on patterned-Si(111) substrates by MOCVD. Arrays of rectangular stripes, squares, and hexagons with a 3.5-um height and different lateral dimensions were patterned and etched on Si substrates using ICP-RIE. A 32-nm-thick AlN (grown at 720°C) was used as the seed layer for growing GaN films of 1- to 2-um thickness. GaN deposition on 1-um-wide ridges terminates with a triangular sharp tip, which can potentially be used to fabricate quantum wires or quantum dots. For ridges wider than 2 um, crack-free flat-top GaN films were obtained with a roughness of 0.7 nm. Localized Raman spectroscopy was conducted to study the stress distribution in the GaN films on Si ridges. Substantial stress relaxation was observed. The results suggest that growing GaN on patterned Si could be a promising technique of obtaining crack-free thick GaN layer for device applications.

(8) As-Grown p-Type GaN Growth by Dimethylhydrazine (DMHy) Nitrogen Precursor: *Eun-Hyun Park*[1]; Joong-Seo Park[1]; Tae-Kyung Yoo[1]; [1]EpiValley Co., Ltd., 51-2, Neungpyeong-Ri, Opo-Eup, Kwangju City Korea

A new method for as-grown P-type GaN layer was developed by employing a new N precursor, instead of NH3. In the Hall measurement, the as-grown p-type sample showed higher mobility and hole concentration than the convention P-GaN. In the PL measurement, the as-grown p-type sample shows similar PL shape with the fully post-activated conventional P-GaN. LED characteristics of as-grown p-type samples also showed better performance in optical power by 10~15%, maintaining Vf and Ir as same as the conventional case. The as-grown p-type layer turned out to remain as a p-type after (NH3+H2) annealing at 800OC and for 10 minutes, which is very much different from the previous works. The mechanism of the as-grown p-type is that NH2 and CH3 from pylolysis of DMHy absorb H-radical in the reactor and minimize the H-Mg complexes formation in P-GaN.

(9) Marker Layers for the Development of a Multistep GaN FACELO Process: *Frank Habel*[1]; Peter Brückner[1]; Ferdinand Scholz[1]; [1]University of Ulm, Optoelect. Dept., Albert-Einstein-Allee 45, Ulm 89069 Germany

Due to the rapid progress in the development of high-end GaN based devices the role of threading dislocations is getting more and more important. One of the most promising techniques to reduce the dislocation density is the growth on structured substrates, e.g. ELO or FACELO. To get a deeper scientific understanding of the growth process we implemented marker layers which allowed to study the development of the crystal facets as growth proceeds. In order to optimize their visibility while keeping any parasitic influence as low as possible, we have compared AlGaN and Si-doped GaN marker layers. These investigations provided access to a precise control of the growth step sequence, enabling a thorough optimization of our FACELO process by inserting additional properly designed growth steps. In these additional growth steps, we found that not only the growth temperature, but also the V/III-ratio and the growth rate need to be carefully adjusted to get best intermediate interfaces.

(10) Characterizations of GaInN Light Emitting Diodes with Distributed Bragg Reflector Grown on Si: *Hiroyasu Ishikawa*[1]; Baijun Zhang[1]; Kenta Asano[1]; Takashi Egawa[1]; Takashi Jimbo[2]; [1]Nagoya Institute of Technology, Rsch. Ctr. for Nano-Device & Sys., Gokiso-cho, Showa-ku, Nagoya 466-8555 Japan; [2]Nagoya Institute of Technology, Dept. of Environmental Tech. & Urban Planning, Gokiso-cho, Showa-ku, Nagoya 466-8555 Japan

We report the improved characteristics of GaInN light emitting diodes (LEDs) on Si substrate by distributed Bragg reflector (DBR). The GaInN LED structures with different pairs of AlGaN/AlN DBR were grown on 2-inch n-Si (111) substrates using a conventional horizontal metalorganic chemical vapor deposition method. No cracks were observed over the entire area of the LED structure grown on DBRs with less than 3 pairs. Reflectivities of the LED structures agree well with the calculated curves, indicating that the LED structures on Si with AlGaN/AlN DBR have good-layered stacks. With the increase of DBR pairs (less than 3 pairs), light output power of the LED structure increases. The light output power of the LED with 3 pairs of DBR is about 2 times larger than that of LEDs without DBR. Thus, the crack-free AlGaN/AlN DBR is very promising for the fabrication of high performance GaInN LED on Si.

(11) Formation and Characteristic of GaN Quantum Dots on Multi-Layer AlN/GaN Stack: Hsin-Hung Yao[1]; Chia-feng Lin[1]; Miao-Chia Ou-yang[1]; Hao-chung Kuo[1]; Shing-Chung Wang[1]; [1]National Chiao Tung University, Inst. of Electro-Optical Engrg., 1001 Ta Hsueh Rd., Hsinchu Taiwan

Group-III nitrides and their low-dimensional quantum structures have attracted much attention, because of their optical device application in the visible and ultraviolet energy range. This paper reports the fabrication of self-assembled GaN QDs in the multilayer AlN/GaN stack structures grown by MOCVD. During the growth of GaN and AlN layers, the ambient gas flow rates for the GaN and AlN were adjusted to obtain the best GaN and AlN layers. We used the growth interruption of H2 ambient gas during growth the stack structure. TEM analysis shows that there are formations of triangles and inverted triangles GaN QDs surrounded by AlN layers with average QD size of 25/25nm(diameter/height). Under different excitation intensity, the PL peak at room temperature was located at 353nm with insignificant shift. The PL peak at low temperature of 80K was around 347.5nm. These PL peaks are blueshifted compared the bulk material indicating strong zero-dimensional confinement characteristic of these QDs structures.

(12) Improvement of Extraction Efficiency from UV LED Using Corrugated Interface Substrate: *Jeong Wook Lee*[1]; Sukho Yoon[1]; Jaehee Cho[1]; Hyun Soo Kim[1]; Youn Joon Sung[1]; Cheolsoo Sone[1]; Yongjo Park[1]; [1]Samsung Advanced Institute of Technology, Photonics Lab., PO Box 111, Suwon 440-600 Korea

The external quantum efficiency of GaN based light-emitting diode (LED) grown on sapphire substrate is usually limited by total internal reflection at the semiconductor-substrate interface. To improve light extraction efficiency from UV LED with an InGaN multi-quantum well (MQW) structure, we introduced a corrugated interfacial substrate. With the use of an optimized corrugated interface design, an increase of over 60% in the extraction output power of the UV LED was achieved experimentally, without detriment to the crucial electrical properties of the UV LED. In this study, the CIS (corrugated interface substrate) pattern was fabricated by standard photolithography and subsequent reactive ion etching (RIE) process. When the flip-chip type CIS-LED was operated at a forward bias current 20mA at room temperature, emission wavelength, output power were characterized to be 400nm, 22mW, respectively.

(13) GaN-Based Blue LEDs Grown and Fabricated on Patterned Sapphire Substrates by MOVPE: Zhihong Feng[1]; Yundong Qi[1]; Zhendong Lu[1]; Yugang Zhou[1]; *Kei May Lau*[1]; [1]HKUST, EEE Dept., Clear Water Bay, Kowloon Hong Kong

GaN-based blue-light-emitting diodes (LEDs) with InGaN multi-quantum-wells (MQWs) were grown and fabricated on patterned sapphire substrates using metalorganic vapor phase epitaxy. Substrates with parallel grooves along the ?´11-20?Äsapphire or ?´10-10?Äsapphire directions and different groove sizes were defined by standard photolithography and subsequently etched using an inductive-coupled-plasma reactive ion etcher (ICP-RIE). Initial study indicated that the EL intensity of blue (468nm) LEDs grown and fabricated on the region with 3?e3 ?Ým grooves (3 ?Ým wide with 3 ?Ým spacing) along the ?´10- 10?Äsapphire direction was about 20% larger than that in the unpatterned region (packaged 5 mm lamps emit over 3 mW of optical power with 20mA drive current). Material characterization by X-ray diffractometry (XRD) and Transmission Electron Microscopy (TEM) did not suggest better material quality in the patterned area. The enhancement in EL may be attributed to greater internal reflection from the patterned sapphire/GaN interface than a smooth one, thereby reflecting more light to the surface of the dies.

(14) Dual Wavelength Emission InGaN/GaN Multi-Quantum Well LEDs Grown by Metalorganic Vapor Phase Epitaxy: *Yundong Qi*[1]; Hu Liang[1]; Wilson Tang[1]; Kei May Lau[1]; [1]Hong Kong University of Science and Technology, Dept. of Elect. & Elect. Engrg., Clear Water Bay, Kowloon, Hong Kong

InGaN/GaN multiple quantum well (MQW) LEDs with different well widths and barrier widths were grown on sapphire substrate using MOVPE. The designed emission wavelengths were blue (465 nm) and green (510 nm). The blue MQWs and green MQWs were deposited sequentially and the growth parameters were separately optimized for single color blue and green emission. Room-temperature PL spectra of the dual wavelength samples under high laser excitation intensity showed dual emission peaks a few nm off from the designed peak positions. Electroluminescence of fabricated LEDs at the typical driving current of 20 mA is predominantly single color, depending on the sequence and the number of blue and green MQWs, and the thickness of the barrier between them. The second emission can be enhanced with a larger drive current and the relative intensity of the two emission peaks can thus be tuned. Total optical power of more than 9 mW can be obtained from an unpackaged 300 um die when over driven.

(15) Structural, Optical and Electrical Properties of GaN and InGaN Grown by MOCVD: *Kunakorn Poochinda*[1]; Tai-Chang Chen[2]; Thomas G. Stoebe[3]; N. Lawrence Ricker[1]; [1]University of Washington, Chem. Engrg., Benson Hall, Box 351750, Seattle, WA 98195 USA; [2]University of Washington, Elect. Engrg., Paul Allen Ctr., Box 352500, Seattle, WA 98195 USA; [3]University of Washington, Matls. Sci. & Engrg., Roberts Hall, Box 352120, Seattle, WA 98195 USA

GaN/InN alloy system has attracted an intense interest in high temperature, high frequency and optoelectronic applications. InGaN can provide a spectral coverage from the near UV to the near IR. Due to the large lattice mismatch between InGaN and sapphire substrates, InGaN is usually deposited on the thick GaN film previously grown on sapphire. The growth of GaN and InGaN films was studied systematically. Structural, optical and electrical properties will be reported using several post-growth analysis techniques, including Auger Electron Spectroscopy, PhotoLuminescence, Absorption Spectroscopy and X-Ray Diffraction. The effects of temperature, buffer layer annealing time and V/III ratio on film properties were determined. Both n and p type doping in InGaN were also characterized. This understanding will lead to a better quality control of the optoelectronic devices.

(16) Optical and Electrical Properties of Mg Doped InxGa1-xN and AlyGa1-yN Grown by MOCVD: *Lee Sung-Nam*[1]; Son JongKon[1]; Lee Wonseok[1]; Sakong Tan[1]; Paek Hosun[1]; Yoon Euijoon[2]; Kim Jiyoung[3]; Cho Yong-Hoon[3]; Nam Okhyun[1]; Park Yongjo[1]; [1]Samsung Advanced Institute of Technology, Photonics Lab., PO Box 111, Suwon, Gyeonggi 440-600 Korea; [2]Seoul National University, CSEL, Sch. of Matls. Sci. &

Engrg., Seoul 151-742 Korea; [3]Chungbuk National University, Dept. of Physics & Inst. for Basic Sci. Rsch., Cheongju, Chungbuk 361-763 Korea

Mg doped p-InxGa1-xN (0≤x≤0.045) and p-AlyGa1-yN (0≤y≤0.08) layers were grown on sapphire substrates by MOCVD. We investigated the activation energy (EA) of Mg dopant in Mg doped p-InxGa1-xN and p-AlyGa1-yN, as confirmed by PL emission energy E(e-, A0) of the band to acceptor transition. Under the same Mg doping concentration of 2x10^19cm-3, E(e-, A0) of p-InxGa1-xN decreased with increasing In composition, whereas that of p-AlyGa1-yN increased with Al composition. The energy difference (ΔE) between Eg and E(e-, A0) was reduced to 123 meV for p-In0.045Ga0.095N, while increased to 300 meV for p-Al0.08Ga0.92N, comparing with ΔE for p-GaN (~170 meV). Additionally, the Hall measurements showed that the hole concentrations of p-In0.045Ga0.0955N and p-Al0.08Ga0.92N were obtained to 2.5x10^18 cm-3 and 8.9x10^16 cm-3, respectively. Thus, it was experimentally confirmed that the Mg activation energy was significantly affected by the Eg of III-nitrides materials : EA decreases as Eg decreases.

(17) Methods of Stress Reduction in the MOCVD Epitaxial Growth of GaN on Silicon: *Matthew B. Charles*[1]; Menno J. Kappers[1]; Ranjan Datta[1]; Ted J. Thrush[2]; Colin J. Humphreys[1]; [1]University of Cambridge, Dept. of Matls. Sci. & Metall., Pembroke St., Cambridge CB2 3QZ UK; [2]Thomas Swan Scientific Equipment Ltd., Buckingway Business Park, Cambridge CB4 5UG UK

The use of silicon substrates for GaN-based device structures is attractive in terms of cost and scale, but there are also inherent drawbacks. In particular, there is a large thermal expansion coefficient mismatch between GaN and silicon which introduces tensile stress, on cooling from the growth temperature, which can result in wafer bowing and cracking of the GaN. Using guidance provided by XRD and TEM analysis, growth schemes incorporating the use of AlN interlayers, AlGaN graded layers, AlN/GaN superlattices and SiN interlayers have been developed to reduce the tensile strain and dislocation density. Using these we have grown GaN films on Si which are uncracked up to a thickness of 2.3 microns, have an AFM roughness down to 0.11nm and have XRD rocking curve FWHM of 500 and 930 arcsec for the (002) and (101) reflections respectively. A functional InGaN/GaN LED structure has also been realised on such a template.

(18) LP-MOCVD Growth of GaAlN/GaN Heterostructures on Silicon Carbide. Application to HEMT's Devices: *Marie-Antoinette di Forte-Poisson*[1]; Michelle Magis[1]; Raphael Aubry[1]; Maurice Tordjman[1]; Marcel Peschang[1]; Erwan Morvan[1]; Sylvain Delage[1]; Jean di Persio[2]; Raymond Quéré[3]; Bertrand Grimbert[4]; Virginie Hoel[4]; Damien Ducatteau[4]; Elisabeth Delos[4]; Christophe Gaquiere[4]; [1]Thales Rechearche & Technology, Domaine de Corbeville, 91404 Orsay Cedex France; [2]Université de Lille, LSPES, 59665 Villeneuve d'Ascq France; [3]IRCOM-CNRS, 7 rue Jules Valles, 19100 Brive France; [4]IEMN-CNRS, Av Poincaré, BP69-59652 Villeneuve d'Ascq France

In this paper we report on the LP-MOCVD growth optimisation of GaAlN/GaN heterostructures grown on silicon carbide substrates for HEMT applications, and on the first device performances obtained with these structures. The critical impact of some growth parameters on the physical properties of the GaAlN/GaN epilayers was identified and studied using High Resolution X-Ray diffraction, AFM, C-V and sonogauge measurements. The SiC substrate surface preparation (both ex-situ and in-situ) and the nucleation layer growth conditions (growth temperature, thickness, composition and strain) were found to be key steps of the GaAlN/GaN/SiC growth process. SiC substrates from different suppliers were evaluated and their influence on the physical properties of the GaAlN/GaN HEMT structures investigated. Static characteristics of the devices such as maximum drain current Idss or pinch-off voltage were correlated with the nucleation layer composition (GaN or GaAlN) of the HEMT structure and the defect density of the SiC substrate. I-V characteristics obtained under pulsed measurements have also revealed a clear impact of the nucleation layer composition on the trap density in the GaAlN/GaN HEMT structure. The first devices related to HEMT wafers with GaN nucleation layers were measured at 10 GHz using a load pull system. A CW output power in excess of 2.8 W/mm was measured for a gate length of 0.5 µm, while the devices related to HEMT wafers with GaAlN nucleation layer exhibited output power up to 4W/mm at 10GHz.

(19) Growth and Characterization of GaN-Based Structures on SiCOI Engineered Substrates: Y. Dikme[1]; P. von Gemmern[1]; H. Kalisch[1]; A. Szymakowski[1]; B. Faure[2]; C. Richtarch[2]; H. Larhéche[5]; P. Bove[5]; F. Letertre[2]; R. H. Jansen[1]; *M. Heuken*[3]; M. Heuken[4]; [1]RWTH Aachen, Inst. für Theoretische Elektrotechnik, Kopernikusstr. 16, Aachen 52074 Germany; [2]SOITEC S.A., Parc Technologique des Fontaines, Bernin 38190 France; [3]AIXTRON AG, Kackertstr. 15 - 17, Aachen 52072 Germany; [4]RWTH Aachen, Inst. für Halbleitertechnik, Templergraben 55, Aachen 52056 Germany; [5]Picogiga International, Place Marcel Rebuffat, Villejust France

SiC shows the best properties as substrate for the growth of GaN and its alloys but suffers from a high price. An innovative alternative for these substrates are SiC/SiO_2/Si (SiCOI) substrates, combining SiC and Si substrate advantages thanks to the Smart Cut™ technology. The substrate consists of thin SiC layers (~270 nm) bonded on (100) Si substrates. Up to 3 µm of GaN could be grown crack-free. The structures were investigated by atomic force microscopy (rms = 0.86 nm), high-resolution X-ray diffraction (full width at half maximum (FHWM) = 474 arcsec) and low-temperature (18 K) photoluminescence (PL) (FWHM = 1.1 nm). Electroluminescence test heterostructures consisting of InGaN/GaN MQW were also deposited on SiCOI. Room temperature PL measurements resulted in a QW emission at around 440 nm with a FWHM of 7.8 nm. At electrical excitation blue light emission could be observed.

(20) Successful Passivation of GaN/AlGaN HFET by Use of Spin-Deposited Polyimide: *Mark D. Hampson*[1]; Uttiya Chowdhury[2]; Michael M. Wong[3]; Dongwon Yoo[2]; Xuebing Zhang[2]; *Russell D. Dupuis*[2]; Milton Feng[1]; [1]University of Illinois, Micro & Nanotech. Lab., Urbana, IL 61801 USA; [2]Georgia Institute of Technology, Sch. of Electric & Computer Engrg., Atlanta, GA 30332-0250 USA; [3]University of Texas, Microelect. Rsch. Ctr., Austin, TX 78758 USA

It is well known that surface traps in nitride HFET structures are a key factor the in degradation of RF performance. A number of passivation schemes are under investigation to reduce the trap related performance degradation. We report on the successful use of spin-deposited polyimide for the passivation of III-nitride HFETs. The device structure investigated was fabricated from an AlGaN/GaN HFET structure grown by MOCVD on a 4H semi-insulating SiC substrate. The devices had a two-finger geometry with 2 x 75 µm total gate-width and 0.23 µm gate length. For devices measured at 18 GHz RF frequency, the passivation scheme yielded an improvement of power density from 2.14 W/mm to 4.02 W/mm and improvement of power-added-efficiency from 12.5% to 24.47%. Additionally, the passivated devices demonstrated a peak RF power density of 7.65 W/mm with a peak power-added-efficiency of 22.58% which demonstrates the promise of this technology.

(21) Selective Growth of GaInN Quantum Dot Structures: *Michael Jetter*[1]; Victoria Perez-Solorzano[1]; Albert Gröning[1]; Monika Ubl[1]; Hedwig Gräbeldinger[1]; Heinz Schweizer[1]; [1]Universität Stuttgart, 4. Physikalisches Inst., Pfaffenwaldring 57, Stuttgart 70550 Germany

The extension to the blue green region for InGaN compounds is very difficult because of the miscibility gap in InGaN. The growth of self organized QD could be one solution to overcome this problem, but because of the weak tendency of the nitride QD to grow in the SK growth mode, a special surface treatment has to be established. We present experiments on selective epitaxy to fabricate a GaN template on which we can grow the InGaN QD. After an AlN nucleation layer grown on a sapphire substrate, a 1µm thick GaN layer was grown at 1120°C (XRD-FWHM: 95 arcsec) with LP-MOVPE. 30 nm SiO2 was deposited on this layer by sputtering. An array of holes (diameters from 2µm to 16µm) was prepared using conventional photolithography. Selective growth of GaN was then performed at growth temperatures between 900°C and 1120°C. We found good selectivity of the mask, which could also be confirmed by CL measurements. SEM pictures show a pyramidal structure with a hexagonal base over the holes. In the next step we perform the growth of InGaN on such a "structured substrate" and examine the results with CL and PL measurements.

(22) MOVPE Growth and Characterization of High-Al-Content $Al_xGa_{1-x}N$/GaN Heterostructures for High-Power HEMTs on 100-mm-Diameter Sapphire Substrates: *Makoto Miyoshi*[1]; Masahiro Sakai[1]; Subramaniam Arulkumaran[2]; Hiroyasu Ishikawa[2]; Takashi Egawa[2]; Takashi Jimbo[2]; Mitsuhiro Tanaka[1]; Osamu Oda[1]; [1]NGK Insulators. Ltd., 2-56 Suda-cho, Mizuho-ku, Nogoya 467-8530 Japan; [2]Nagoya Institute of Technology, Rsch. Ctr. for Nano-Device & Sys., Gokiso-cho, Showa-ku, Nagoya 466-855 Japan

For the practical use and the high-power applications of GaN-based electronic devices, we examined the growth of high-Al-content $Al_xGa_{1-x}N$/GaN heterostructures with the highest x value of 0.70 on large-area 100-mm-diameter sapphire substrates by MOVPE. The good in-wafer uniformity of the alloy composition, within ± 3%, was obtained even for the sample with the Al content x of 0.70, and no relaxation in the $Al_xGa_{1-x}N$ layers occurred for any samples. The minimum sheet resistance of approximately 387 Ωcm and the in-wafer distribution of 1.6% were obtained for the sample with the Al content x of 0.52. High-electron-mobility transistors (HEMTs) fabricated on these epitaxial wafers exhibited good dc characteristics. The highest extrinsic transconductance of approximately 228 mS/mm and the maximum source-drain current density of approximately 1033 mA/mm were obtained for $Al_{0.52}Ga_{0.48}N$/GaN HEMTs with the gate length of 2.0 µm and the gate width of 15.0 µm.

(23) MOVPE GaN Growth: Determination of Activation Energy Using In-Situ Reflectometry: *Nicoleta Kaluza*[1]; Hilde Hardtdegen[1]; Roger Steins[1]; Hans Lueth[1]; [1]Research Center Juelich, Institute of Thin Films and Interfaces, Juelich 52425

Since uniformity and reproducibility are prerequisites for the growth of device structures it is extremely important to control all growth parameters from run to run and across the wafer. For GaN growth the most important parameter to control is the growth temperature. Although there are many studies in ersatz-reactors for the different reactions which take place in parallel and successively, a careful investigation of the growth rate as a function of temperature in the growth equipment under true deposition conditions is useful to assess the temperature influence in all growth steps. Qualitatively in MOVPE, three growth temperature regimes can be established from an Arrhenius plot. For GaN growth, the activation energies corresponding to these regimes were determined using in-situ reflectometry. The growth limiting factors were identified. The results will be presented and put into perspective to uniform and reproducible growth for device applications.

(24) Aluminum Incorporation Control in AlGaN MOVPE: Experimental and Modeling Study: *Roman A. Talalaev*[1]; Alexey V. Kondratyev[1]; Wsevolod V. Lundin[2]; Alexey V. Sakharov[2]; Andrew V. Tsatsul'nikov[2]; Evgeny E. Zavarin[2]; Alexander V. Fomin[2]; Dmitry S. Sizov[2]; [1]Soft-Impact Ltd., Epitaxial Process Modlg., PO Box 33, St. Petersburg 194156 Russia; [2]A.F. Ioffe Physico-Technical Institute of Russian Academy of Sciences, Ctr. of Nanoheterostructure Physics, 26 Politehnicheskaya str., St. Petersburg 194021 Russia

Aluminum-rich AlGaN is one of the key materials for production of the optoelectronic devices operating in UV and blue-green range. At the same time there are well known difficulties in growing such layers by MOVPE associated with low efficiency of aluminum incorporation in AlGaN caused by parasitic gas-phase reactions. In this paper the results of a combined experimental and modeling study of AlGaN growth in production scale multiwafer (6x2") AIX2000HT Planetary Reactor are reported. The effects of reactor pressure, total flow rate and metalorganic flow rate variations on aluminum incorporation have been studied experimentally. Detailed simulations of flow dynamics and chemistry have enabled to identify the mechanisms responsible for aluminum losses in the gasphase. Model predictions have been found in a good agreement with the experimental data in a wide range of growth conditions and AlGaN compositions. From the results obtained, possible strategies of growing Al-rich AlGaN are proposed.

(25) Influence of AlGaN Nucleation Layers on Structural and Electrical Properties of GaN on 4H-SiC: Steven Boeykens[1]; M. R. Leys[1]; M. Germain[1]; G. Borghs[1]; R. Belmans[2]; [1]IMEC vzw, MCP - ART, Kapeldreef 75, Leuven B - 3001 Belgium; [2]K.U. Leuven, ESAT/ELECTA, Kasteelpark Arenberg 10, Leuven B-3001 Belgium

Using low pressure MOVPE with a close-coupled showerhead reactor Si doped GaN layers on 4H-SiC substrates were grown. On substrates with 8° off orientation $Al_{0.6}Ga_{0.4}N$ nucleation layers were grown at 1020°C with thicknesses ranging from 8 to 250 nm. At least 250 nm thickness was required to obtain specular, crack-free GaN layers of 3 µm thick. At this thickness the FWHM of the GaN (0002) rocking curve is 286 arcsec. A clear relation between AlGaN layer thickness and GaN FWHM exists. We have investigated lower Al-content layers on exactly oriented 4H-SiC in order to prepare devices with vertical conduction. Si doped GaN layers were grown on $Al_{0.3}Ga_{0.7}N$ and $Al_{0.1}Ga_{0.9}N$ nucleation layers deposited at temperatures varying from 930 to 1100°C. The lowest FWHM of the GaN (0002) rocking curve achieved to date using $Al_{0.1}Ga_{0.9}N$ grown at 1100°C was 231 arcsec. Electrical data and further structural investigations will be presented.

(26) Study of AlGaN/GaN HEMTs Grown on Silicon Substrates: *Shiping Guo*[1]; David W. Gotthold[1]; Brian Albert[1]; Boris Peres[1]; Alexei Vertaichich[2]; Lester F. Eastman[2]; [1]EMCORE Corporation, 145 Belmont Dr., Somerset, NJ 08873 USA; [2]Cornell University, Ithaca, NY 14853 USA

AlGaN/GaN based HEMTs have emerged as attractive candidates for high power and high frequency applications and are typically grown on SiC and sapphire substrates. However, due to production complexities SiC will be difficult to scale to large diameters, and sapphire has very poor thermal properties. Silicon substrates, with their very low cost and readily available large diameter, are an alternative choice for these applications. To date, there have been only few reports of devices grown on silicon. In this work, a study of AlGaN/GaN HEMTs grown on Si was performed. Crack-free surfaces were achieved with GaN thickness up to 2 µm using an EMCORE proprietary buffer technology. An excellent sheet resistance uniformity with a SD of ~ 2.9% was obtained for AlGaN/GaN HEMTs grown on 4" Si with an average R_s of 363 Ω/sq. Initial device process shows a good DC performance with a full channel current of 600mA/mm.

(27) Observation of Localized Carrier Effect in Novel Dilute Nitride Material GaInPN: *Shuo-Hsien Hsu*[1]; Cheng-Hsien Wu[1]; Yan-Kuin Su[1]; Shoou-Jinn Chang[1]; Pei-hsuan Wu[1]; Kuang-I. Lin[2]; [1]National Cheng Kung University, Inst. of Microelect., Dept. of Elect. Engrg., Tainan 701 Taiwan; [2]National Cheng Kung University, Dept. of Physics, Tainan City 701 Taiwan

We report a detailed study of the localized carrier effect and optical characterization of the novel dilute niride GaInNP films. These films were grown by metal organic vapor phase epitaxy on GaAs (100) substrates. These epitaxial layers were then characterized by a high-resolution x-ray rocking curve (XRC), modulation photoreflectance (PR) and photoluminescence (PL)masurements. With nitrogen incorporation, the PL peak red shifts, indicating that bandgap reduction and the line width broadening increase due to the increase of non-radiative centers. The S-shape in temperature dependence of the PL spectra shows a considerable number of carriers detrap from localized states to higher bound exciton states as the increasing temperature. The PR spectrum is used to confirm the nitrogen induced localization. Furthermore, this localization phenomenon observed in low temperature PL no longer exsits after RTA process. This result suggests that the crystal quality is significantly improved by thermal treatment.

(28) Three-Step Method for Growth of High-Quality GaN on Sapphire Substrates by Mass-Production Metalorganic Vapor Phase Epitaxy: *Shugo Nitta*[1]; Jun Yamamoto[1]; Yoshihisa Koyama[1]; Yuzaburoh Ban[1]; Kiyoshi Takahashi[1]; [1]Nippon EMC Ltd., R&D Ctr., 2008-2 Wada, Tama, Tokyo 206-0001 Japan

Blue, green, and UV LEDs are in great demand for applications such as indicators, display backlights, white LED lamps, etc. To answer these trends, high quality and uniformity of nitride epi-layers are requested for commercially available mass-production MOVPE equipment. The most common procedure for GaN growth on sapphire substrates is to first deposit a low-temperature buffer layer and then grow presumably high-quality GaN. However, the process window for high-quality GaN is narrow for this procedure and, thus, not well suited for mass-production MOVPE. We have developed a three-step method for easy and stable growth of high-quality GaN on sapphire substrates. The three steps involve a low-temperature buffer layer, facet-controlled GaN (FC-GaN) and a high-quality GaN layer. The FC-GaN has a rough morphology with intentionally formed facets. In this presentation we will show how the FC-GaN growth condition affects the XRD FWHM and surface morphology of the subsequently deposited GaN layer.

(29) High Performance GaN/InGaN Heterostructure FETs with Carrier Confinement Layers: Ta-ming Kuan[1]; Shoou-Jinn Chang[1]; Yan-Kuin Su[1]; Jia-Ching Lin[1]; Chuan-I. Huang[1]; James B. Webb[2]; Jennifer A. Bardwell[2]; Haipeng Tang[2]; Wen-Jen Lin[3]; Ya-Tung Cherng[3]; [1]National Cheng Kung University, Inst. of Microelect., No.1, Ta-Hseuh Rd., Tainan 701 Taiwan; [2]National Research Council, Inst. for Microstruct. Sci., 1200 Montreal Rd., Ottawa, Ontario K1A 0R6 Canada; [3]Chung Shan Institute of Science & Technology, Matls. R&D Ctr., PO Box. 9000-8-6, Lung-Tan 325 Taiwan

Nitride-based $GaN/In_{0.12}Ga_{0.88}N$ heterostructure field effect transistors (HFETs) with carrier confinement layers were successfully fabricated. The as-grown layers exhibited a very smooth surface. The DC and RF characteristics of these HFETs were also found to be good. Devices with a 0.75 µm gate length showed a maximum drain current (I_{DS}) of 421 mA/mm, and a maximum g_m of about 85.6 mS/mm at VGS between -0.5 V ~ -3 V. The device had very good pinch-off, and the mesa isolation was excellent. The RF characteristic of devices showed the current gain cutoff frequency, f_T, was 7.45 GHz and the maximum oscillation frequency, f_{MAX}, was 12.36 GHz.

(30) Structure Optimization of InGaN-GaN Ultraviolet Light-Emitting Diodes with a Low Energy Electron Injection Mechanism: Tae Geun Kim[1]; *Kyoung Chan Kim*[1]; Dong Ho Kim[1]; Suk Ho Yoon[2]; Cheol Soo Sone[2]; Yong Jo Park[2]; [1]KwangWoon University, Elect. Matls. Engrg., 447-1, Wolgye1-dong, Nowon-gu, Seoul 139-701 Korea; [2]Samsung Advanced Institute of Technology, Photonics Lab., San 14-1, Nongseo-ri, Giheung-eup, Yongin-si, Gyeonggi-do 449-901 Korea

The structure optimization of InGaN-GaN ultraviolet (UV) light-emitting diodes (LEDs) with electron tunneling barriers (ETBs), to reduce hot electrons overflowing out of multiple quantum well (MQW) during operation, is systematically carried out in both theoretical and experimental aspects. The InGaN-GaN MQW UV LEDs with and without (Al)GaN ETBs, grown by metal organic chemical vapor deposition, are fabricated and characterized for this purpose. One of the LEDs optimized with ETBs shows an 11.5 % increase in normalized photodiode currents as well as larger reverse breakdown voltages as compared with the reference LED. A reduction of the number of hot electrons overflowing to the p-side from MQW in terms of low-energy electron tunneling injection and a blocking of upward dislocations by the (Al)GaN ETB layers are likely to be primary reasons for the improvement.

(31) Reduction of Point Defect Density in Cubic GaN Epilayers on (001) GaAs Substrates Using AlGaN/GaN Superlattice Underlayers: *Taiki Nosaka*[1]; Mutsumi Sugiyama[1]; Tomonori Suzuki[1]; Takashi Koida[2]; Kiyomi Nakajima[3]; Toyomi Aoyama[4]; Masatomo Sumiya[5]; Toyohiro Chikyow[6]; Akira Uedono[1]; Shigefusa F. Chichibu[1]; [1]University of Tsukuba, Inst. of Applied Physics, 1-1-1 Tennodai, Tsukuba, Ibaraki 305-8573 Japan; [2]Japan Science and Technology Agency (JST), NICP, Exploratory Rsch. for Advd. Tech. (ERATO), 4-1-8 Honcho, Kawaguchi, Saitama 332-0012 Japan; [3]National Institute for Materials Science (NIMS), 1-1-1 Sengen, Tsukuba, Ibaraki 305-0047 Japan; [4]Tokyo Institute of Technology, Matls. & Structures Lab., 4259 Nagatsuta, Midori-ku, Yokohama 226-8503 Japan; [5]Shizuoka University, Dept. of Elect. & Elect. Engrg., 3-5-1 Johoku, Hamamatsu, Shizuoka 432-8561 Japan; [6]Combinatorial Materials Exploration and Technology (COMET), NIMS

Cubic(c-) GaN and related alloys are attracting attention because of their structural advantage over the hexagonal(h-) one that they do not suffer from the polarization fields normal to the (001) growth plane. However, they are supposed to be heteroepitaxially grown on lattice-mismatched substrates due to the lack of c-GaN substrate. Consequently, misfit dislocations are formed at the initial stage of the growth, and therefore stacking faults and h-GaN are generally involved in the films. In this work, effects of the insertion of short-period AlGaN/GaN superlattice(SL) underlayers are investigated to overcome these problems. As a result of the SL insertion, the Doppler-broadening S parameter, which reflects the density and/or size of Ga vacancy defects, of the c-GaN epilayers was reduced from 0.454 to 0.448. Simultaneously, the value of excitonic PL lifetime at 293 K was improved from 20 ps to 230 ps, indicating a tremendous reduction of nonradiative point defect density.

(32) Monolithic InGaN/GaN Light-Emitting Diodes with Near White-Light Emission from Crossed Blue/Green Quantum Well Structure: *Tzu Chi Wen*[1]; C. S. Chang[1]; J. K. Sheu[2]; [1]National Cheng-Kung University, Inst. of Microelect., Dept. of Elect. Engrg., Tainan 70101 Taiwan; [2]National Central University, Inst. of Optical Sci., Chung-Li 320 Taiwan

Tremendous progresses have been achieved in GaN-based white light emitting diodes (LEDs) which combined a phosphor wavelength converter with a GaN blue or UV LED chip. Phosphor-free white light LEDs can also be produced by the combination of two or three different LED chips, if these two or three LED chips emit photons at proper wavelengths with a proper power ratio. However, the driving circuits of these white LEDs are more complex than those phosphor-converted white LEDs. Previously, GaN-based LEDs with two groups of MQW(blue and green) have been demonstrated to achieve white light emission. However, the emission property of the dichromatic white light strongly depends on the thickness of each QW and/or of the separation layer between the two groups of MQW. To produce a monolithic white LED showing a blue and green emission with a relative power ratio of approximately 1, In this study, GaN-based LEDs were designed to have a multi-quantum-well active region including a green and a blue quantum well in one period. Eelectroluminescence measurements show two emission bands originating from the two different well regions. In electroluminescence, the intensity ratio of the two emission bands is nearly dependent of low DC injection current corresponding to a color temperature of around 6500 K (at a driving current of 20 mA). However, as the high injection currents were applied to the monolithic LEDs, the intensity of green band is increasingly higher than the blue band. This behavior is attributed to carrier transport between the two QWs and to the different carrier injection dynamics and will be discussed in the forthcoming conference.

(33) Modulation Doped Superlattice AlGaN Barrier GaN/AlGaN HFETs: Uttiya Chowdhury[1]; Kirk Price[2]; Michael M. Wong[3]; Dongwon Yoo[1]; Xuebing Zhang[1]; Milton Feng[2]; *Russell D. Dupuis*[1]; [1]Georgia Institute of Technology, Sch. of Elect. & Computer Engrg., 778 Atlantic Dr., Atlanta, GA 30332-0250 USA; [2]University of Illinois, Micro & Nanotech. Lab., Urbana, IL 61801 USA; [3]University of Texas, Microelect. Rsch. Ctr., Austin, TX 78758 USA

For nitride HFETs, the heterojunction forming the electron barrier has to be designed based on trade-offs between lattice mismatch, 2-DEG concentration and alloy scattering. In this work, we study the use of a superlattice based barrier which effectively increases the heterojunction barrier while reducing the lattice mismatch and alloy scattering. The structure studied consists of a 5 period superlattice of 2nm+2nm 30% and 20% AlGaN on GaN grown using MOCVD on 6H conducting SiC substrate. The wells of the second and third period of the superlattice are Si-doped to give the effect of modulation doping. Devices fabricated from the structure exhibit a high gm of ~212 and high Idsmax of 0.83 A/mm. In addition, the devices show a significant reduction in knee voltage (knee voltage~ 4V) in the family of curves and also in contact resistance as measured by transmission line measurements (TLM). To our knowledge, this is the first investigation of the use of superlattice structure for improvement of barrier properties in an HFET.

(34) Influence of Reactor Total Pressure on Optical Properties of MOCVD-Grown InGaN Layers: Lars Reißmann[1]; André Strittmatter[1]; Robert Seguin[1]; Sven Rodt[1]; Anja Brostowski[1]; *Udo W. Pohl*[1]; Dieter Bimberg[1]; [1]Technische Universität Berlin, Inst. für Festkörperphysik, Hardenbergstr. 36, Berlin 10623 Germany

Formation of InGaN quantum dots (QDs) with a high optical quality in GaN matrix is a demanding issue for visible light emitters. Since In incorporation and ensuing strain for QD formation in InGaN/GaN layers increases at higher pressures, we studied its effect. Layers with 1-2 nm thickness were grown on Si(111)-substrates at 800°C in N2/NH3 ambient. The excitonic ensemble maximum, measured by integral cathodo- or photoluminescence, shifts from 3.3 eV to 2.99 eV upon increase of the reactor pressure from 100 to 400 mbar, confirming increased In incorporation. Spatially resolved high-resolution CL spectra reveal that the spectrum of samples grown at 400 mbar - in contrast to growth at lower pressure - entirely consists of narrow single lines with 480 µeV minimum halfwidth, indicating their zero-dimensional origin. Spectral diffusion detected for some of these lines in time-resolved measurements indicates a common origin in quantum dots subjected to quantum-confined Stark effect.

(35) Growth of AlGaN Layers on Planar and Patterned Substrates: *Uwe Rossow*[1]; Daniel Fuhrmann[1]; J. Bläsing[2]; A. Krost[2]; G. Ecke[3]; M. Greve[1]; N. Riedel[1]; A. Hangleiter[1]; [1]Technical University Braunschweig, Inst. f. Techn. Phys., Mendelssohnstr. 2, Braunschweig 38106 Germany; [2]Otto-von-Guericke University Magdeburg, Inst. f. Exp. Physik, Magdeburg 39016 Germany; [3]Technical University Ilmenau, Inst. f. Festkörperelektronik, Ilmenau 98684 Germany

AlGaN layers are applied in various devices based on group-III-nitride semiconductors. Crystalline quality, composition and morphology need to be controlled by properly adjusting growth processes. Here we report on AlGaN growth by low pressure MOVPE (Aixtron AIX200RF) on planar and patterened surfaces of sapphire and 6H-SiC(0001) with focus on Al-incorporation and lateral growth. Precursor used are trimethylgallium, trimethylaluminium, trimethylindium and ammonia with hydrogen as carrier gas. Total pressure is varied between 20 and 200mbar and growth temperature 1460K (uncorrected thermocouple reading). All layers show good surface morphology, near bandedge luminescence and no sign of phase separation (Al-concentration < 50%). The Al-incorporation depends critically on growth parameters. For high pressures of 200mbar Al is hardly incorporated which can be understood as a result of prereactions involving TMAl and ammonia. For patterened substrates PL indicates lateral variation in Al composition as a consequence of mass transport and a reduced lateral growth rate compared to GaN.

(36) Self-Assembling GaN Dots on Al0.11Ga0.89N by Alternating Supply of Source Precursors: *Wen Cheng Ke*[1]; Huai Ying Huang[1]; Ching Shun Ku[1]; Ling Lee[1]; Wei Kuo Chen[1]; Ming Chin Lee[1]; Wen Hsiung Chen[1]; Wu Ching Chou[1]; Wen Jen Lin[2]; Yi Cheng Cherng[2]; Ya Tong Cherng[2]; [1]National Chiao Tung University, Electrophysics, Hsinchu 300 Taiwan; [2]Chung-Shan Institute of Science and Technology, Tao-Yuan 325 Taiwan

In this study, self-organized GaN dot structure is successfully grown on a slightly lattice-mismatched Al0.11Ga0.89N epilayer using flow-rate modulation epitaxy (FME) growth technique. From the variation of dot density with growth temperature (i.e. 840 ~ 960?•), we can find the GaN dot growth here is controlled predominately by the surface diffusion of Ga adatoms for substrate temperatures below 915°C and by re-evaporation at higher temperatures. The corresponding activation energy for surface diffusion at low temperatures and binding energy of adatom to the adsorption site at high temperatures are calculated to ~ 0.64 eV and ~ 1.2 eV, respectively. We believe the GaN dot growth in our study is mainly through Volmer-Weber growth mode, not the commonly used Stranski-Krastanow growth.

(37) Influence of Laser Power on Crystalline Quality of InGaN with High Indium Content Grown by Pulse Laser Assisted MOVPE: *Yoshihiro Kangawa*[1]; Ken-nosuke Hida[1]; Yoshinao Kumagai[1]; Akinori Koukitu[1]; Norihito Kawaguchi[2]; [1]Tokyo University of Agriculture and Technology, Dept. of Appl. Chmst., 2-24-16 Naka-cho, Koganei, Tokyo 184-8588 Japan; [2]Ishikawajima-Harima Heavy Industries Co., Ltd., Tech. Dvlp. & Engrg. Ctr., Yokohama 235-8501 Japan

In our theoretical study, it has been found that homogeneous InGaN film is grown at low temperature while inhomogeneous one is grown at high temperature. However, it is known that crystalline quality of the film becomes poor when it is grown at low temperature because migration length of the elements is not long enough to form high quality films. To obtain high quality and highly homogenized films with high indium content, we irradiated Nd: YAG pulse laser, which may enhance the migration of the elements without increase of temperature, on growth surface during MOVPE at low temperatures. The results suggest that suitable power of the laser prevents forming indium droplet and make the FWHM of omega-scan XRD InGaN(0002) peak profile narrower, while etching occurs if the laser power is higher than suitable power. This implies that energy of laser changes to kinetic energy and enhance the migration of the elements, however etching occurs if the converted energy is larger than the desorption energies.

(38) The Origins of Double Emission Peaks in Electroluminescence Spectrum from InGaN/GaN MQW LED: *Zhizhong Chen*[1]; Zhixin Qin[1]; Xiaodong Hu[1]; Yuzhen Tong[1]; Guoyi Zhang[1]; [1]Peking University, State Key Lab. of Artificial Microstruct. & Mesoscopic Physics, Physics Sch., Beijing 100871 China

InGaN/GaN multiple quantum wells (MQWs) light emitting diodes (LEDs) were grown by MOCVD. Double peaks in electroluminescence (EL) spectrum can be observed. With the current increases, the long-wavelength peak appears first, and its intensity was almost linear to the exponent of current. However, the intensity of the short-wavelength peak increased rapidly, then tended to saturate. In order to study the origins of the double emission peaks, the LED samples were annealed at 650, 750°C for 20 min, and 850, 950°C for 5 min. X-ray diffraction (XRD) , photoluminescence (PL) and PL excitation (PLE) measurements were performed on these annealed samples. With the annealing temperature increasing, the intensity of long-wavelength peak decreased compared to that of short one. And the indium content increased. It was concluded that there were two competitive processes in light emission of InGaN/GaN MQW: (1) emission from QDs, (2) emission from quantum wells.

Tuesday AM - June 1, 2004

Plenary Session

Tuesday AM Room: Kihei
June 1, 2004 Location: Westin Maui Hotel

Session Chairs: J. J. Coleman, University of Illinois, Urbana, IL 61801 USA; H. Amano, Meijo University, Nagoya, Japan

8:20 AM Invited
Growth Mechanism of Atmospheric Pressure MOVPE of GaN and its Alloys: *Koh Matsumoto*[1]; Akitomo Tachibana[2]; [1]Nippon Sanso Corporation, Mktg. Dept. Elect. Sales Div., 1-16-7 Nishi-Shimbashi, Minato-ku, Tokyo 105-8442 Japan; [2]Kyoto University, Dept. of Engrg. Physics & Mech., Kyoto 606-8501 Japan

Atmospheric pressure growth of GaN and related alloys are important for high quality optical devices. However, a parasitic reaction between TMA and NH3 impedes AlGaN growth at higher growth pressure. In this paper, we will try to present a comprehensive model of vapor phase reaction of GaN and its alloys, and will show our attempt of controlling parasitic reaction. At first, we will present a quantum chemical study of monomolecular and bi-molecular reactions of adduct with regard to experimental observations.[1] The calculated energy of each transition state to oligomer formation can well explain the experimental observation that TMGa-NH3 adduct formation and cracking is reversible, while TMA-NH3 adduct would react irreversibly to form higher order oligomers. Calculation suggests TMI-NH3 system would also be more likely to form polymer. Calculation implies that a transition state of TMG associated with two NH3 molecules would be the most probable path for methane elimination. Growth experiment by a reactor with recirculation flow showed a non-linear GaN growth rate variation along the flow direction at the growth rate of more than 2um/hr, while a laminar flow 3-layer gas injection reactor showed a linear growth rate variation even with growth rate of 10um/hr under atmospheric pressure. This contrasting result would possibly be explained if we consider a reaction among TMG, NH3 and a back diffusing DMGa-NH2 that has been reported to enhance dissociation of TMG.[2] By this 3 layer injection configuration, AlGaN with Al composition of ~30% on 4 inch diameter platen and more than 15% over 6 inch diameter platen can be grown under atmospheric pressure. These results show a vital usefulness of quantum chemical analysis to improve reactor design for controlling parasitic reactions. References: [1]K.Nakamura, O.Makino, A.Tachibana and K.Matsumoto, J. Organometallic Chem. 611(2000)514-524. [2]R.M.Watwe, J.A.Dumesic and T.F.Kuech, J. Crystal Growth 221(2000)751-757.

9:00 AM Invited
Recent Progress in GaSb-Based III-V Materials Grown by OMVPE: *C. A. Wang*[1]; [1]Massachusetts Institute of Technology, Lincoln Lab., Lexington, MA 02420-9108 USA

GaSb-based III-V semiconductor alloys are attractive for optoelectronic devices such as mid-infrared lasers, detectors, thermophotovoltaics (TPVs), and electronic devices such as high-speed transistors and resonant-tunneling diodes. Alloys of particular interest are based on the binaries GaSb, AlSb, InSb, GaAs, AlAs, and InAs. These materials are extremely versatile from the perspective of electronic bandgap engineering and of lattice-matched or strained-layer heterostructures. The energy gap can be adjusted over a very wide wavelength range from 0.8 µm for AlSb to 12 µm for InAsSb. In addition, a variety of diverse band alignments (type I, type II-staggered, type II-broken) are possible while still maintaining nearly lattice-matched alloys to substrates, such as InP, GaSb, or InAs; or if applicable, designing deliberate strain-layer heterostructures. The growth of Sb-based alloys, however differ significantly from the more conventional As- and P-based materials, both for fundamental and practical reasons. This paper will review recent advances in the GaSb-based alloys grown by organometallic vapor phase epitaxy, with particular emphasis on alloys lattice matched to GaSb for thermophotovoltaics and lasers.

Nitride Devices II

Tuesday AM Room: Kihei
June 1, 2004 Location: Westin Maui Hotel

Session Chairs: M. Hansen, Cree Inc., Santa Barbara, CA 93117 USA; K. Onabe, University of Tokyo, Tokyo 113-8656 Japan

9:50 AM
Sapphire Free Deep UV LED: *John F. Kaeding*[1]; [1]University of California, Matls., Santa Barbara, CA 93106-5050 USA

A novel, vertically conducting, sapphire free, low dislocation density deep-UV LED structure has been tried to mitigate the effects of self-heating and current crowding for improved device performance, using low pressure (76 torr) MOCVD combined with laser-assisted lift-off. First, a 2.1 ?Ým thick, low defect AlN template film is grown at 1125?aC on c-plane sapphire, using a group III to group V ratio of 25. Characterization by planview TEM reveals a low dislocation density of 5 x 109 cm-2, an order of magnitude reduction from previous high quality AlN thin film efforts. AlGaN n-type, active region, and p-type layers were deposited followed by a 20 nm p-GaN contact layer. A 248 nm KrF excimer laser is used to successfully separate the structure from the sapphire substrate at the defective AlN/sapphire interface region. Standard processing techniques are employed to produce a vertically conducting LED structure exhibiting superior thermal management.

10:10 AM
280 nm Deep Ultraviolet LED's Grown on SiC: *Craig Gunar Moe*[1]; Pablo Cantu[2]; Kenneth Vampola[1]; Stacia Keller[2]; Steven DenBaars[1]; David Emerson[3]; [1]University of California, Matls. Engrg., Santa Barbara, CA 93106 USA; [2]University of California, Elect. & Computer Engrg., Santa Barbara, CA 93106 USA; [3]Cree, 4600 Silicon Dr., Durham, NC USA

Deep ultraviolet light emitting diodes with a peak wavelength of 280 nm were grown by metalorganic chemical vapor deposition on (0001) 4H silicon carbide. The active region consisted of four quantum wells of 7 nm Al(0.47)Ga(0.53)N:Si/ 3 nm Al(0.38)Ga(0.62)N:UID. Despite the fact that it absorbs light in the deep ultraviolet spectrum, silicon carbide was chosen as a substrate rather than sapphire for its improved thermal conductivity and the potential for vertically conducting devices. A maximum output power of 9µW was observed at 100mA DC, on-wafer testing, using a broad area silicon photodiode. Optimization of the nucleation layer and the AlGaN:Mg layer growth conditions was essential to reduce additional emissions at 350 and 370 nm. Introduction of an n-type short period alloy superlattice (SPASL) also supressed emissions at undesired wavelengths. In addition we will discuss the effects of quantum well parameters on the device performance. The authors wish to acknowledge the support of the the DARPA SUVOS program (managed by LTC John Carrano).

10:30 AM
Low Pressure MOCVD Deposition of High Quality AlGaN Heterostructures for 250-280nm Deep Ultraviolet Light Emitting Diodes: V. Adivarahan[1]; W. Sun[1]; J. P. Zhang[2]; M. Shatalov[1]; A. Chitnis[1];

M. Asif Khan[1]; [1]University of South Carolina, Dept. of Elect. Engrg., 301 Main St., Columbia, SC 29208 USA; [2]Sensor Electronic Technology, Inc., 1195 Atlas Rd., Columbia, SC 29209 USA

We will discuss the growth and characterization of AlGaN multiple quantum well based deep ultraviolet light emitting diodes with emission at 245-280 nm. The use of Migration Enhanced Metal Organic Chemical Vapor Deposition (MEMOCVD) epitaxial technique for the growth of AlN/AlGaN buffer and strain-relief layers resulted in devices with record performance levels. Room temperature DC and pulsed powers as high as 1.53 mW (450 mA) and 24 mW (1.5 A) were measured for a 200 µm x 200 µm devices with emission at 280 nm. In this paper we will present the epitaxy, the device fabrication and testing details. Initial results for devices with peak emission at 250 nm will also be presented for the first time.

10:50 AM Break

Dots I

Tuesday AM
June 1, 2004

Room: Kula
Location: Westin Maui Hotel

Session Chairs: J. M. Redwing, Pennsylvania State University, Univ. Park, PA 16802 USA; J. S. Kim, Electronics and Telecommunications Research Institute, Daejeon Korea

9:50 AM

The Role of Antimony in the Growth of Indium Arsenide Quantum Dots by Metalorganic Vapor-Phase Epitaxy: *Robert F. Hicks*[1]; Yan Sun[1]; Dick Cheng[1]; Jeff Cederberg[2]; Robert Biefeld[2]; [1]UCLA, Chem. Engrg., 5531 Boelter Hall, Los Angeles, CA 90095 USA; [2]Sandia National Laboratory, PO Box 5800, Albuquerque, NM 87185 USA

The effect of sub-monolayer antimony coverages on the growth of InAs quantum dots on GaAs has been studied during metalorganic vapor-phase expitaxy. After depositing 1 to 2 bilayers of InAs at 723 K, the samples were quenched, transferred to ultrahigh vacuum, and characterized by scanning tunneling microscopy and x-ray photoelectron spectroscopy. Previous studies found that Sb is a surfactant in the heteroepitaxy of semiconductors, such as InGaAsN on GaAs and Ge on Si, where it promotes two-dimensional growth. By contrast, we observe that Sb incorporates into the crystal lattice, forming InAsSb alloys. The increased strain from Sb incorporation leads to reduced surface wetting and more densely clustered quantum dots. Moreover, the critical thickness for onset of quantum dot formation is less than that observed for InAs layers without Sb. We will discuss the quantum dot formation mechanism, and propose methods for controlling antimony incorporation relative to surface segregation.

10:10 AM

Real-Time Control of Quantum Dot Laser Growth Using Reflectance Anisotropy Spectroscopy: *Udo W. Pohl*[1]; Konstantin Pötschke[1]; Ilia Kaiander[1]; Jörg-Thomas Zettler[2]; Dieter Bimberg[1]; [1]Technische Universität Berlin, Inst. für Festkörperphysik, Hardenbergstr. 36, 10623 Berlin Germany; [2]LayTec GmbH, Helmholtzstr. 13-14, 10623 Berlin Germany

The complexity of advanced device growth stimulates demand for online diagnostic tools. We use spectroscopic reflectance to control epitaxy of InGaAs/GaAs quantum dots (QDs) and QD lasers. Optical real-time transients recorded at fixed photon energy show a detailed complex response within the initial seconds after InGaAs deposition. Characteristic features to successive process steps in the formation of different InAs and InGaAs dot types indicate a response on changes of both, morphology and surface stoichiometry. Real-time response on doping of GaAs layers and on composition of AlGaAs layers which clad the active QD core in laser structures were studied in addition, yielding online evaluation on doping levels, refractive indices and compositions. We present here RAS spectra of complete device runs including the first vertical cavity surface emitting laser (VCSEL) with active QDs grown using MOCVD. A first processed InGaAs QD device shows 0.7 mW cw ouput power at room temperature.

10:30 AM

Formation of High-Density (>1.5x10^{11} cm^{-2}) GaN Self-Assembled Quantum Dots by MOCVD: *Katsuyuki Hoshino*[1]; Yasuhiko Arakawa[1]; [1]University of Tokyo, Rsch. Ctr. for Advd. Sci. & Tech., & Inst. of Industrial Sci., 4-6-1 Komaba, Meguro-ku, Tokyo 153-8505 Japan

We have successfully obtained GaN self-assembled quantum dots (QDs) with high density (>1.5x10^{11} cm^{-2}) by the Stranski-Krastanow (SK) growth mode in a metalorganic chemical vapor deposition under low V/III ratios. An abrupt transition from two-dimensional to three-dimensional growth mode is observed by depositing over the critical thickness of GaN. The typical diameter and height of the QDs are 15 nm and 1.5 nm, respectively. The density of the QDs can be changed between 10^{9} and 10^{11} cm^{-2}. Furthermore, the photoluminescence peaks from both the QDs and the wetting layer are clearly observed even in uncapped QD structures at room temperature. These results clearly demonstrate that the QDs are formed with the SK growth mode. The growth technique of the GaN QDs developed here is promising for application to highly efficient UV light emitters. This work is supported by the IT program, MEXT.

10:50 AM Break

Basic Growth I

Tuesday AM
June 1, 2004

Room: Kihei
Location: Westin Maui Hotel

Session Chairs: T. F. Kuech, University of Wisconsin, Madison, WI 53706 USA; F. Scholz, University of Ulm, Germany

11:30 AM

Growth of Mn Doped III-V Semiconductors in MOVPE: *Markus Pristovsek*[1]; S. Weeke[1]; A. Philippou[1]; C. Kaspari[1]; F. Poser[1]; W. Richter[1]; [1]TU-Berlin, Inst. f. Festkoerperphysik, PN6-1, Hardenbergstr. 36, Berlin 10623 Germany/RFA

Ferromagnetic semiconductors are promising candidates for the manufacturing of spintronic devices. But up to now the Curie temperature of the most investigated compound - GaMnAs - is less than 150 K. Furthermore, at the higher growth temperatures necessary in MOVPE (above 450°C) cluster formation occurs in GaMnAs. Therefore we studied other candidates, namely the nitrides and phosphides. While InMnP was among the first reported ferromagnetic III-V semiconductors, InMnN is predicted the highest Curie temperature of all III-V Mn-doped semiconductors. We used standard hydrides and MOs together with dimethylcyclopentadienyl-manganese and tertiery-Butylhydrazine for Mn and N precursors. Using in-situ RAS we could successful monitor the change of hole concentration, the onset of cluster formation and roughening due to layer relaxation.

11:50 AM

The Role of the Surface Adsorption Layer During InGaAsP MOVPE Growth Analyzed by the Flow Modulation Method: *Takayuki Nakano*[1]; Masakazu Sugiyama[2]; Yoshiaki Nakano[3]; Yukihiro Shimogaki[1]; [1]University of Tokyo, Dept. of Matls. Engrg., 7-3-1, Hongo, Bunkyo-ku, Tokyo 113-8656 Japan; [2]University of Tokyo, Dept. of Elect. Engrg., 7-3-1, Hongo, Bunkyo-ku, Tokyo 113-8656 Japan; [3]University of Tokyo, Rsch. Ctr. for Advd. Sci. & Tech., 4-6-1, Komaba, Maguro-ku, Tokyo 151-8904 Japan

We had investigated the growth of InGaP on GaAs and found that In atoms segregate to the surface. The thickness of the surface In-rich layer was always 10% of the total InGaP layer. This phenomenon could not be explained by the normal MOVPE growth model, in which the group-III element adsorbed on the surface is directly converted into a crystal thin film. Hereby, we propose a novel crystal growth model considering the liquid-like surface adsorbed layer. The In surface segregation can be easily explained by assuming that the reaction rate to incorporate atoms from gas-phase and the rate to convert the adsorbed species into solid crystal have a significant difference. We have performed a quantitative analysis on the existence of the surface adsorbed layer using the flow modulation method.

12:10 PM

Ordering Structure Along the [001] Direction of InAlAs: *Kaori Kurihara*[1]; *Hideo Namita*[2]; Rie Ueda[2]; Masaki Takashima[2]; Koichi Akimoto[3]; Kohzo Sakata[2]; Toshiya Takahashi[3]; Tomohisa Nakamura[2]; Kenji Shimoyama[1]; [1]Mitsubishi Chemical Corporation, Opto-Elect. Lab., 1000, Higashi-Mamiana, Ushiku, Ibaraki 300-1295 Japan; [2]STRC Mitsubishi Chemical Group, 8-3-1, Chu-o, Ami, Inashiki, Ibaraki 300-0332 Japan; [3]Nagoya University, Quantum Engrg., Furo-cho, Chikusa-ku, Nagoya, Aichi 464-8603 Japan

We have found a new type natural superlattice (NSL) in InAlGaAs materials on InP substrate. Generally the NSL is toward to [111] or its equivalent direction. However, this NSL stacks along the [001] i.e. perpendicular to the substrate. InAlGaAs layers on sulfur-doped vicinal (001) InP substrates were grown by LP-MOVPE. We used TMIn, TMAl, TMGa, PH3 and AsH3 as the III and V group precursors. The growth temperature was 650°C and the V/III ratio was 200. In the experiments, we used samples, which showed lattice matching against an InP substrate within 0.1% of average strain. We investigated the ordering using TEM from the [110] and [-110] directions and found 3ML pitch horizontal stripes in both directions. From reciprocal mapping, we also confirmed that this periodical structure is stacked along the [001] direction with a 3ML pitch.

Dots II

Tuesday AM Room: Kula
June 1, 2004 Location: Westin Maui Hotel

Session Chairs: D. Huffacker, University of New Mexico, Albuquerque, NM 87131 USA; M. Leys, IMEC vzw, Leuven B-3001 Belgium

11:30 PM
Advancements in the Growth and Applications of Pyramidal Quantum Dots: *Pelucchi Emanuele*[1]; Watanabe Shinichi[1]; Anton Malko[1]; Martin H. Baier[1]; Klaus Leifer[1]; Benjamin Dwir[1]; Christof Constantin[1]; Alok Rudra[1]; Eli Kapon[1]; [1]Swiss Federal Institute of Technology Lausanne (EPFL), Lab. of Physics of Nanostructures, Inst. of Quantum Photonics & Elect., Sch. of Basic Scis., PHB-Ecublens, Lausanne, Canton de Vaud CH-1015 Switzerland

Pyramidal quantum dots (QDs) grown by MOVPE on patterned (111)B substrates are standing out as an important alternative to Stranski-Krastanow QDs for emerging quantum information technologies and cavity quantum electrodynamic experiments. They naturally provide site control and demonstrated sharp excitonic features with the highest emission energy uniformity of QD ensembles so far reported. Flexible energy tuning by growth parameters and a wide choice in the possible densities (from isolated to ~10E9 dots/cm2) are also acknowledgeable properties. Single photon emission from such Pyramidal QDs and their incorporation into light emitting diodes were also demonstrated. The possibility of simultaneous control of position and emission energy simply via the modification of the pattern features is a unique, striking characteristic of this system. This QD engineering is made possible by the different growth rates of the patterned (111)A planes and unpatterned (111)B surfaces on the wafer. Exploitation of such control in novel photonic crystals will be discussed.

11:50 PM
Selective Growth of InGaAs Quantum Dots by Selective Area Epitaxy MOCVD Growth: *Victor C. Elarde*[1]; Terence S. Yeoh[1]; Radhika Rangarajan[1]; *James J. Coleman*[1]; [1]University of Illinois, Elect. Engrg., Micro & Nanotech. Lab., 208 N. Wright St. #268, Urbana, IL 61801 USA

Control over the location, distribution, and size of quantum dots is essential for the engineering of next generation semiconductor devices employing these remarkable nanostructures. We describe two approaches for achieving some level of this control in the InGaAs/GaAs material system. The first allows a degree of spatial selectivity by using strain differences in patterned InGaAs thin films as preferential sites for quantum dot growth. This method results in patterns of dots similar to those grown by self-assembly on an unpatterned InGaAs layer. The second method employs more conventional selective area epitaxy using a thin silicon dioxide mask patterned by electron beam lithography. This method allows control over the location of each quantum dot and variation of dot size through manipulation of the mask pattern. We present data on arrays of highly uniform InGaAs quantum dots fabricated in this manner.

12:10 PM
1.55 µm Emission from InAs Quantum Dots Grown on GaAs: *Tung-Po Hsieh*[1]; Nien-Tze Yeh[2]; Pei-Chin Chiu[1]; Wen-Jeng Ho[2]; Jen-Inn Chyi[1]; [1]National Central University, Dept. of Elect. Engrg., No.300, Jungda Rd., Taoyuan, Jhongli 32054 Taiwan; [2]Chunghwa Telecom Co., Telecomm. Labs., 12, Lane 551, Min-Tsu Rd. Sec.5,Taoyuan, Yang-Mei 32054 Taiwan

We report a comparative study on the growth of InAs quantum dots (QDs) on GaAs by metal-organic vapor phase epitaxy (MOVPE) using triethylgallium (TEG) and trimethylgallium (TMG) for the GaAs cap layer. Quantum dots exhibit 1.3 µm photoluminescence (PL) at room temperature as the GaAs cap layer is directly grown on the quantum dots. The PL emission can be extended to 1.49 µm when an In0.25Ga0.75As strain reducing layer (SRL) is inserted between the cap layer and the InAs QDs. The use of TMG or TEG for the growth of the GaAs cap layer becomes essential for further increasing the emission wavelength of the InAs QDs by employing an In0.31Ga0.69As SRL. Strong PL emission with wavelength as long as 1.55 µm (FWHM < 30 meV) can be obtained as the GaAs cap layer is grown by TEG while the optical property is severely degraded when using TMG. To the best of our knowledge, this is the longest emission wavelength obtained from InAs QDs prepared by MOVPE.

Tuesday PM - June 1, 2004

Plenary Session

Tuesday PM Room: Kihei
June 1, 2004 Location: Westin Maui Hotel

Session Chairs: S. Stockman, Lumileds Lighting, San Jose, CA 95131 USA; R. D. Dupuis, Georgia Institute of Technology, Atlanta, GA 30332-0250 USA

2:00 PM
MOVPE Growth Characteristics and Device Applications of (GaIn)(NAs)/GaAs-Heterostructures: Wolfgang Stolz[1]; Kerstin Volz[1]; [1]Philipps-University Marburg, Matl. Scis. Ctr. & Dept. of Physics, Central Tech. Lab., D-35032 Marburg Germany

The experimentally observed large band gap bowing for mixed III/V nitrides as a function of the nitrogen content, has led to tremendously increasing research activities in the growth of the novel quaternary material system (GaIn)(NAs). This material opens up the possibility of achieving wavelengths up to 1.3 and 1.55 µm emission based on GaAs substrates, which is extremely important e.g. for telecommunication applications. Due to the metastability of the dilute nitrides extreme non-equilibrium growth conditions at low deposition temperatures have to be used. We present detailed MOVPE (metal organic vapour phase epitaxy) growth studies of the quaternary material system and its characteristics. MOVPE growth is performed by using the more efficiently decomposing group V precursors tertiarybutylarsine (TBAs) and 1,1 dimethylhydrazine (UDMHy) in a commercial Aix 200 reactor system. As group III precursors triethylgallium (TEGa) and trimethylindium (TMIn) are used. N incorporation into the quaternary metastable alloy using MOVPE is characterized by N-desorption as well as group V competition, resulting in complex dependencies of the composition on growth parameters, like e.g. growth rate, deposition temperature, V/V- as well as V/III-ratios. Unintentional carbon incorporation of the material also strongly depends on the chosen growth conditions. Intrinsic characteristics of the metastable quaternary material system include morphological phase transitions if a critical N-content is exceeded as well as an annealing induced blueshift of the bandgap which is caused by local N-atomic rearrangement during the annealing process. This paper will summarize the present status of the understanding of the MOVPE growth conditions, the specific structural as well as electronic properties and the correlation to device characteristics.

2:40 PM Break

Novel Materials I

Tuesday PM Room: Kihei
June 1, 2004 Location: Westin Maui Hotel

Session Chairs: S. Stockman, Lumileds Lighting, San Jose, CA 95131 USA; T. Fukui, Hokkaido University, Sapporo, Hokkaido 060-8628 Japan

4:00 PM
Heteroepitaxy and Nitrogen Doping of High-Quality ZnO: *A. Dadgar*[1]; N. Oleynik[1]; J. Blaesing[1]; S. Deiter[1]; D. Forster[1]; F. Bertram[1]; A. Diez[1]; M. Seip[2]; A. Greiling[2]; J. Christen[1]; A. Krost[1]; [1]Otto-von-Guericke-Universitaet Magdeburg, FNW/IEP, Universitaetsplatz 2, Magdeburg 39106 Germany; [2]Mochem GmbH, Hannah-Arendt-Str. 3-7, Marburg 35037 Germany

ZnO is an interesting wide-gap semiconductor for a variety of electronic and optoelectronic applications. Although ZnO substrates are available their fair quality and nucleation problems are still a problem for the homoepitaxial growth of ZnO. We developed a two step growth process for ZnO on GaN templates and achieve high quality ZnO layers with XRD rocking curve FWHMs of the (0002) reflection of ~180" and narrow cathodoluminescence of 1.3 meV of the dominant I8 emission. For the application in devices p-type doping is still a major problem and has until now not worked out to be reliable enough to produce a p-n homojunction device. We have investigated several nitrogen sources as NH3, UDMHy and NO for doping. While no or only a low amount of nitrogen can be incorporated using NO we observe a brownish colour of the samples when using NH3 or UDMHy for higher dopant flows. With it we also find an increase in the electron carrier concentration from 10^{16} cm^{-3} to above 10^{18} cm^{-3}. Thus, these nitrogen precursors do not support p-type conductivity for higher flows. Because the crystalline quality degrades as can be seen in XRD measurements p-type doping is likely only possible in a small parameter window. For some samples grown with lower dopant flows we observe a decrease in the carrier concentration upon annealing. Especially when using UDMHy we observe N-correlated luminescence and phonon replica up to the fifth order. We will present details of the growth process and latest results on N-doping.

4:20 PM

Ferromagnetic (MnGa)As/GaAs-Cluster Hybrid Layers by MOVPE for Spin-Opto-Electronics: *Michael Lampalzer*[1]; Kerstin Volz[1]; Clemens Pietzonka[1]; Werner Treutmann[1]; Torsten Torunski[1]; Siegfried Nau[1]; Wolfgang Stolz[1]; [1]Philipps-University Marburg, Central Tech. Lab. & Matl. Scis. Ctr., Hans-Meerwein-Strasse, Mehrzweckgebaeude C6321, Marburg D-35032 Germany

In the recent years the interest on diluted magnetic III/V-semiconductors as a basis for spin-(opto-) electronics has been strongly increased. Here, we present our studies of successful epitaxial growth by MOVPE of ferromagnetic hybrid structures consisting of a GaAs:Mn matrix and defect-free embedded (MnGa)As clusters. Growth rate, reactor temperature and V/III-ratio have been varied to control the cluster growth and thereby simultaneously the magnetic properties. The high structural quality of these defect-free embedded cluster layers is verified by means of atomic force microscopy (AFM) and in particular transmission electron microscopy (TEM). Investigations by SQUID-magnetometer show ferromagnetism in these samples with Curie temperatures above room temperature. In combination with the successfully achieved n-type Te-codoping of the matrix, these clusters layers are enabling the growth of structures for studying spin-polarizing effects. We are presenting and discussing results of our realized LED- and Laser-devices using cluster hybrid structures as spin-aligner.

4:40 PM

Artificial Control of ZnO Nanostructures Grown by MOCVD: *Shizuo Fujita*[1]; Sang-Woo Kim[2]; Masaya Ueda[2]; Shigeo Fujita[2]; [1]Kyoto University, Internatl. Innovation Ctr., Yoshida-honmachi, Sakyo-ku, Kyoto 606-8501 Japan; [2]Kyoto University, Dept. Elect. Sci. & Engrg., Katsura, Ukyo-ku, Kyoto 615-8510 Japan

Control technique for position, shape, and size of self-assembled ZnO nanostructures has been investigated. A nanohole (e.g., 50-nm diameter and 5-nm depth) fabricated on a SiO_2 substrate by FIB-etching could successfully accommodates a ZnO nanodot (e.g., 30-nm diameter and 5-nm height) deposited by MOCVD using diethylzinc and N_2O. Two-dimensional array of more than 2,500 nanodots (50x50) with the period of smaller than 200nm was demonstrated by using this technique. Nanowire and the similar structures have been synthesized using size-controlled Au nanoparticles spin-coated on a SiO_2 substrate as catalysts. MOCVD allowed low temperature (400-550°C) growth of various nanostructures compared to the high growth temperature in the previous vapor phase growth techniques. Exciton-related phenomena such as biexciton emission as well as stimulated emission due to exciton-exciton scattering have been observed in nanodot and nanorod structures. It is shown that MOCVD well contributes to extract unique and attractive functions of high-quality ZnO nanostructures.

5:00 PM

MOVPE Growth of Nitrogen-Doped p-Type ZnO: *Koki Saito*[1]; Kouhei Nagayama[1]; Yasushi Hosokai[1]; Koichi Ishida[1]; Kiyoshi Takahashi[1]; Makoto Konagai[2]; [1]Teikyo University of Science and Technology, Dept. of Media Sci., 2525 Yatsusawa, Uenohara-machi, Kitatsuru-gun, Yamanashi 409-0193 Japan; [2]Tokyo Institute of Technology, Dept. of Elect. & Elect. Engrg., 2-12-1 O-okayama, Meguro-ku, Tokyo 152-8552 Japan

Nitrogen-doped ZnO layers were grown using diethylzinc (DEZ) and water (H_2O) as Zn and O precursors and monomethylhydrazine (MMHy) or tertiarybutylamine (t-BuNH_2) as nitrogen source. Raman spectra revealed nitrogen-related vibrational modes at 275, 510, 582 and 643 cm^{-1} in addition to the host phonons of ZnO. The intensity of these additional modes was increased with increasing the amount of nitrogen source. These ZnO samples were thermally annealed under an oxygen ambient to activate nitrogen as an acceptor. By increasing the annealing temperature from 700 °C to 900 °C, the intensity of additional modes was decreased, which indicates the dissociation and re-evaporation of nitrogen complexes. By capacitance-voltage (C-V) measurements, undoped ZnO layers showed n-type conductivity with net donor concentration of about 10^{19} cm^{-3}. In contrast, nitrogen-doped ZnO layer annealed at 800 °C showed p-type conductivity with net acceptor concentration of $2x10^{15}$ cm^{-3}.

Devices I

Tuesday PM Room: Kula
June 1, 2004 Location: Westin Maui Hotel

Session Chairs: R. D. Dupuis, Georgia Institute of Technology, Atlanta, GA 30332-0250 USA; S. Yoon, Samsung Advanced Institute of Technology, Yongin-si, Gyeonggi-do 449-901 Korea

4:00 PM

1550nm VCSEL Structure Optimization for High-Power and High-Temperature Operation: Mereuta Alexandru[1]; Sirbu Alexei[1]; Iacovlev Vladimir[1]; *Rudra Alok*[2]; Caliman Andrei[2]; Suruceanu Grigore[1]; Berseth Claude-Albert[1]; Deichsel Eckart[2]; Kapon Eli[2]; [1]BeamExpress SA, PSE-EPFL Batiment C, Lausanne 1015 Switzerland; [2]EPFL, IPEQ, 1015 Lausanne Switzerland

In this work we present epitaxial growth and design optimisation of 1550m VCSEL structures for high power, single mode and high temperature operation. All epitaxial layers were grown by low-pressure MOVPE in nitrogen atmosphere. The final VCSEL structure comprises a strain-compensated InAlGaAs MQW active region, a p++/n++ In(Al)GaAs tunnel junction and top and bottom AlGaAs/GaAs fused distributed Bragg reflectors. Excellent optical and electrical confinement is obtained by wafer-bonding of top mirror on tunnel junction pre-etched mesas. Devices with 7 μm aperture show single transverse mode CW operation up to 3 mW at room temperature with 30-35 dB side-mode suppression ratio and a far field divergence angle of 9°. A record output power level of 0.75 mW at 80°C is demonstrated for the first time by off-set optimization between the peak of photoluminescence spectrum of the InAlGaAs MQWs and the VCSEL cavity mode.

4:20 PM

Impact of Thermal Annealing on the Characteristics of InGaN/GaN LEDs on Si(111): K. Fehse[1]; T. Riemann[1]; *A. Dadgar*[1]; T. Hempel[1]; J. Christen[1]; A. Krost[1]; [1]Otto-von-Guericke-Universitaet Magdeburg, FNW/IEP, Universitaetsplatz 2, Magdeburg 39106 Germany

InGaN/GaN blue light emitting diodes (LEDs) were grown on Si(111) substrates in an AIX-200/4 RF-S reactor. The active region consists of an InGaN/GaN:Si multiple quantum well embedded between GaN:Si and AlGaN:Mg followed by GaN:Mg. While cracking of the diode stack is avoided by the insertion of low-temperature AlN, a reduction of the threading dislocation density is achieved by ultra-thin SiN interlayers. Subsequent to MOVPE growth, these LED structures were thermally annealed under oxygen to achieve optimized activation of the p-GaN top layer. The impact of annealing on the LED emission is assessed by photoluminescence and scanning cathodoluminescence microscopy (CL). For increasing annealing times both methods prove a drastic reduction of the donor-acceptor-pair recombination originating from the top p-GaN layer, while the emission of the n-GaN:Si remains unchanged even for long annealing times. The modification of the p-GaN:Mg is in agreement with a rise of the hole concentration in C-V measurements and will be correlated with the electrical characteristics of the LEDs. The vertical carrier transport properties before and after annealing are quantitatively evaluated by CL for different LED setups.

4:40 PM

Characteristics of Long Wavelength (λ=1.41 μm) InGaAsN Quantum Well Lasers: Jeng-Ya Yeh[1]; *Luke J. Mawst*[1]; Nelson Tansu[2]; [1]University of Wisconsin, Reed Ctr. for Photonics, Dept. of Elect. & Computer Engrg., 1415 Engrg. Dr., Madison, WI 53706 USA; [2]Lehigh University, Ctr. for Optical Tech., Dept. of Elect. & Computer Engrg., 7 Asa Dr., Bethlehem, PA 18015 USA

Long wavelength InGaAsN single quantum-well (QW) lasers with AlGaAs cladding layers are grown by one-step low-pressure metalorganic chemical vapor deposition (MOCVD). The QW composition and barrier materials (GaAsP or GaAsN) are shown to have a strong influence on the device performance, providing insights into the nonradiative recombination processes. Photoluminescence studies indicate a 50% reduction in PL intensity with similar FWHM (35 meV) when GaAs barriers are replaced by GaAsN. In-situ thermal annealing for QW's with GaAsN barriers exhibit significantly less (40-60% less) blueshift compared with GaAs barrier structures, allowing the p:AlGaAs cladding layer of the laser structure to be grown at higher temperature (700 °C). A QW growth temperature of 490 °C allows for an emission wavelength of 1.49 μm. Lasers with wavelengths as long as 1.41 μm are achieved employing GaAsN barriers, representing the longest lasing wavelength reported for MOCVD growth InGaAsN lasers. Threshold current densities range from 250 A/cm^2 at λ=1.32 μm to 1900 A/cm^2 at λ=1.41 μm.

5:00 PM
MOCVD Growth of High-Performance Strain-Compensated InGaAs:Sb-GaAsP-GaAs (Wavelength = 1.27 μm) Vertical Cavity Surface Emitting Lasers: *Hao-chung Kuo*[1]; H. H. Yao[1]; Y. S. Chang[1]; M. Y. Tsai[1]; S. C. Wang[1]; L. H. Laih[2]; [1]National Chiao-Tung University, Inst. of Electro-Optical Engrg., 1001 Ta Hsieh Rd., Hsin-Tsu city 300 Taiwan; [2]M-com Corporation, Hsin-Tsu City 300 Taiwan

In this paper, we present high performance strain-compensated In0.4Ga0.6As:Sb/GaAsP quantum-wells (QWs) vertical cavity surface emitting lasers (VCSELs) on GaAs substrates, grown by low-temperature (550 degree C) MOCVD. The incorporation of Sb(~1.5%) during growth of InGaAs/GaAsP QWs significantly enhances the optical properties of the QWs and high quality InGaAs:Sb/GaAsP QWs with emission wavelength extended to 1.24μm were achieved from the optimized growth condition. With a 30nm gain-cavity detuning, 1.27μm InGaAs:Sb/GaAsP VCSELs were grown and fabricated using oxide-confined process with 4x4 um2 confined aperture. These devices show excellent performance with threshold currents ~1.5mA, and the single mode peak power upto 1.2mW at 6mA. The threshold current change with temperature is minimal ~ -0.2mA to 1.3mA and the slope efficiency drops less than ~40% when the substrate temperature is raised to 90oC. The eye diagram of VCSEL operating at 2.125Gb/s with 4mA bias and 10dB extinction ratio shows very clean eye.

Quantum Structures Poster Session - 6:00 to 8:00 PM

Tuesday PM
June 1, 2004

Room: Lahaina
Location: Westin Maui Hotel

Session Chair: E. Yoon, Seoul National University, Seoul 151-742 Korea

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(1) Scanning E-Beam Pumped Resonant Periodic Gain VCSEL Based on MOVPE-Grown GaInP/AlGaInP MQW Structure: *A. B. Krysa*[1]; V. Yu. Bondarev[2]; V. I. Kozlovsky[2]; J. S. Roberts[1]; Ya. K. Skasyrsky[2]; [1]University of Sheffield, EPSRC Natl. Ctr. for III-V Tech., Dept. of Elect. & Elect. Engrg., Mappin St., Sheffield S1 3JD UK; [2]P.N. Lebedev Physical Institute of RAS, 53 Leninsky prospekt, Moscow 119991 Russia

17- and 25-period Ga0.5In0.5P/(Al0.7Ga0.3)0.5In0.5P MQW structures were grown by MOVPE on GaAs substrates misoriented by 10deg from (001) to (111)A. Each structure was fabricated into a microcavity with dielectric oxide mirrors. Under scanning electron beam longitudinal pumping, lasing in the 619-644 nm spectral range with an output power up to 9 W was achieved at RT. The laser wavelength and output power is dependent on the misalignment between the material gain and the MQW period. The minimum threshold current density at electron energies of 40 keV was 8 A/cm2. It is shown that low threshold and high power lasing requires the position of the QWs to coincide with the antinodes of the cavity mode and the maximum of the gain spectrum at the QW ground state energy. We find that to maintain a threshold within 10% of the minimum, the MQW period should be tuned within an accuracy of 1% of the optimum value.

(2) Optimization of GaAs/AlGaAs Quantum Wells Using Misoriented GaAs Substrates: *Alok Rudra*[1]; Emanuele Pelucchi[1]; Daniel Oberli[1]; Nicolas Moret[1]; Eli Kapon[1]; [1]Ecole Polytechnique Fédérale de Lausanne, Lab. of Physics of Nanostruct., Inst. of Quantum Elect. & Photonics, Sch. of Basic Scis., CH-1015 Lausanne Switzerland

Low temperature photoluminescence (PL) combined with atomic force microscopy (AFM) was used to optimize the structural and optical quality of 2-15nm thick GaAs/AlGaAs quantum wells (QWs) grown by low pressure MOVPE under nitrogen ambient at 730°C (thermocouple temperature). GaAs wafers, misoriented off (100) towards <111>A and <111>B were used, covering the 0-0.6° misorientation range in steps of 0.1±0.02°. A previous report on comparable structures grown under hydrogen had shown a linewidth reduction with 0.5 and 1° misorientation towards <111>B. Here, a dramatic reduction in the 10K PL linewidth is observed for all 0.2-0.3° misorientations, as compared to nominally oriented wafers: on 2, 5 and 15nm thick QWs, linewidths fall from 23, 8 and 3meV to 6, 3 and 2.5meV respectively, among the narrowest reported to date. Above 0.3° misorientation, the emission broadens to become, at 0.6°, comparable or worse than for the exact (100) samples. These results will be discussed in terms of the growth front as observed under AFM.

(3) MOVPE-Grown Long Wavelength InGaAs/InP Quantum-Well Infrared Photodetectors: *A. P. Shah*[1]; M. R. Gokhale[1]; A Majumdar[2]; D. C. Tsui[2]; S. Ghosh[1]; S. Sen[3]; B. M. Arora[1]; [1]Tata Institute of Fundamental Research, Dept. of Condensed Matter Physics & Matls. Sci., Homi Bhabha Rd., Mumbai 400005 India; [2]Princeton University, Dept. of Elect. Engrg., Princeton, NJ USA; [3]Institute of Radio Physics and Electronics, Kolkata 700009 India

Most InP-based quantum-well infrared photodetectors (QWIPs) so far have been synthesized by MBE. Very few reports exist of QWIPs grown by MOVPE. We report a detailed investigation of MOVPE-grown QWIPs based on bound-to-bound intersubband transitions. Structure consists of 30 periods of 6.8nm doped $In_{0.53}Ga_{0.47}As$ QWs separated by 34nm InP barriers. HRXRD, photoluminescence, Hall effect and FTIR were used to characterize the structures. The detectors show absorption peak at 8.5μm wavelength. Extremely large peak responsivity values R_{pk} = 6.9 and 5.6A/W at bias voltage V^b = 3.4 and -3.5V, respectively have been observed. These large responsivities arise from large detector gain ~18-20, because of the influence of InP barriers giving larger photoelectron lifetime versus the transit time. The background-limited temperature with F/1.2 optics is T^{BLIP} = 65K. The highest value of peak detectivity is $D^{\lambda *}$ = 5.4x10^{9}cmHz$^{1/2}$W at V^b = 2.9V and T=77K, while for $T < T^{BLIP}$, the background-limited detectivity is D^{BLIP*} = 3x10^{10}cmHz$^{1/2}$W.

(4) Growth of Abrupt InAs/GaAs Heterojunctions and Quantum Wells by MOVPE: *E. Hulicius*[1]; O. Pacherova[1]; J. Pangrac[1]; A. Hospodkova[1]; T. Simecek[1]; K. Melichar[1]; J. Oswald[1]; Z. Sourek[1]; T. Chraska[1]; I. Vavra[2]; L. Ouattara[3]; [1]Academy of Science of Czech Republic, Inst. of Phys., Prague Czech Republic; [2]Electrotechnical Institute of Slovak Academy of Science, Bratislava; [3]Lund University SRR, Box 118, Lund 22100

InAs/GaAs heterostructures are grown with the aim to prepare lasers based on very thin QWs and QDs for many years. Both epitaxial technologies MBE and MOVPE are used. The general feeling is that MOVPE has heterojunction abruptness limits, mainly due to In memory effect. We have grown these structures using AIXTRON 200 and studied them by STM, TEM, X-ray diffraction and other standard optical and electrical methods. We have found that the abruptness and symmetry of monoatomic layers is achievable it is also possible to grow SL with more than ten QWs in 10 nm. We will demonstrate that TEM, AFM and STM pictures with lower than atomic resolution are not giving the real thickness and separation of very thin QWs. We will present also the results of optical and electrical measurements of these structures suitable for new generation of QW lasers.

(5) Microscopic Spatial Distribution of Bound Excitons in High-Quality ZnO: *Frank Bertram*[1]; Daniel Forster[1]; Nikolay Oleynik[1]; *Armin Dadgar*[1]; Juergen Christen[1]; Alois Krost[1]; [1]Otto-von-Guericke-University Magdeburg, Inst. of Experimental Physics, Uni-Platz 2, Magdeburg, SA 39106 Germany

The samples were grown by MOVPE on 1μm thick GaN layers on silicon substrates. The ZnO growth took place in a two step growth process: First, a low-temperature ZnO buffer was deposited at 450°C using tertiary-butanol as O-source and dimethyl-zinc (DMZn). In the second step, the overgrowth with a high-temperature ZnO layer above 800°C (N_2O as O-source and DMZn) occurred. A direct correlation of structural and optical properties of these ZnO sandwich layers has been achieved on a microscopic scale using highly spatially and spectrally resolved cathodoluminescence. The laterally integrated spectrum of each sample is dominated by narrow (<1.3 meV) I_8 luminescence from the surface and donor related luminescence from within surface defects like pits. Local spectra taken at the edges of domains show a pronounced emission line at I_0, I_1, whereas inside of the domains no enhanced intensity in this spectral region is found. Monochromatic images prove a selective incorporation of impurities at the grain boundaries of domains.

(6) Interdiffusion in Highly-Strained InGaAs-QWs for High Power Laser Diode Applications: *Frank Bugge*[1]; Ute Zeimer[1]; Heiko Kissel[1]; Hans Wenzel[1]; Goetz Erbert[1]; Marcus Weyers[1]; [1]Ferdinand-Braun-Institut, MT, Albert-Einstein-Str. 11, Berlin 12489 Germany

Laser diodes emitting above 1100nm have a high potential for very high output power with a target or more than 10W from a single broad area device. To obtain such long wavelengths the In(x)Ga(1-x)As quantum wells (with x>0.3) are grown at much lower temperature (530°C) than the AlGaAs or GaInP cladding layers. Thus during growth of the upper cladding indium diffusion out of the QW can result in a blue shift of the QW emission. A post growth annealing at AlGaAs growth temperatures of InGaAs QWs grown at 530°C results in a comparable shift. We have observed up to 50 nm shift for single 6nm thick Ga(0.65)In(0.35)As QWs. The effect of applied V/III-ratio, growth temperature of cladding layers and GaAsP strain compensation on indium diffusion and laser performance has been studied for structures with single and double quantum wells.

(7) The Effect of Strain on the Properties of InGaAsN/GaAsP Quantum Wells Grown by MOVPE: *Gangyi Chen*[1]; Yan Sun[1]; Dick Cheng[1]; Robert F. Hicks[1]; Atif Noori[2]; Mark S. Goorsky[2]; Ravi Kanjolia[3]; Leslie Smith[3]; [1]University of California, Chem. Engrg. Dept., 5531 Boelter Hall, Los Angeles, CA 90095 USA; [2]University of California, Dept. of Matl. Sci. & Engrg., Los Angeles, CA 90095 USA; [3]Epichem Inc., 26 Ward Hill Ave., Haverhill, MA 01835 USA

Indium gallium arsenide nitride (1.0 eV bandgap) deposited on GaAs often exhibits too high a defect density. This problem may be overcome by lowering nitrogen levels and using GaAsP barrier layers to compensate the strain in InGaAsN quantum wells. We have investigated the effects of strain on the properties of $In_{0.25}Ga_{0.75}As_{0.995}N_{0.005}$ single and multiple quantum wells using scanning tunneling microscopy, x-ray photoemission spectroscopy, x-ray diffraction and photoluminescence. We found that the nanoscale roughness of the wells transitioned from 0.1 nm (atomically smooth) to 0.3-1.5 nm (3D) with increasing strain. In single wells, strain compensation of >50% was required to maintain a sharp interface, and yield high PL intensities. Conversely, the morphology of multi-quantum wells rapidly degraded with thickness when there was any residual strain. The relationship between strain, layer structure and optical properties of the QWs will be discussed at the meeting.

(8) MOVPE Growth of AlGaInAs-InP Highly Tensile-Strained MQW's for 1.3 µm Low-Threshold Lasers: *Jean Decobert*[1]; Nadine Lagay[1]; Cornelia Cuisin[1]; Beatrice Dagens[1]; [1]Alcatel-CIT, OPTO+, Rte. de Nozay, Marcoussis 91460 France

The low pressure metalorganic vapor phase epitaxy (LP-MOVPE) of tensile AlGaInAs MQW's for TM 1.3 µm emitting lasers is presented. TM lasing is required for such a new application as laser/isolator integration. Al-containing wells have been mostly studied with compressive strain for TE lasers. We report on highly tensile-strained AlGaInAs well layers (0.65-1.65%) grown with compressive-strained AlGaInAs barrier layers (0.6%). Different Al/Ga ratio and therefore barrier heights were tested at this strain. An enhanced separation between light hole and heavy hole transitions is clearly observed by room temperature photoluminescence as strain increases. Broad area lasers with 1.21% tensile-strained MQW, exhibit threshold current densities of 60 and 76 A/cm^2 per QW for 6 and 10 wells respectively. Component characteristics with respect to temperature will be presented.

(9) Growth and Optimization of Extremely High-Pulse-Power GRINSCH QW AlGaAs/InGaAs Laser Diodes with Broadened Waveguide: *Jizhong Li*[1]; R. U. Martinelli[1]; V. B. Khalfin[1]; A. M. Braun[1]; D. R. Patterson[1]; Z. Shellenbarger[1]; B. B. Price[1]; M. G. Harvey[1]; B. I. Willner[1]; J. M. Carpinelli[1]; J. H. Abeles[1]; [1]Sarnoff Corporation, 201 Washington Rd., Princeton, NJ 08543-5300 USA

Material quality is an essential prerequisite and major challenge for the fabrication of high-power 980 nm strained-quantum-well InGaAs lasers. We report our work aimed at MOCVD growth optimization and epitaxial quality analysis of varies GRINSCH QW AlGaAs/InGaAs laser structures. Systematic investigations on controlling doping level and minimizing oxygen incorporation in AlGaAs were performed. A background oxygen level as low as 1016 cm-3 has been obtained with n(Si)/p(C) doped concentrations as high as 3x1018 cm-3/2x1018 cm-3 for Al0.4Ga0.6As layers. DC X-ray, RT-PL, Hall, CV and SIMS were utilized routinely in evaluating material quality. A damage-free method was developed to monitor PL wavelength on as-grown full structure wafers. PL uniformity of better than 2 nm over entire 2" wafer has been measured using automated PL mapping techniques. A record multi-mode pulsed output power of 50 W has thereby been obtained from 100 µm x 2 mm broad-stripe lasers. The devices demonstrate low threshold current, low cavity losses, and kink-free light-current (L-I) characteristics.

(10) Performance Comparison Between Integrated Devices Grown by SAG and Butt Joint SAG: *Jintian Zhu*[1]; Luca Billia[1]; David Bour[1]; Scott Corzine[1]; Chao-Kun Lin[1]; Gloria Hofler[1]; [1]Agilent Technologies, CORL, 3500 Deer Creek Rd., Palo Alto, CA 94304 USA

A key component for high-speed communication systems is the electro-absorption modulator (EAM). An EAM integrated with a passive waveguide section or a DFB laser has been explored to reduce cost and simplify packaging. Several approaches have been developed to accomplish monolithic integration. These technologies include butt-joint coupling (in which the laser and EAM are grown separately) and selective-area growth. Butt-joint (BJ) coupling is attractive because it allows independent optimization of the laser and EAM. However, it requires multiple growths. In contrast, selective-area growth is an elegant solution because both the active regions of the laser and modulator can be grown in a single epitaxial growth with spatial wavelength shift ~ 100 nm and the vertical alignment between them is ensured. In this talk, we will discuss the growth conditions necessary to obtain high-quality overgrowth required for both SAG and BJ integration processes. The interfaces between laser and waveguide sections grown with SAG and BJ were characterized via optical low-coherence reflectormeters (OLCR). An electro-absorption modulator integrated with a long passive wave-guide region shows an extinction ratio higher than 13 dB biased at 2.9 V peak-to-peak at 40 Gb/s.

(11) Flat Surface Growth Conditions of InP Capping Layer Over InAs Quantum Dots on (001)InP Substrate: *Kazuyoshi Hirose*[1]; Satoshi Okamoto[1]; Junya Yamamoto[1]; Tomonari Shioda[1]; Kazuhiko Shimomura[1]; [1]Sophia University, Dept. Elect. & Elect. Engrg., 7-1, Kioi-cho, Chiyoda-ku, Tokyo 102-8554 Japan

We have shown the flat surface growth condition of InP capping layer over InAs quantum dots (QDs) on (001)InP substrate by using low pressure MOVPE. InAs QDs were grown under the Stranski-Krastanov growth mode after the growth of GaInAs buffer layer on the InP substrate. InAs QDs growth temperatrue was 500, 540°C, pressure was 15 torr, the supplied source was TMI and tBA with 54 V/III ratio, and growth interruption time was 60 sec. The diameter and density of bare InAs QDs were about 30 nm, and 8E10 cm^{-2}, respectively at 500°C. After the InAs QDs growth, InP capping layer was grown under 500 and 540°C. By observing the morphology of the capped QDs, the flatness of 540°C sample was improved compared to the 500°C sample. The PL spectrum of the capped QDs were observed around 1.5 µm wavelength.

(12) Optical Investigation of InGaAsN/GaAs Quantum Wells Grown by Low-Pressure Metalorganic Vapor Phase Epitaxy: Sakuntam Sanorpim[1]; Fumihiro Nakajima[1]; Ryuji Katayama[1]; *Kentaro Onabe*[1]; [1]University of Tokyo, Dept. of Advd. Matls. Sci., c/o Dept. of Applied Physics, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656 Japan

Optical properties of dilute nitrogen InGaAsN/GaAs alloy films and quantum wells (QWs) grown by low-pressure (60 Torr) metalorganic vapor phase epitaxy have been investigated by photoluminescence (PL) and photoreflectance (PR) spectroscopy. The quantum confinement of the carriers was confirmed by both PL and PR for the QWs. The results can be interpreted in terms of the localized (low temperatures) and free (high temperatures) excitons, which are dominant in the radiative recombination process. The significant improvement after rapid thermal annealing (RTA) suggests the existence of high-density defects acting as the nonradiative recombination centers in the as-grown samples. The as-grown QWs showed a behavior characterized by the two activation energies (ΔE_1 =5-10 meV and (ΔE_2 =18-30 meV) due to the defect-related states and the alloy potential fluctuations, respectively. After RTA, the activation energies were one from the alloy potential fluctuations and another from the difference between the quantum-well levels (100-120 meV).

(13) Self Assembled In(Ga)As Islands on Ge Substrate: Lauri Olavi Knuuttila[1]; Markku Sopanen[1]; Harri Lipsanen[1]; [1]Helsinki University of Technology, Optoelectronics Lab., Tietotie 3 Po Box 3500, FIN-02015 TKK, Espoo Finland

Self assembled InAs and $In_{0.5}Ga_{0.5}As$ islands fabricated on a germanium substrate by metalorganic vapor phase epitaxy are extensively investigated. The effects of growth temperature and deposition thickness on the formation, size, density, and uniformity of the islands are examined. Atomic force microscopy images show formation of both InAs and InGaAs islands for a submonolayer deposition. InAs islands grown at 450 °C show an island density of $4.2*10^9$ cm^{-2} when the nominal deposition thickness is as low as 0.4 monolayer. For the InGaAs islands a maximum density of $3.5*10^{10}$ cm^{-2} is measured at a nominal three monolayers deposition thickness. The results encourage the use of self assembled In(Ga)As islands on germanium both for buffer layer and electro-optic applications.

(14) InAs Quantum Dots Over InGaAs for Infrared Photodetectors: *Mauricio Pamplona Pires*[1]; Sandra Landi[1]; Christiana Villas-Bôas Tribuzy[1]; Euclydes Marega[2]; Patricia Lustoza de Souza[1]; [1]PUC-Rio, LabSem/CETUC, Rua Marques de São Vicente 225, Gávea, Rio deJaneiro 22453-900 Brazil; [2]Instituto de Fisica de São Carlos, USP, Caixa Postal 369, São Carlos, São Paulo 13560-970 Brazil

Self-assembled semiconductor quantum dots (QDs) are attractive candidates for middle- and long-wavelength infrared (IR) photodetectors due to their intrinsic sensitivity to normally incident IR light. For this purpose, InAs QDs were grown over InGaAs on InP substrates. Several characteristics such as QD size, its density and photoluminescence spectra were studied as a function of different QD growth conditions. The role of the InGaAs alloy composition and the number of QDs stacks on the QD parameters were also analyzed. We have achieved QDs density as high as 10^{10}cm^{-2} and average height of 7 nm with a standard deviation of 0.7 nm. The absorption and photocurrent spectra are measured for optimized structures. Based on these results, the potential for the use of such structures for IR detectors will be discussed.

(15) Synthesis and Characterization of GaAs and GaAs/InAs/GaAs Heterostructure Nanowires Grown via MOVPE Using the Vapor-Liquid-Solid Technique: *R. Kamalakaran*[1]; A. Bhattacharya[1]; R. Banerjee[2]; M. R. Gokhale[1]; B. A. Chalke[1]; S. Ghosh[1]; J. Bhattacharyya[1]; K. L. Narasimhan[1]; B. M. Arora[1]; [1]Tata Institute of Fundamental Research, Dept. of Condensed Matter Physics & Matls. Sci., Homi Bhabha Rd., Mumbai 400005 India; [2]Ohio State University, Dept. of Matls. Sci. & Engrg., Columbus, OH 43210 USA

There is considerable effort towards the synthesis of nanowires in many semiconductor systems using processes based on the vapor-liquid-solid (VLS) growth technique. The ability to grow designed heterostructures within nanowires has opened up new approaches towards nanoscale devices. We have investigated the growth of Au-catalyzed compound semiconductor nanowires (whiskers) using metal-organic vapor phase epitaxy (MOVPE). The growth of GaAs and GaAs/InAs/GaAs heterostructure nanowires was optimized by varying parameters like the annealing and growth temperatures, and the growth rate. Using Au/GaAs (100) substrates (sputtered Au on GaAs, annealed in the MOVPE chamber at 500°C for 5 min. in H_2AsH_3) nanowires with 10nm-40nm diameter were grown at 400°C-450°C using TMGa, TMIn and AsH_3. Details of the synthesis and characterization of the nanowires will be presented. SEM and HRTEM studies were used for structural characterization and understanding the growth kinetics of these whiskers. The GaAs/InAs/GaAs heterostructures have been investigated using surface photovoltage spectroscopy.

(16) Red VCSEL for High-Temperature Applications: *Robert Roßbach*[1]; Rainer Butendeich[1]; Tabitha Ballmann[1]; Heinz Schweizer[1]; Michael Jetter[1]; Ferdinand Scholz[2]; [1]Universität Stuttgart, 4. Physikalisches Inst., Pfaffenwaldring 57, Stuttgart 70550 Germany; [2]Universität Ulm, Abteilung Optoelektronik, Albert-Einstein-Allee 45, Ulm 89081 Germany

Vertical cavity surface emitting lasers (VCSEL) based on GaInP/AlGaInP material system have attracted much interest as potential key components for low-cost optical data communication via plastic optical fibres (POF). This material system seems to fail the requirements of e.g. automotive applications (+125°C) due to the poor electron confinement and therefore they show high temperature sensitivity. We investigated the temperature limits of VCSEL with different aperture diameters to determine the intrinsic limit of the GaInP/AlGaInP material system. We analysed from the wavelength shift the internal temperatures of continuous-wave-lasing VCSEL. These measurements showed internal temperatures of +130°C at the required power of 1mW (660nm). In the next step we investigated VCSEL (670nm, 9µm aperture) under ultrashort pulsed operation (0.3µs, 200Hz) to avoid any internal heating. At a temperature of +120°C the device showed more than 0.5mW output power, even at +160°C we still measured 25µW.

(17) Effects of Radiative Recombination and Photon Recycling on Minority Carrier Lifetime in Epitaxial GaInAsSb Lattice-Matched to GaSb: *S. Anikeev*[1]; D. Donetsky[1]; G. Belenky[1]; S. Luryi[1]; C. A. Wang[2]; D. A. Shiau[2]; M. Dashiell[3]; J. Beausang[3]; G. Nichols[3]; [1]State University of New York, Elect. & Computer Engrg., Stony Brook, NY 11794 USA; [2]Massachusetts Institute of Technology, Lincoln Lab., Lexington, MA 02420 USA; [3]Lockheed Martin Corporation, Schenectady, NY 12301 USA

Radiative recombination was comprehensively studied for wide-gap semiconductors, while for 0.5-0.6 eV materials the available experimental data are limited and demonstrate about an order of magnitude variation. This paper will discuss the carrier recombination mechanisms in 0.54-eV GaInAsSb grown by OMVPE. Low-excitation electron lifetime was measured by time-resolved photoluminescence in isotype (p=2x10^{17} cm^{-3}) double heterostructures with AlGaAsSb confinement layers. GaInAsSb layer thickness was varied in the range W=0.15 to 4.5 µm to separate contributions from interface and radiative recombination processes. Interfacial recombination velocity of <30 cm/s was determined from data on structures with W<1 µm. This result is indicative of high quality of AlGaAsSb passivation layers. Increase of the lifetime with structure thickness for W>1 µm is attributed to effect of reabsoprtion of photons within the active layer (photon recycling effect). With the large range of layer thicknesses, radiative coefficient can be determined.

(18) Long-Wavelength Self-Assembled InAs Quantum Dots Laser Grown by Metal-Organic Chemical Vapor Deposition: Sung Ui Hong[1]; [1]Electronics and Telecommunications Research Institute, Basic Rsch. Lab., 161 Gajeong-Dong, Yuseong-Gu, Daejeon Korea

Self-assembled InAs quantum dots (QDs) on InP (100) substrates grown by metal-organic chemical vapor deposition were investigated. Various growth parameters such as growth temperature of QDs and V/III ratio were attempted to find the optimum growth condition for InAs-QDs. Optical and structural properties of QDs were characterized by photoluminescence, transmission electron microscopy and atomic force microscopy. InAl(Ga)As materials system, lattice matched to InP, were used for cladding layers and barriers in a laser structure. As the active layer, five stacked InAs-QDs separated by InAlGaAs barriers with a thickness of 30 nm were inserted between the N- and P-type InAlAs cladding layers. Broad stripe lasers with a stripe width of 75 um, were fabricated. The lasing from InAs-QDs was observed up to 130 K and the emission wavelength was around 1.42 um.

(19) Tuning the Emission Wavelength of Self-Assembled InAs Quantum Dots Grown by Metal-Organic Chemical Vapor Deposition: Sung Ui Hong[1]; *Jin Hong Lee*[1]; Jin Soo Kim[1]; Ho-Sang Kwack[1]; Won Seok Han[1]; Chul Wook Lee[1]; Dae Kon Oh[1]; [1]Electronics and Telecommunications Research Institute, Basic Rsch. Lab., 161 Gajeong-Dong, Yuseong-Gu, Daejeon Korea

We controlled the emission peak position of self-assembled InAs quantum dots (QDs) on InP(100) grown by low pressure metal-organic chemical vapor deposition. The photoluminescence (PL) peak position emitted from InAs-QDs were varied from 1.38 to 1.66 um by growth technique and/or structural modification. With an increase in growth interruption time after deposition of the InAs QD layer, the PL peak position of InAs QDs was red-shifted from 1.48 to 1.66 um, and the PL intensity was significantly enhanced. By introducing a thin InAlGaAs layer on top of the InAs QD layer, the PL peak position of QDs was blue-shifted from 1.48 to 1.38 um and the PL intensity was enhanced with an increase in the thickness also. Based on the results, we can systematically control the emission peak position of InAs QDs by varying the growth interruption time and inserting a thin layer.

(20) Optical and Structural Studies of (Ga, Al) 3D Structures Selectively Grown by MOCVD: Colombier Isabelle[2]; Donatini Fabrice[2]; Vial Jean-Claude[2]; Baldeck Patrice[2]; Herino Roland[2]; Duc-Maugè Alexandre[3]; Godfroyd Jérome[3]; Lacroute Yvon[1]; *Sacilotti Marco*[1]; [1]Universite de Bourgogne, FR2604-CNRS, 9, Av. Alain Savary, Dijon 21078 France; [2]Université Joseph Fourier, LSP-CNRS, St. Martin d'Hères 38 France; [3]RSA Le Rubis SA, BP 16, Jarrie-Grenoble 38560 France

The (Ga, Al, In)N system represents a very important kind of materials for optoelectronic visible devices applications. Shortening the size of optoelectronics devices is an important step within the industrial application and its improvement. This paper presents the growth and characterization of novel (Ga, Al) metallic 3D structures, selectively grown by the MOCVD technique. To support these 3D (Ga, Al) structures, GaAs, Si, SiO2, quartz, Al2O3 substrates can be utilized. Metal-organic precursors were utilized to allow for the growth of these structures. The growth temperature was varied between 500 to 750 °C and the reactor pressure varied between 100 to 760 torr. Nitrogen was utilized as carrier gas. In these conditions many 3D (Ga, Al) structures could be obtained : balloons (montgolfiers), cylinder, scepter and cauli-flower like structures. They morphology depend principally on the growth temperature and substrate surface conditions. These structures stick to the substrate by a very thin base. Micrometer structure size can be obtained. 3D (Ga, Al) selective growth could also be obtained on suitably prepared substrates. These 3D structures can be suitable nitrogen incorporate to obtain GaN like structures. To study these 3D (Ga, Al) structures, SEM, XRD, EDX, CL and Luminescent characterization techniques results will be presented. CL and Luminescence show visible light emission from these nitrided 3D structures.

(21) Growth and Characterization of InAlP/InGaAs Double Barriers RTDs: *Stefan Neumann*[1]; Peter Velling[1]; Werner Prost[1]; Franz Josef Tegude[1]; [1]University Duisburg-Essen, Solid-State Elect. Dept., Lotharstrasse 55, Duisburg, NRW 47057 Germany

The material system InAlP/InGaAs is of interest especially due to the high conduction band discontinuity at the heterojunction. In this work we present the first double barrier $In_{0.67}Al_{0.33P}/In_{0.55/}Ga_{0.45}As/In_{0.67}Al_{0.33}P$ RTD. The composition of $In_{0.67}Al_{0.33P}$ results in a bandgap of $E_{G,InAlP}$=2.01eV. The device function is very sensitive to interface effects like roughness, abruptness and homogeneity. However, the growth of this material system is complicated because of the large lattice mismatch of the Al containing material to InP. A fully non-gaseous source-(ngs-)LP-MOVPE configuration is used for the growth. The RTD structures are characterized by HRXRD measurements, which are compared to simulation result and dc measurement. A record high peak current density of Sp= 3x10^5 A/cm^2 at V_{Peak}=1.3V with a peak to valley current ratio PVR=1.2 has been achieved. The symmetric behaviour of the dc-measurement and in addition the x-ray results shows the high quality of the layerstack and interfaces and enable the characterization of the highly strained barrier layers.

(22) Growth of Single-Walled Carbon Nanotubes in a Standard MOCVD Reactor: *Sungsoo Yi*[1]; Grant Girolami[1]; Ying-Lan Chang[1]; Danielle R. Chamberlin[1]; Mark Juanitas[1]; Nick Moll[1]; Ron Moon[1]; [1]Agilent Technologies, 3500 Deer Creek Rd., Palo Alto, CA 94304 USA

Carbon nanotubes (CNTs) have been the focus of intense research due to their remarkable electronic and mechanical properties and potential applications in nanoelectronic devices. Recently, synthesis of CNTs by metal-catalyzed chemical vapor deposition (CVD) in a tube furnace reactor has been extensively investigated because the CVD method provides a controlled catalytic growth process and is a promising approach to the control over the location, diameter, and length of CNTs. We report the growth of high-quality single-walled CNTs using methane in a standard MOCVD reactor. Synthesis of CNTs in a standard MOCVD reactor offers a route to large-scale production in a controlled process and opens up the possibility of integrating CNTs with compound semiconductors. Single-walled CNTs with diameters < 2 nm were synthesized by catalytic decomposition of methane over Fe/Mo/Al_2O_3 catalyst. The morphology and structural properties of single-walled CNTs were analyzed by AFM, SEM, TEM, XPS, and Raman spectroscopy.

(23) A Comparative Study of the Growth Mechanism of InAs/GaAs and GaP/GaAs Strained Layered Superlattices by Atomic Layer Epitaxy: *Tomohiro Haraguchi*[1]; Takeshi Takeuchi[1]; Masashi Ozeki[1]; [1]University of Miyazaki, Dept. of Elect. & Elect. Engrg., Faculty of Engrg., 1-1 Gakuen Kibanadai-nishi, Miyazaki, Miyazaki-ken 889-2192 Japan

Atomic layer epitaxy (ALE) has received considerable attention as a novel approach to crystal growth in nanotechnology. A central idea in ALE is a self-limiting mechanism that automatically stops the layer growth at a certain atomic layers and therefore allows complete control of the layer thickness with single atomic layer accuracy. In homoepitaxies, ALE proved a great success. However, many difficulties appeared in some heteroepitaxies where the self-limiting was easily broken. We have investigated the self-limiting mechanism in the ALE of InAs/GaAs and GaP/GaAs strained layered superlattices. Superlattices were grown on GaAs(001) and InP(001) by "Pulsed-Jet-Epitaxy" with trimethylgallium, trimethylindium, trisdimethyl-aminoarsine, and phosphine as source materials. We report that the strain between epitaxial layer and the substrate, an atomic level surface morphology, and an interface electric neutrality had great effects on the self-limiting mechanism in heteroepitaxy.

(24) Low Turn-on Voltage in GaInNAs and InGaAs Base Double Heterojunction Bipolar Transistors Growth by MOVPE: Wei-Chang Chen[1]; Yan-Kuin Su[1]; Cheng-Hsien Wu[1]; Chi-Cheong Sio[1]; [1]National Cheng Kung University, Inst. of Microelect., Dept. of Elect. Engrg., University Rd. No. 1, Tainan 701 Taiwan

A new quaternary material of GaInNAs has been proposed as base material for GaAs-based double heterojunction bipolar transistors (DHBTs). Using InGaAs as base material obtains lower bandgap energy of base layer in heterojunction bipolar transistors (HBTs) followed by the smaller turn-on voltage. However, compressive strain induced by InGaAs grown on GaAs diminishes the influence of indium-adding-induced bandgap energy reduction, and thus abate turn-on voltage reduction. By incorporating suitable amount of indium (In) and nitrogen (N) into GaAs, a smaller bandgap material of GaInNAs lattice-matched to GaAs substrate can be achieved. In this study, N-p-n InGaP/Ga0.985In0.015N0.005As0.995/GaAs DHBTs has been demonstrated. A turn-on voltage reduction of 215 mV over the conventional HBT with GaAs base layer was obtained. The device has a peak current gain of 85 and shows good high frequency characteristics of fT and fMAX both higher than 40GHz.

(25) Controlling the Morphology of InP Quantum Dots on InAlGaP Matrices Grown by Metalorganic Chemical Vapor Deposition: Xue-Bing Zhang[1]; Jae-Hyun Ryou[1]; Gabriel Walter[2]; Nick Holonyak[2]; *Russell D. Dupuis*[1]; [1]Georgia Institute of Technology, Sch. of Elect. & Computer Engrg., Atlanta, GA 30332 USA; [2]University of Illinois, Micro & Nanotech. Lab., Urbana, IL 61801 USA

We report on the growth of InP quantum dots (QDs) on InAlGaP matrices on GaAs substrates by metalorganic chemical vapor deposition. The morphology of InP QDs was characterized by atomic force microscopy. Effects of Al composition, surface morphology, surface misorientation (i.e., (001)-off-axis surfaces), and residual strain in InAlGaP matrices are systematic studied. We found that the interfacial alloying effect between the InP QDs and the matrices, the atomic-step structures on the matrix surfaces, the inhomogeneous strain in the matrices play important roles in the growth of InP QDs. Well ordered QDs aligned in the [1-10] crystallographic direction, or orthogonal <110> directions or orthogonal <100> directions have been realized.

(26) Hetero-Epitaxial Growth of GaInAs on GaAs by Low-Pressure Metalorganic Chemical Vapor Deposition: *Yasuo Sato*[1]; Tomonori Hino[1]; Hironobu Narui[1]; [1]Sony Corporation, Matls. Labs. , 4-14-1, Asahi-cho, Atsugi-shi, Kanagawa 243-0014 Japan

Hetero-epitaxial layers of GaInAs with high In content on GaAs substrate are useful for high-performance electronic and optoelectronic devices. There is, however, a large lattice mismatch between GaInAs and GaAs, which results in numerous dislocations and leads to poor crystalline quality. Therefore, it is important to establish growth methods for a buffer layer, which prevents the generation of dislocations. In this work, we investigate the growth of $Ga_{0.55}In_{0.45}As$ (3% lattice mismatch) on GaAs substrate by low-pressure MOCVD using a graded In-composition buffer layer. By optimizing the structure and the growth condition of this graded buffer layer, we can reduce the dislocation density to $1.7\times10^{6}cm^{-2}$. In addition, we report the fabrication of a photodiode (λ=1.31µm) consisting of $Ga_{0.55}In_{0.45}As$ with low dislocation density. At a bias of -5V, the photodiode with a photo-sensitive area of 50µm diameter has a dark current of 7.3nA, a response of 0.85A/W, and -3dB bandwidth of 3.6GHz.

(27) Extremely Low Recombination Velocity in GaInAsSb/AlGaAsSb Heterostructures Grown by Organometallic Vapor Phase Epitaxy: *C. A. Wang*[1]; D. Donetsky[2]; S. Anikeev[2]; D. A. Shiau[1]; G. Belenky[2]; S. Luryi[2]; [1]Massachusetts Institute of Technology, Lincoln Lab., Electro-Optical Matls. & Devices, 244 Wood St., Lexington, MA 02420 USA; [2]State University of New York, Dept. of Elect. & Computer Engrg., Rm. 246 Light Engrg. Bldg. MS-2350, Stony Brook, NY 11794 USA

The performance of minority carrier devices such as light-emitting diodes, photovoltaics, and heterojunction bipolar transistors depends on minority-carrier lifetime. Ideally, nonradiative bulk and surface recombination should not limit the efficiency of these devices, and numerous studies aimed at minimizing surface recombination velocity (SRV) have been reported for heterostructures comprised of GaAs- and InP-based III-V alloys. More recently, mid-infrared III-V materials based on GaSb are being investigated, and GaSb/GaInAsSb/GaSb and AlGaAsSb/GaInAsSb/AlGaAsSb double heterostructures (DHs), which were grown by organometallic vapor phase epitaxy (OMVPE), exhibited SRV of 1140 and 380 cm/s, respectively.1 The lower SRV value was attributed to better carrier confinement afforded by AlGaAsSb compared to GaSb. This work reports significantly lower SRV values of less than 50 cm/s for AlGaAsSb/GaInAsSb/AlGaAsSb DHs grown by OMVPE. These substantial improvements were achieved by eliminating long growth interruption times (~60 s) between GaInAsSb and AlGaAsSb epilayers, which were required due to different optimum growth temperatures of the two alloys. In the previous study1, GaInAsSb and AlGaAsSb were grown at 525 and 550°C, respectively. In this work, growth conditions were adjusted for growth of both alloys at 525°C. Triethylgallium, trimethylindium, tertiarybutylaluminum, trimethylantimony, and tertiarybutylarsine were used as precursors, with dimethylzinc as the p-type dopant. Epilayers were characterized by in-situ spectral reflectance and ex-situ high-resolution x-ray diffraction, Rutherford back-scattering, photoluminescence (PL), and time-resolved PL. This paper will discuss the effect of the lower growth temperature on AlGaAsSb quality; the growth of AlGaAsSb/GaInAsSb/AlGaAsSb DHs; and the characterization of these DHs with extremely low SRV.

Wednesday AM - June 2, 2004

Plenary Session

Wednesday AM	Room: Kihei
June 2, 2004	Location: Westin Maui Hotel

Session Chairs: G. Stringfellow, University of Utah, Salt Lake City, UT 84112 USA; O. Briot, University of Montpelier, Montpelier Cedex 5, 34095 France

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8:20 AM Invited

Vapor-Liquid-Solid Growth and Characterization of Semiconductor Nanowires: *Joan M. Redwing*[1]; Kok-Keong Lew[2]; Tim Bogart[2]; Ling Pan[2]; Elizabeth C. Dickey[2]; Marco Cabassi[3]; Yanfeng Wang[3]; Theresa Mayer[3]; Soham Dey[2]; Suzanne E. Mohney[2]; [1]Pennsylvania State University, Depts. of Matls. Sci. & Engrg. & Elect. Engrg., Matls. Rsch. Inst., Univ. Park, PA 16802 USA; [2]Pennsylvania State University, Dept. of Matls. Sci. & Engrg., Matls. Rsch. Inst., Univ. Park, PA 16802 USA; [3]Pennsylvania State University, Dept. of Elect. Engrg., Matls. Rsch. Inst., Univ. Park, PA 16802 USA

The fabrication of semiconductor nanowires, in which composition, size and conductivity can be controlled in both the radial and axial direction of the wire is of interest for fundamental studies of carrier confinement as well as nanoscale device development. In this study, group IV semiconductor nanowires, including Si, Ge and SixGe1-x alloy nanowires were fabricated by vapor-liquid-solid (VLS) growth using gaseous precursors (SiH4 and GeH4). In the VLS process, gold is used to form a liquid alloy with Si and Ge which, upon supersaturation, precipitates a semiconductor nanowire. Nanoporous alumina membranes with pore diameters ranging from 25 nm to 200 nm were used as templates for the VLS growth process. Nanoporous membranes offer several advantages for nanowire growth including control of nanowire diameter via membrane pore size, high nanowire density and the ability to fabricate vertically-aligned nanowire arrays and multilayered metal-semiconductor-metal nanowires. Silicon nanowire samples with average nanowire diameters ranging from 40 nm to 200 nm were obtained using this templating approach. The synthesis of SixGe1-x alloy nanowires and heterostructures and intentionally doped Si nanowires was investigated. The decomposition chemistry of the precursor sources was found to impact the structural and compositional homogeneity of the nanowires. In the case of SixGe1-x alloys, reduced VLS growth temperatures (<425°C) were required to suppress Ge deposition on the outer surface of the nanowires during growth due to the different thermal stabilities of the SiH4 and GeH4 sources. The addition of B2H6 for p-type doping resulted in the formation of a thick amorphous Si coating on the outer surface of the nanowire. This problem was eliminated through the use of trimethylboron (TMB) as the p-type dopant source, which is more thermally stable than B2H6. Intentional boron and phosphorous doping over the range from ~1x1018 cm-3 to 5x1019 cm-3 was achieved using TMB and PH3 dopant sources, respectively, during Si nanowire growth. Field-assisted assembly was used to align and position individual silicon nanowires onto prepatterned test bed structures for four-point resistivity measurements and gate dependent I-V characterization. The gate dependence of the conductance was consistent with p-type conductivity for both undoped and B-doped nanowires. The resistivity of the TMB-doped Si nanowires decreased with increasing TMB/SiH4 ratio used during growth, consistent with increased intentional doping.

9:00 AM Invited
MOCVD Growth of Layers and Nanostructures of Indium Nitride: *Olivier Briot*[1]; [1]GES, CC074 Universite Montpellier II, Place E. Bataillon 34095, Montpellier, Cedex 5 France

Indium Nitride (InN) is a very promising material for optoelectronics, hyper frequency and terahertz applications. Its predicted low field electron mobility is already very high for a nitride semiconductor, and its high field electron drift velocity is expected to be even higher than in GaN and GaAs. Concerning its optoelectronic applications, InN band gap has been recently re-evaluated to be in the range of 0.6 - 0.8 eV, instead of the 1.9 eV previously reported. With such a bandgap energy, InN could be employed in telecommunication applications at 1.55 µm. However, the bandgap issue is not yet totally clear, and this is mainly due to the material quality. As a matter of fact, InN is extremely difficult to grow, due to its low thermal stability and its lack of suitable substrate. We have been able to improve the MOCVD growth process for InN to the point where we obtain mirror like layers over two inches diameter sapphire substrates, with a rms roughness below 0.6 nm, as measured by Atomic Force Microscopy. In this paper, we will report our current understanding of the growth of InN by MOCVD, and present the results obtained by optical spectroscopy, raman spectroscopy, transport, AFM and X-ray diffraction. From our optical data, we will discuss the possibility that the bandgap lie at higher energy than recently reported. Furthermore, we have investigated the growth of InN nanostructures by MOCVD. We will demonstrate that the dot size and density can be controled by different growth parameters, such as growth temperature, V/III molar ratio and deposition time. We have been able to obtain quantum dot densities in the range of 108cm-2, which opens the possibility of adressing a single quantum dot. Different substrates have been used (Si, GaN, AlN), and we will discuss their influence on the growth kinetics and dot shape. X-ray diffraction have been used to investigated the dot residual strain, and the results will be reported here.

Basic Growth II

Wednesday AM   Room: Kihei
June 2, 2004   Location: Westin Maui Hotel

Session Chairs: S. Yi, Agilent Technologies, Palo Alto, CA 94304 USA; M. Lampalzer, Philipps-University Marburg, Marburg D-35032 Germany

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9:50 AM
In-Situ Deep Etching in a MOVPE Reactor: *Tomonobu Tsuchiya*[1]; Takeshi Kitatani[1]; Kiyoshi Ouchi[1]; Masahiro Aoki[1]; [1]Hitachi, Ltd., Central Rsch. Lab., 1-280 Higashi-Koigakubo, Kokubunji-shi, Tokyo 185-8601 Japan

With the aim of increasing the characteristic temperature of InP-based semiconductor lasers, InGaAlAs multiple-quantum-well (MQW) lasers have been studied. However, in the case of InGaAlAs integrated optical devices, regrowth on aluminum-containing layers is difficult because of strong surface oxidization. In this study, aiming at avoiding surface oxidization, we investigated in-situ deep etching in a MOVPE reactor. The etching pattern at the mask edge was limited by the (111)B plane. The etching rates for InP and InGaAs were similar, and increased with increasing etching temperature. In the case of InGaAlAs, the etching rate decreased as the aluminum content increased. Moreover, in-situ gas etching did not occur for InAlAs. On the other hand, for InP/InAlAs structures, in-situ gas etching was possible. This result indicates that no etching for InAlAs is due to the surface oxidization. Moreover, a smooth surface morphology was obtained, even for InP regrowth on an InGaAlAs/InAlAs structure.

10:10 AM
AlInGaP High-Brightness LEDs Grown by MOVPE on Alternative Ge Substrates: *Peter Stauss*[1]; Arndt Jaeger[1]; Kristof Dessein[2]; Torsten Pietzonka[1]; Klaus Streubel[1]; [1]OSRAM Opto Semiconductors, Wernerwerkstr. 2, Regensburg 93049 Germany; [2]Umicore EOM, Watertorenstraat 33, Olen 2250 Belgium

Today GaAs is the substrate of choice for the growth of commercial AlInGaP HB-LEDs. A viable alternative could be Germanium, which is already used in the fabrication of III/V solar cells. Compared to GaAs, Ge offers a number of technical advantages and lower substrate costs. In addition, the use of Ge might offer the possibility to fabricate As-free AlGaInP devices. We report on successful heteroepitaxial growth of AlInGaP HB-LEDs in a multiwafer MOVPE reactor using 4 inch Ge substrates. The analysis of the epitaxial layer growth by TEM showed a distinct bunching of atomic steps, which is correlated to the specific growth conditions and the substrate orientation. The electrical characterisation revealed an impurity level in the AlInGaP layers, which could be attributed to the incorporation of Ge. Its concentration depends strongly on the growth parameters. The electrical properties of the Ge impurity and it?s effect on the LED performance was studied in detail.

10:30 AM
Phase Control of GaN on Si by Nanoscale Faceting - Growth of Cubic Phase GaN on a V-Groove Fabricated on a Si(001) Substrate in Metal-Organic Vapor-Phase Epitaxy: *S. C. Lee*[1]; X. Y. Sun[1]; S. D. Hersee[1]; S. R.J. Brueck[1]; [1]University of New Mexico, Ctr. for High Tech. Matls. & Dept. of Elect. & Computer Engrg., 1313 Goddard, SE, Albuquerque, NM 87106 USA

Phase stability of GaN on (111) and (001) Si nanofacets is investigated. Nanofaceting is accomplished with large-area interferometric lithography and anisotropic wet etching. By relying on the nucleation and lateral growth dependence on orientation and crystal structure, the spatial separation of a cubic phase region from hexagonal phase GaN regions, which initiate on the facing Si(111) sidewalls of a 355-nm period V-grooved Si surface, is achieved. Cubic phase GaN appears with rapid planarization after only 70 - 80 nm of deposition, which is comparable to the depth of the V-groove. The boundary between cubic and hexagonal phases is clearly revealed along the Si(111) sidewalls. A dielectric mask is used to confine the deposition of GaN to a range of micro- to macroscales. This paper will describe the phase separation and the stress distribution of GaN selectively grown on nanofaceted Si surfaces.

10:50 AM Break

Nanostructures I

Wednesday AM   Room: Kula
June 2, 2004   Location: Westin Maui Hotel

Session Chairs: R. Moon, Agilent Technologies, Palo Alto, CA 94304 USA; F. Scholz, Universität Ulm, Ulm 89081 Germany

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9:50 AM
MOVPE Selectively Grown GaAs Nano-Wires with Self-Aligned W Side Gate: *N. Ooike*[1]; J. Motohisa[1]; T. Fukui[1]; [1]Hokkaido University, RCIQE, N. 13 W. 8 Kitaku, Sapporo, Hokkaido 060-8628 Japan

We have been studying GaAs single electron transistors (SETs) and their integrated circuits fabricated by using selective area(SA) MOVPE. In this report, we demonstrate GaAs/AlGaAs quantum well wire structures having novel self-align W gate electrode by SA-MOVPE. W works as a mask for GaAs wire growth as well as a side gate electrode. We use SiO2/W stacked film as SA-MOVPE mask to prevent significant lateral overgrowth onto W mask. Advantage of this stacked mask is that W side gate is formed automatically during growth, and additional top gates can be attached to form multi-gate SET logic circuits as a future application. We successfully suppress lateral overgrowth and observed Schottky I-V characteristics between GaAs wire channel and W gate. Furthermore, with an appropriate control of the wire width and the distance between channel and gate, transistor action with good pinch-off characteristics was demonstrated.

10:10 AM
Large-Scale Synthesis of GaN Nanoneedles and Nanowires via MOCVD: *George T. Wang*[1]; J. Randall Creighton[1]; [1]Sandia National Laboratories, Chem. Procg. Scis., PO Box 5800, MS 0601, Albuquerque, NM 87185-0601 USA

GaN nanoneedles and nanowires have been synthesized using a metal organic chemical vapor deposition (MOCVD) process in a rotating disk reactor. The nanowires were primarily grown on sapphire substrates coated with thin Ni catalyst films using trimethylgallium and ammonia as growth precursors. The majority of nanowires grown are several to tens of microns in length and have typical tip diameters between 50-150 nm. TEM, EDS, and photoluminescence studies indicate that the nanowires are single-crystalline GaN with Ni clusters at the tips, suggesting growth via the vapor-liquid-solid (VLS) mechanism. It was found that the presence of catalysts enhanced film nucleation as well, raising the issue of competition between GaN film nucleation and nanowire growth. The effects on nanowire growth and quality of different process conditions and variables, including temperature, pressure, catalyst treatment, substrate orientation and roughness, and gas flows, have been explored and will be discussed.

10:30 AM
Transport Mechanisms in Growth of III-V Nanowires: *Ann Ingeborg Persson*[1]; B. Jonas Ohlsson[1]; Sören Jeppesen[1]; Linus E. Jensen[1]; Lars Samuelson[1]; [1]Lund University, Solid State Physics, Box 118, Lund 221 00 Sweden

Growth of epitaxially nucleated nanowires (nanowhiskers) is usually described by the vapor-liquid-solid (VLS) growth mechanism, where metallic seed particles are used to form a eutectic system with the semiconductor growth material. Irrespective of contact with a crystalline support surface, the nanowires will preferentially grow in the (111) B direction. The advantage of whiskers grown in contact with a single crystalline surface, is improved control of direction and position, but add surface processes that might influence and make wire growth more complicated to control. The growth of nanowires depend on the transport of growth species to and through the seed particle. Here we present results of investigations of growth rate of Au-catalyzed GaAs and InP nanowires by Chemical Beam Epitaxy (CBE), as a function of V/III ratio and surface condition. We also report results indicating the seed particle to be solid, rather than liquid as suggested by the VLS-mechanism.

10:50 AM Break

Nanostructures II

Wednesday AM   Room: Kula
June 2, 2004   Location: Westin Maui Hotel

Session Chairs: R. Moon, Agilent Technologies, Palo Alto, CA 94304 USA; F. Scholz, Universität Ulm, Ulm 89081 Germany

11:30 AM
Growth of Non-Tapered InP/InAs Nanowire Superlattices by Metalorganic Chemical Vapor Deposition: *Sungsoo Yi*[1]; Grant Girolami[1]; Jun Amano[1]; [1]Agilent Technologies, 3500 Deer Creek Rd., Palo Alto, CA 94304 USA

Semiconductor nanowires (NWs) are nanoscale building blocks that could enable the development of nanoscale electronic and photonic devices without any advanced lithographies. It is crucial to control the diameter and shape of NWs, which strongly affect their electrical and optical properties. Growth of non-tapered NWs by laser catalytic growth method and chemical beam epitaxy has been reported but MOCVD-grown NWs are generally known to taper significantly from the base to the tip. We report a novel growth process of non-tapered InP/InAs NW superlattices by MOCVD. Au nanoparticles with average diameter of 20 nm deposited randomly on the SiO$_2$ substrates were used as the catalysts to grow NWs with corresponding diameters via the metal-catalyzed vapor-liquid-solid mechanism. The NW diameter along the growth axis is remarkably uniform over a length scale > 1 μm. The morphology, structure and composition of NWs were characterized by SEM, TEM, and EDX.

11:50 AM
Growth of Nanotrees by Sequential Seeding of 1D Nanowires: Kimberly A. Dick[1]; Knut Deppert[1]; Magnus W. Larsson[2]; *Werner Seifert*[1]; L. Reine Wallenberg[2]; Lars Samuelson[1]; [1]Lund University, Solid State Physics, Box 118, Lund 221 00 Sweden; [2]Lund University, Matls. Chmst., Box 124, Lund 221 00 Sweden

Complex nanostructures are becoming increasingly important for the development of nanoscale devices and functional nanomaterials. Precise control of size and morphology of these structures is critical to their fabrication and exploitation. We have developed a method for stepwise growth of tree-like nanostructures via the vapour-liquid-solid (VLS) growth mode. Here we present a detailed study of the growth of these complex structures. This method uses the initial seeding of nanowires by catalytic aerosol nanoparticles to form the trunk, followed by sequential seeding of branching structures. Properties of each generation of branching can be determined via control of growth time, source material concentration, growth temperature, seed particle diameter, and seed particle number density. We show clear relationships between growth parameters and resulting branch properties, allowing for precise control of the structure of nanotrees.

12:10 PM
Catalyst-Free Selective-Area MOVPE of Semiconductor Nanowires on (111)B Oriented Substrates: Junichi Motohisa[1]; Jinichiro Noborisaka[1]; Junichiro Takeda[1]; Masaru Inari[1]; *Takashi Fukui*[1]; [1]Hokkaido University, Rsch. Ctr. for Integrated Quantum Elect., N13 W8, Sapporo, Hokkaido 060-8628 Japan

We report on a catalyst-free approach for the growth of semiconductor nanowires which are attracting interest as an building block for the nanoscale electronics and circuits. Our approach is based on selective-area MOVPE and nanowires are grown from small circular openings of SiO$_2$ mask defined on (111)B-oriented substrates. At optimized conditions, extremely uniform array of GaAs and InGaAs nanowires with diameter of about 200nm was grown on GaAs and InP substrates, respectively. The nanowires have hexagonal cross-section and are perpendicular to the substrates, indicating that they are surrounded by {110} facet sidewalls. By reducing the mask opening size, nanowires with diameter down to 50nm and length more than 6μm were successfully formed. Formation of such high-aspect ratio nanowires is owed to their extraordinarily fast growth rate, and fast diffusion of growth species along sidewalls is suggested. Detailed growth mechanism will be presented.

Nitrides Growth I

Wednesday AM   Room: Kihei
June 2, 2004   Location: Westin Maui Hotel

Session Chairs: K. Matsumoto, Nippon Sanso Corporation, Minato-ku, Tokyo 105-8442 Japan; M. G. Craford, Lumileds Lighting, San Jose, CA 95131 USA

11:30 AM
High Power Laser Structures Grown on Bulk GaN Crystals: *Pawel Prystawko*[1]; Robert Czernetzki[3]; Lucy Gorczyca[2]; Przemek Wisniewski[1]; Piotr Perlin[1]; Marcin Zielinski[4]; Tadeusz Suski[1]; Mike Leszczynski[3]; [1]Unipress, High Pressure Research Center, PAS, Nitride Epitaxy Lab., Sokolowska 29/37, Warsaw 01-142 Poland; [2]University of Science and Technology, Matl. Scis. & Ceram., Al Mickiewicza 30, Krakow Poland; [3]TopGaN Ltd., Sokolowska 29/37, Warsaw 01-142 Poland; [4]University of Montpellier II, GES-CNRS, Case courrier 074, Montpellier 34095 France

High pressure-grown bulk GaN crystals have the best reported structural quality and the lowest defect density among all available GaN substrates. We report on MOVPE growth, device processing and properties of high power laser structures on such substrates. In this work we describe very high optical output power per laser facet of 1.89W from single LD device with 15_{μ}mx500_{μ}m cavity. The measured value is to the best of our knowledge the highest nitride laser power reported. Also the electrical and optical power densities, yet pulsed are the highest reported for broad area lasers what confirms that nitride-based wide bandgap structures are capable of handling very high power. From thermally accelerated electrical ageing tests we extracted the activation energy of one of degradation mechanisms to be 3.2eV. Catastrophic Optical Damage was not observed at 20MW/cm^2. Demonstrated results show that the availability of very low defect density GaN substrates is clearly the key issue in fabrication of highly reliabile devices and high power LD.

11:50 AM
Growth and Electrical Characterization of Nonpolar a-Plane p-Type GaN and p-n Junction Diodes: *Arpan Chakraborty*[1]; Huili Xing[1]; Michael D. Craven[2]; Thomas M. Katona[1]; Stacia Keller[1]; James S. Speck[2]; Steven P. DenBaars[1]; Umesh K. Mishra[1]; [1]University of California, Elect. & Computer Engrg. Dept., Santa Barbara, CA 93106 USA; [2]University of California, Matls. Dept., Santa Barbara, CA 93106 USA

The growth and electrical properties of Mg-doped p-type nonpolar a-plane GaN films, grown on r-plane sapphire substrates via metalorganic chemical vapor deposition, were investigated as a function of Mg doping, growth rate, the V/III ratio, and the growth temperature. The films were characterized by Atomic Force microscopy (AFM), Hall effect measurements, and Secondary Ion Mass Spectroscopy (SIMS). An optimum Mg-doping concentration was found, for which the resistivity and the surface roughness exhibited a minimum. Generally, the electrical conductivity of the a-GaN films showed a strong dependence on the growth rate and the V/III ratio. SIMS measurements revealed that more Mg was incorporated at higher growth rates. The effects of the growth conditions on the Mg incorporation in a-plane GaN will be compared to the incorporation in concurrently loaded c-plane samples. The p-n junction diodes fabricated on non-polar a-plane GaN showed a sharp turn-on between 3-4 V.

12:10 PM
Optimization of GaN MOVPE and HVPE Growth on Patterned and Masked Substrates Using Spectroscopic In-Situ Reflectance: André Strittmatter[1]; Thomas Trepk[2]; *Udo W. Pohl*[1]; Dieter Bimberg[1]; Jörg-Thomas Zettler[2]; [1]Technische Universität Berlin, Inst. für Festkörperphysik, Hardenbergstr. 36, 10623 Berlin Germany; [2]LayTec GmbH, Helmholtzstr. 13-14, 10587 Berlin Germany

In real-time monitoring of III-Nitride growth on patterned and masked substrates by spectroscopic reflectance, a characteristic interference pattern - generated by the superposition of wave-fronts reflected at different µm-sized structures at the sample surface - is measured. Up to now this time- and wavelength-dependent pattern was used only for empirical fingerprint-evaluation of III-Nitride growth processes which employ patterning or masking for bulk defect reduction. In this paper we report the first truly quantitative analysis of real-time spectroscopic reflectance data measured in the range 300-800 nm during the epitaxial growth of GaN and AlN on structured Si(111) substrates. The successful implementation of a three-dimensional interference model into conventional thin-film analysis algorithms enables the quantitative analysis of characteristic vertical and lateral growth rates and overgrowth mechanisms involved. The new method is applied to optimize III-Nitride growth processes on patterned silicon substrates used for subsequent III-Nitride device growth.

Wednesday PM - June 2, 2004

Plenary Session

Wednesday PM	Room: Kihei
June 2, 2004	Location: Westin Maui Hotel

Session Chairs: S. Keller, University of California, Santa Barbara, CA 93106 USA; H. Bernhard Schlegel, Wayne State University, Detroit, MI 48202 USA

2:00 PM Invited
High Efficiency GaN Based LEDs and Lasers for Blue to UV Optoelectronics: *John Edmond*[1]; Dave Emerson[1]; Mike Bergman[1]; Amber Abare[1]; Kevin Haberern[1]; Dave Slater[1]; [1]Cree Inc., 460 Silicon Dr., Durham, NC USA

Blue and Ultraviolet (UV) light emitters have recently become the focus of intense research due to the number of potential applications, such as solid-state white lighting via phosphor excitation, biochemical detection, and enhanced density of optical data storage. By using chip shaping and improvements in epitaxial layer quality CREE has achieved blue LEDs with output powers as high as 22mW at 20mA, and external efficiencies as high as 40%. White LEDs have been fabricated with these chips via phosphor excitation and exhibit luminous efficacies of 74 lm/W, which is considerably more efficient than standard light-bulbs. Through improvements in the materials properties and defect densities through varying MOCVD growth conditions we have obtained CW laser diode operation as short as 348nm, and pulsed operation as short as 343nm. Ultra-violet light emitting diodes were fabricated and achieved output powers as high as 1mW at 20mA for 340nm emission wavelength. The authors gratefully acknowledge the support of the DARPA SUVOS program for the UV emitter work Dr. John C. Carrano).

2:40 PM Break

Industry/Safety Poster Session - 2:40 to 4:00 PM

Wednesday PM	Room: Lahaina
June 2, 2004	Location: Westin Maui Hotel

Session Chairs: D. Vanderwater, Lumileds Lighting LLC, San Jose, CA 95131 USA; B. Kroll, Matheson Tri-Gas, Montgomeryville, PA 18936 USA; Karl Olander, ATMI, Danbury, CT 06810 USA

Industry

(1) Improve Process Control, Lower Costs and Reduce Risks Through the Use of Non-Destructive Mobility and Sheet Charge Density Measurements on pHEMTs: *Austin Blew*[1]; [1]Lehighton Electronics, Inc.

Non-destructive measurements eliminate difficult and costly contact preparation on thin-cap Hall wafers. Eliminating Hall wafers will reduce delays in starting production, and cut revenue losses that result from running unfilled reactors. Data and maps are available for each product wafer. Wafers will be run with the same fixed recipe for both thin-cap Hall and production wafers. Tests will include destructive Hall measurements on thin-cap wafers, and non-destructive measurements at the same location on both wafers. The tests will include provisions to enable comparison between the two measurement methods, and between the production wafer non-destructive measurements and device measurements. Inter- and intra-wafer measurements may be used to see how they compare, and to determine if intra-wafer uniformity data is a predictor of device yield or performance.

(2) In-Situ Metrology Advances in MOCVD Growth of GaN Based Materials: Mikhail Belousov[1]; Boris Volf[1]; Jeffrey Ramer[1]; Eric Armour[1]; *Alexander Gurary*[1]; [1]Veeco TurboDisc Operations, 394 Elizabeth Ave., Somerset, NJ 08873 USA

In-situ characterization techniques are necessary tools in modern MOCVD equipment for both the research and production environments. In this presentation, we will describe two recently developed in-situ devices for high-speed rotating disk MOCVD systems: (1) an emissivity-compensated pyrometer and (2) a deflectometer. Emissivity-compensated pyrometers provide for accurate process temperature measurements of the SiC coated graphite wafer carriers during the growth process, where dynamic changes in emissivity occur due to the changing deposits on the carrier. In-situ deflectometry allows real-time measurement of wafer bowing, resulting from strain caused by lattice-mismatch and spatial temperature gradients. The deflectometer also provides carrier warpage measurements, along with tilt angle of wafers relative to the carrier. Both devices can measure the spatial profile of reflectivity across individual wafers, and determine the resulting growth rate, layer thickness, and composition. We will discuss the concepts and techniques behind these in-situ tools, along with providing examples of their application to the development and production of GaN-based LEDs.

(3) III-Nitride Materials for High Power Microwave Devices: *Adam Saxler*[1]; Yifeng Wu[2]; Jason Jenny[1]; R. Peter Smith[1]; Scott Sheppard[1]; Prashant Chavarkar[2]; Primit Parikh[2]; Scott Allen[1]; John Palmour[1]; [1]Cree, Inc., 4600 Silicon Dr., Durham, NC 27703 USA; [2]Cree, Inc., Santa Barbara Tech. Ctr. , 340 Storke Rd. , Goleta, CA 93117 USA

III-Nitride based heterostructures were grown on semi-insulating, on-axis, Si face 4H-SiC substrates. Excellent uniformity was achieved on 3" diameter substrates as indicated by sheet resistivity maps. Typically, standard deviation values are <1% with values under 0.25% observed. However, certain substrate imperfections may lead to increased standard deviation in the sheet resistivity. Use of AlN barrier structures instead of conventional HEMT structures leads to significant reductions in sheet resistivity to under 300 ohms/square. Higher breakdown voltages are enabled through iron doping of the buffer layers. The III-Nitride material quality coupled with the device design and the high thermal conductivity of the high purity 4H-SiC substrates enabled high-power microwave device performance. Over 30W/mm continuous-wave power density with over 50% power-added efficiency has been demonstrated for field plate devices fabricated using AlN barrier structures with iron doped buffer layers grown on 3" diameter high-purity semi-insulating 4H-SiC substrates.

(4) Ammonia and Arsine Purification by Novel Lanthanide/Manganese Oxide Materials: *Dan Alvarez*[1]; Joshua Cook[1]; Troy Scoggins[2];

[1]Mykrolis Corporation, Gas Microcontamination BU, 6975 Flanders Dr., San Diego, CA 92121 USA; [2]Mykrolis Corporation, Gas Microcontamination BU, 915 Enterprise Blvd., Allen, TX 75013 USA

The removal of contaminants from NH3 and AsH3 to low or sub-ppb levels is required in order to ensure the quality and performance of Compound Semiconductor devices. Oxygen, introduced into the epi-layer by H2O and O2, is a p-type dopant. It counteracts the physical properties achieved by n-type dopants and also leads to crystal lattice defects. Optical and electrical qualities are highly dependant on precursor (NH3, AsH3) gas purity. A novel technology for hydride gas purification utilizing Lanthanide/Manganese oxide based materials has been developed. Negative ion Atmospheric Pressure Ionization Mass Spectrometry (APIMS) studies will be presented that show moisture and oxygen levels in ammonia gas streams before and after purification. Detection limits of less than 1.0 part per billion for H2O in ammonia have been achieved. FT-IR and moisture hygrometer data will also be presented showing the compatibility and effectiveness of these materials for the purification of Arsine.

(5) Production MOCVD Growth of AlGaN/GaN HEMTs on 4" Sapphire: *David W. Gotthold*[1]; Shiping Guo[1]; Brian Albert[1]; Boris Peres[1]; [1]EMCORE Corporation, 145 Belmont Dr., Somerset, NJ 08873 USA

AlGaN/GaN HEMTs are of great interest for high power and high frequency device applications due to their superior material properties. While high power RF devices are commonly grown on SiC, other applications, such as low frequency power electronics, require much lower costs and do not need the superior thermal properties of SiC. For these applications, wafer size and substrate costs are very important factors in final device cost. In addition, 4" SiC is still not commercially available in sufficiently quantities for even pilot production levels. In this work, the production MOCVD growth of AlGaN/GaN HEMTs on 4" sapphire was addressed. An excellent sheet resistance (R_s) and thickness uniformities were achieved with a standard deviation of ~2% for R_s and ~3% for thickness across the 4" wafer, respectively. A good wafer-to-wafer uniformity within a platter and run-to-run reproducibility were also obtained, indicating the capability for production scale MOCVD growth of AlGaN/GaN HEMTs on large area substrates at EMCORE.

(6) Sapphire Substrate Misorientation Effects on GaN Nucleation Layer Properties: *Dong Lu*[1]; Doru I. Florescu[1]; Dong S. Lee[1]; Vinod Merai[1]; Jeff C. Ramer[1]; Rudy Parekh[1]; Eric A. Armour[1]; [1]Veeco, TurboDisc Operations, 394 Elizabeth Ave., Somerset, NJ 08873 USA

We investigate the c-plane sapphire substrate misorientation angle (0.00 to 0.45 degrees range) effects on MOCVD GaN nucleation layer properties. X-Ray rocking curves show both a narrow peak and a broad diffusive component representing the GaN nucleation islands misorientation and constrained orientation, respectively.[1] The intensity ratio of the sharp to the broad component integrated along the longitudinal direction indicates that the GaN nucleation layer on sapphire under a slight misorientation is constrained by the substrate. X-Ray diffraction data relates the substrate miscut effects to both the GaN nucleation layer correlation length[2] and grain coalescence. AFM evaluation reveals the smallest peak-to-valley range on substrates with ~0.3 degrees misorientation. X-Ray reflectance at grazing incidence illustrates distinct oscillation fringes, indicative of a relatively sharp interface between the nucleation layer and substrate. Reflectance simulation results reveal GaN nucleation layer thickness dependence to the substrate misorientation, with a minimum thickness at ~0.3 degree miscut angle for samples grown under similar conditions. From the above results, the superior surface morphology, crystalline and optical properties of GaN LEDs grown on ~0.3 degree miscut sapphire reported earlier[3] can also be related to the nucleation conditions. [1]. M.S. Yi, H.H. Lee, D.J. Kim, S.J. Park, and D.Y. Noh, C.C. Kim and J.H. Je, Applied Physics Letters, Vol.75, 2187 (1999). [2]. Q. Zhu, A. Botchkarev, W. Kim, O. Aktas, A. Salvador, B. Sverdlov, andH. Morkoc, S. C.Y. Tsen and David J. Smth, Applied Physics Letters, Vol.68, 1141 (1996). [3]. D. Lu, D. I. Florescu, D. S. Lee, V. Merai, J. C. Ramer , R. Parekh, E.A. Armour, Physica Status Solidi, A, 200, 71 (2003).

(7) Correlation of Film Properties and Reduced Impurity Concentrations in Sources for III/V-MOVPE Using High Purity Trimethylindium and Tertiarybutylphosphine: *Deo V. Shenai*[1]; Michael L. Timmons[1]; Ronald L. DiCalo[1]; Michael B. Power[1]; Artashes Amamchyan[1]; Egbert Woelk[1]; William B. Grant[1]; Robert A. Ware[1]; [1]Rohm and Haas Electronic Materials, L.L.C., Metalorganics, 60 Willow St., N. Andover, MA 01845 USA

Trimethylindium (TMI) and Tertiarybutylphosphine (TBP) are becoming the preferred sources for MOVPE of InP-based compounds. TBP is used to deposit high quality layers at significantly lower V/III ratios, and is considered as the safer and less hazardous liquid alternative to phosphine gas. Although source purities have improved considerably during the past few years, consistent quality remains a major concern. In the present work, metallic and organic impurities in the sources were measured at ppb levels, using improved analytical techniques such as FT-NMR, GC-MS, and ICP-OES. The impurity profiles were compared with the electrical properties of InP grown by MOVPE at 600° C and V/III ratio of 20. The films showed typical 77 K and 300 K Hall mobilities of 140,000 and 4,850 sq. cm/Vs, with total impurity concentration about 1.5E14 per cc. The impact of deleterious impurities on optoelectronic properties is discussed along with the synthetic strategies to metalorganic sources.

(8) High Uniformity of InGaAsP Layers Grown by Multi-Wafer MOVPE System: *Eiichi Shimizu*[1]; Shizuo Sugawara[1]; Hirofumi Nakata[1]; [1]Nikko Materials, Dvlp. Ctr., 3-17-35, Niizo-Minami, Toda-shi, Saitama 335-8502 Japan

Compositional uniformity of lattice matched quaternary (InGaAsP) epitaxial layers on InP substrate was examined with multi-wafer MOVPE growth. The vertical high-speed rotating-disk reactor was used to grow the epitaxial layers on maximum six 2-inch InP wafers for the same growth batch. Epitaxial layers with the photoluminescence wavelength 1.3um were obtained with standard deviation 0.6nm in a single wafer, 1.0nm in all four wafers, and 1.6nm in all six wafers for the same growth batch. In this material system, As/P composition is very sensitive to the growth temperature. It is important to suppress the temperature difference between a wafer and a wafer carrier. The structure of wafer carrier was optimized by computational fluid dynamics (CFD) analysis of the thermal contact resistance of a wafer and a wafer carrier. The wafer carrier temperature was successfully controlled to the same as the wafer, so that compositional uniformity of epitaxial layers was improved.

(9) Influence of Growth Pressure on AlGaN and Mg Doped GaN Grown by Multi Wafer MOCVD System: *H. Tokunaga*[1]; A. Ubukata[1]; Y. Yano[1]; A. Yamaguchi[1]; N. Akutsu[1]; T. Yamasaki[1]; K. Matsumoto[1]; [1]Nippon Sanso Corporation, Elect. Sales Div./Compound Semiconductor Project, 10 Ohkubo, Tsukuba, Ibaraki 300-2611 Japan

Today, most of a GaN laser diodes and UHB-LEDs are produced by atmospheric pressure MOCVD in Japan, since higher quality layer is obtained. However, it is also known that a design of a large-scale AP-MOCVD reactor is very difficult because of a parasitic reaction between organo-metals and NH3. Therefore, it is very important to understand an impact of growth pressure on materials properties and the parasitic reaction in light of a tradeoff between them. In this paper, we have investigated the effect of growth pressure on AlGaN growth and the materials property of GaN:Mg by using a multi-wafer AP-MOCVD reactor. By using this reactor, we can grow Al0.09Ga0.91N with a growth rate of 0.8um/h, and GaN:Mg with a carrier concentration of 1.4X10E18cm-3 with 3.5um/h at 1atm.

(10) Oxygen and Carbon Incorporation in (AlGa)As Grown by MOVPE Using TBAs: *Joerg Koch*[1]; Nada El-Zein[2]; Arnd Greiling[1]; Stefan Reinhard[3]; Kerstin Volz[3]; Wolfgang Stolz[3]; [1]Akzo Nobel, High Purity Metalorganics, G-Hof, Emil-von-Behring-Str. 76, Marburg 35041 Germany; [2]Akzo Nobel, High Purity Metalorganics, 525 W. Van Buren St., Chicago, IL 60607-3823 USA; [3]Philipps-University, Central Tech. Lab., Matl. Scis. Ctr., Hans-Meerwein-Str., Marburg 35032 Germany

High purity (AlGa)As layers are of key importance for electronic as well as optoelectronic applications. However, the incorporation of Al leads to a drastic increase in O-sensitivity and higher intrinsic C-doping levels. Thus, changes in growth conditions as well as usage of highest quality source materials are mandatory. (AlGa)As-layers have been grown using different quality TMGa, TMAl and TBAs. Growth parameters (temperature, V/III-ratio, growth rate) have been varied in a wide range. Impurity up-take has been studied quantitatively by secondary ion mass spectrometry (SIMS) for high Al-content layer structures. The results obtained are correlated to the optical properties of (Al0.3Ga0.7)As-double heterostructures at room temperature. The various origins of the impurity incorporation for (AlGa)As layers as a function of growth conditions will be presented and dicussed in particular with respect to the realization of state-of-the-art low O-content (1-2 1016 cm-3 for Al0.85Ga0.15As) at low growth temperatures using the more efficiently decomposing TBAs.

(11) Reactor Design Optimization Based on 3D Modeling of Nitrides Deposition in MOCVD Vertical Rotating Disc Reactors: *L. Kadinski*[1]; B. Mitrovic[1]; A. Parekh[1]; J. Ramer[1]; V. Merai[1]; E. Armour[1]; A. Gurary[1]; [1]Veeco, TurboDisc Operations, 394 Elizabeth Ave., Somerset, NJ 08873 USA

MOCVD Vertical Rotating Disc Reactors (RDR) are widely used for large scale production of GaN based semiconductor devices such as blue and green LEDs, UV LEDs, and FETs. In RDRs, rotation of the wafer carrier results in an effective averaging of the deposition rate distribution and this is a key mechanism providing growth of epitaxial layers with highly uniform properties. The necessity to utilize many different precursors for nitrides deposition, many of which actively react with each other in the gas phase, presents significant challenges for the process reactor development, particularly the reactant injection elements. Proper design of such components is practically impossible without detailed modeling that addresses optimization of both reactor components and process parameters and is based on the ability to predict growth rate and uniformity under different process conditions. We designed a new modification of a 75mm RDR (1x2'') TurboDisc reactor that is based on three-dimensional modeling of nitrides deposition. The main improvements introduced were for the injector plate design by optimizing the geometrical positions of all alkyl zones to provide for optimal control of the growth rate uniformity across the substrate. We will describe an optimization technique based on a Design Of Experiment (DOE) approach that allowed a significant reduction in the amount of calculations required. We will report on comparison between trends in effects of rotation rate, chamber pressure and reactant flow as obtained from experimental growth results and modeling computations. It will be shown that the use of modeling has drastically reduced the process development time to a few runs even in the case when iterations between modeling and experiment are required.

(12) GaN Layer Improvements Applying "N+1" Reliable Hydrogen Source: *Lawrence Rabellino*[1]; [1]SAES Pure Gas, 4175 Santa Fe Rd., San Luis Obispo, CA 93401 USA

MOCVD process repeatability and throughput are directly proportional to the purity of the materials used. As an example, trace levels of impurities in Hydrogen gas such as carbon monoxide, carbon dioxide and moisture contain elements known to act as shallow donors and acceptors in GaN. These contaminants must be removed to create intrinsic GaN with high purity. The MOCVD group at University of California, Santa Barbara (UCSB) recently experienced a systematic rise in the background carrier concentration for unintentionally doped GaN template layers. Investigation into the root cause identified an undetected loss of gas purity from the existing purification system. In order to prevent further unscheduled downtime and loss of product, the team at UCSB re-evaluated the hydrogen delivery system for opportunities to maintain gas purity, improve consistency and ultimately make the system more robust. This paper will detail the process UCSB employed to arrive at a system that cost effectively provides the necessary gas purity with N+1 reliability.

(13) TMI Transport Studies: The Effect of Different Bubbler Designs: *Lesley M. Smith*[1]; Rajesh Odedra[1]; Andrew J. Kingsley[1]; Kathleen M. Coward[1]; Simon A. Rushworth[1]; Graham Williams[1]; Ravi K. Kanjolia[2]; Thomas A. Leese[1]; Ashley J. Purdie[1]; [1]Epichem Ltd., Rsch., Power Rd., Bromborough, Wirral, Merseyside CH62 3QF UK; [2]Epichem Inc., Rsch., 1429 Hilldale Ave., Haverhill, MA 01832-1300 USA

In today's MOVPE processes a steady, controllable flux of precursor into the reaction chamber is key when fabricating highly complex device structures employing ternary and quaternary layers. For solid precursors the simple diptube bubbler design does not meet all customer requirements, especially at high indium transport rates. Channelling effects are deemed the main cause of pick up variations and different container geometries have been proposed to achieve improved gas phase saturation and transport efficiency. This study reports data obtained for a number of alternative bubbler designs when tested under different usage parameters. The best results, with exceptionally stable flux output across a wide range of operating parameters throughout the bubbler lifetime, were obtained using a novel perforated disc design. This design is an extension of the cross dipleg to provide multiple gas pathways to minimise channelling effects and allow uniform depletion of the bubbler contents.

(14) High Throughput MOVPE Production System for AlGaInP Based LED and Solar Cell Structure: K. Christiansen[1]; J. Hofeldt[1]; A. Tiedemann[1]; B. Schineller[1]; J. Kaeppeler[1]; *M. Heuken*[1]; [1]AIXTRON AG, Kackertstr. 15 - 17, Aachen 52072 Germany

Fast progress in the compound semiconductor industry requires MOVPE reactors with higher throughput and improved efficiency. To meet the markets requests AIXTRON has developed 12x4? and 49x2? configurations standing for 50% and 40% increase in wafer area capacity, respectively. These configurations were developed with special focus on the efficiency of the metalorganic precursors. In AlGaInP layers on 4? substrates efficiency values for TMAl and TMGa above 35% and for TMIn above 30% could be achieved. The next logical step to raise the productivity of a system is to shorten the process time by increasing the growth rate. In the 12x4? configuration we demonstrated growth rates of 17µm/h for GaAs and 3.6µm/h for Al20GaInP, which are representative layers for LED-structures. The Al20GaInP layers show excellent wavelength homogeneity with a range of ±1.4nm at an average wavelength of 620nm. The efficiency for metalorganic precursors remains at values above 35% for TMAl and TMGa and 30% for TMIn.

(15) Effect of 4 Inch Sapphire Substrate Bow on Wavelength Uniformity in MOCVD Grown InGaN/GaN: O. Schoen[1]; A. Alam[1]; *M. Luenenbuerger*[1]; B. Schineller[1]; *M. Kaeppeler*[1]; M. Heuken[1]; [1]AIXTRON AG, Kackertstr. 15 - 17, Aachen 52072 Germany

The differences of thermal expansion coefficient and lattice constant between sapphire and the growing GaN layer can lead to a bowing of the wafer during growth, resulting in an uneven thermal contact to the epitool's susceptor. This effect is found to be more dominant in 4 inch wafers compared to 2 inch. We have investigated the influence of substrate thickness (varied between 650-850µm) and processing on the resultant wafer bow using temperature sensitive InGaN Multi-Quantum-Well structures as test-vehicles. All growth experiments were carried out in an AIX 2600G3 HT Planetary Reactor® in the 8x4 inch configuration. As the total layer thicknesses were increased from 3 to 6µm the standard deviation of the PL uniformity increased from 1.1-2.6% for structures in the blue spectral range, limiting the total feasible device thickness. This effect was more prominent in substrates of lower thickness. Strategies to avoid wafer bowing will be presented and documented by additional results.

(16) MOCVD Growth of InAlGaP/InGaP Heterostructures Using TBP: *Nada A. El-Zein*[1]; Brian McDermott[3]; Arnd Greiling[1]; Joerg Koch[1]; Wolfgang Stolz[2]; [1]Akzo Nobel, HPMO, 525 W. Van Buren, 15th Floor, Chicago, IL 60607 USA; [2]Philipps-University, Matl. Scis. Ctr., Central Tech. Lab., Marburg D-35032 Germany; [3]EpiWorks Inc., 1606 Rion Dr., Champaign, IL 61822 USA

AlInGaP red laser diodes have become increasingly attractive as light sources for various applications. High quality InAlGaP and InGaP layers are of key importance for the performance of these lasers. In this report we explore the growth of red lasers using a fully liquid process, i.e replacing the hydrides with liquid MO-V sources. This report will show material data (Xray, PL, SIMS etc...) on In(Al)GaP layers grown using TBP. The material performance of InAlGaP & InGaP layers grown using TBP and having different compositions will be compared to similar layers grown using PH3. Growth parameters (temperature, V/III-ratio) that will be presented will outline the advantages of MO-V growth such as lower growth temperatures and lower V/III ratios , as well as potential benefits on the maintenance of the reactor. Finally, we will show preliminary data on the full red laser epitaxial stack using the optimized growth conditions for each layer.

(17) Advances in Photoreflectance Characterisation of Epitaxial Device Material Wafers: Patrick Vincent Kelly[1]; *Martin Edward Murtagh*[1]; [1]Optical Metrology Innovations Ltd., 2200 Cork Airport Business Park, Cork Airport, Co. Cork Ireland

Advances in the photoreflectance (PR) spectroscopy of epiwafer device material wafers are presented. PR is a laser pumped electro-absorptive modulation reflectance spectroscopy technique which probes the electric field modulated density-of-states (DOS). PR yields important band structural information including critical point type, interband transition energy levels, and resonances. Ternary and quaternary alloy mole fractions can be deduced from PR. Uniquely, as a consequence of its electro-optic character, PR can measure in-built surface and interfacial electric field strengths in the epiwafer structure. PR has traditionally been applied to heterojunction bipolar transistor (HBT) epiwafer characterisation. Pump intensity dependent PR results are presented. The emergence of wide variable angle of incidence PR has opened its application to VCSEL device material. Results from nominally 850nm and 980nm VCSELs, corresponding to cavity (top/bottom) emission between AlGaAs(AlAs) distributed Bragg reflector (DBR) stack mirrors, reveal the technologically important cavity resonance mode and ground state quantum well exciton structures.

(18) MOVPE of InP and Related Alloys Using Tertiarybutylphosphine and Tertiarybutylarsine: *Robert F. Hicks*[1]; Gangyi Chen[1]; Dick Cheng[1]; Atif Noori[2]; Mark S. Goorsky[2]; Ravi Kanjolia[3]; Leslie Smith[3]; [1]University of California, Chem. Engrg., 5531 Boelter Hall, Los Angeles, CA 90095 USA; [2]University of California, Dept. of Matl. Sci. & Engrg., Los Angeles, CA 90066 USA; [3]Epichem, Inc., 26 Ward Hill Ave., Haverhill, MA 01835 USA

Indium phosphide, aluminum indium phosphide, and indium gallium arsenide phosphide have been deposited using tertiarybutylphosphine and tertiarybutylarsine. Indium phosphide films were grown with 300 and 77 K Hall mobilities of 4,970 and 135,000 cm^2/Vs. The impurity level in these films was less than 3.0x10^{14} cm^{-3}. Good-quality InGaAsP alloys were produced, as revealed by x-ray diffraction and photoluminescence. The segregation curve for phosphorus and arsenic, yielded an As distribution factor of 23 at 610°C. This compares to a value of 125 obtained with hydride sources at the same temperature. Consequently, the organometallic compounds provide improved control over quaternary alloys deposited by MOVPE. The oxygen contamination in AlInP epilayers is below 10^{16} cm^{-3}, and is 100 times lower than the results reported for growth with phosphine. At the meeting, we will discuss the implication of these results for fabricating InP-based materials.

(19) Advantages of a New V-Purge System for Palladium Membrane Hydrogen Purifiers: Rick Paczewski[1]; [1]Johnson Matthey, Gas Purification Technology, 1397 King Rd., W. Chester, PA 19380 USA

Palladium membrane hydrogen purifiers, a staple in the compound semiconductor industry, have been acknowledged as the purification technology of choice for MOVPE processes such as MOCVD. They are highly effective in removing impurities from hydrogen streams by effectively blocking out all impurities. Certain process changes and upset conditions, such as power interruptions or emergency shutdowns can affect the life of the palladium membrane. Under these conditions, the operating temperature of the membrane falls allowing the hydrogen that is absorbed in the crystal lattice of the palladium membrane to be trapped causing an expansion of the membrane and subsequent distortion and stress on the brazed joints. This results in decreased life of the membrane. Various methods of purging the membrane with nitrogen or with other inert gases have been employed to remove the hydrogen. A new and more effective purging design is presented. Significant benefits in rapid hydrogen purging and rapid return to full UPH flow were observed with the new design.

(20) Commercialization of GaN-Based Field Effect Transistors: *Shawn R. Gibb*[1]; Daniel S. Green[1]; Christopher Palmer[1]; Brook Hosse[1]; Joseph A. Smart[1]; [1]RF Micro Devices, Infrastruct. Product Line, 10420-A Harris Oaks Blvd., Charlotte, NC 28269 USA

GaN-based Field Effect Transistors have attracted considerable attention due to their ability to withstand higher operating voltages, operate at higher frequencies and higher power densities compared to existing Silicon and GaAs technologies. A low-pressure OMVPE growth process has been utilized in a custom built, high-throughput (8 x 100 mm, 12 x 3 inch, or 18 x 2 inch) production tool capable of repeatably producing GaN transistor material with state of the art uniformities on SiC, Sapphire, and Silicon substrates. Typical measured transport properties yield room temperature electron mobilities and sheet carrier concentrations of 1200-1300 cm^2/Vs and $1.2x10^{13}$ cm^{-2} respectively, yielding Rs < 380 Ohm/sq with a variation of 2%. The development of this stable growth process has allowed for the correlation of device performance and reliability to material growth parameters and epitaxial profiles. Trade-offs between obtaining high resistivity buffer layers and device performance will be given.

(21) Electrochemical CV-Profiling of MOVPE (Al,In)GaN Structures: *Thomas Wolff*[1]; Michael Rapp[1]; Thomas Rotter[2]; [1]Ingenieurbuero WEP, Bregstrasse 90, Furtwangen D-78120 Germany; [2]Universitaet Erlangen-Nuernberg, Lehrstuhl fuer Elektronische Bauelemente (LEB), Cauerstrasse 6, Erlangen D-91058 Germany

We report on the implementation of a robust and reproducible electrochemical CV characterization for the (In,Al)GaN system. We developed a new wet etch procedure in weak alkaline electrolytes (usually 0.01 M KOH), which we call cyclic oxidation. In the first time cycle the nitride semiconductor is electrochemically oxidized: UV illumination and forward voltage is applied to oxidize n-GaN and p-GaN, respectively. The established thin oxide film - essential for smooth etching - is dissolved by jet-pumping with fresh electrolyte during the complementary time cycle. High etch rates of up to 2 µm/h combined with mirror like etch morphologies are achieved with our newly developed ECV equipment. This key technology is applied to profile the doping concentration of various MOVPE Nitride samples. In this work, emphasis is placed on the evaluation of the substrate material´s influence on the carrier concentration in the nucleation range.

(22) Automated Electrochemical CV-Profiling of MOVPE Structures on Wafer Scale: *Thomas Wolff*[1]; Michael Rapp[1]; Thomas Rotter[2]; [1]Ingenieurbuero WEP, Bregstrasse 90, Furtwangen D-78120 Germany; [2]Universitaet Erlangen-Nuernberg, Lehrstuhl für Elektronische Bauelemente (LEB), Cauerstrasse 6, Erlangen D-91058 Germany

Presentation of novel equipment tool to perform electrochemical CV profiling on MOVPE grown structures is given. The setup is PC controlled and fully automated to handle small sample sizes from approximately 5*5 square millimeters up to 6 inch wafers. Fully automated loading of the electrochemical cell, fluid handling, drying and unloading are incorporated into the setup. Using a wafer stepper as an option even surveys on wafer scale are feasible. Especially for the case to profile nitride semiconductors, the hardware makes use of a etch technique named "cyclic oxidation" recently developed by us. Resulting in mirror-like etched surfaces for n-type as well as p-type material. Characterization of various (In,Al)GaN MOVPE heterostructures, including HEMTs will be presented. The reproducibility of the measurement process is evaluated with large homogeneously doped both GaAs and GaN MOVPE samples.

(23) Transient Modeling and Experimental Analysis of III-Nitride MOVPE in Commercial Vertical High-Speed Rotating-Disk Reactors: Kirill M. Mazaev[1]; Eugene V. Yakovlev[1]; Anna V. Lobanova[1]; Roman A. Talalaev[1]; Alexander O. Galyukov[1]; *Yuri N. Makarov*[1]; Lev Kadinski[2]; Jeff Ramer[2]; Alex Gurary[2]; [1]STR, Inc., PO Box 70604, Richmond, VA 23255-0604 USA; [2]Veeco TurboDisc Operations, 394 Elizabeth Ave., Somerset, NJ 08873 USA

A combined modeling and experimental analysis of GaN/InGaN deposition in commercial vertical high-speed rotating disk multi-wafer VEECO reactors is performed. Rotation of the wafer carrier results in effective averaging of the deposition rate distribution and this is a key mechanism providing growth of epitaxial layers with highly uniform properties. Normally, steady modeling is applied, assuming the same growth conditions on the wafer carrier and the wafers themselves. However, deposition conditions may be different, so some transient effects can be expected due to time-dependent boundary conditions. To analyze these effects, the model has been extended by accounting for time variations of the boundary conditions. It is demonstrated that the growth patterns depend on both the number of wafers loaded on the carrier and wafer diameter. Modeling results are compared with experimental observations. The transient modeling can be used to improve the layer uniformity in a wide range of the growth conditions.

(24) Chemical Kinetics and Design of Gas Inlets for III-V Growth by MOVPE in a Quartz Showerhead Reactor: *Zhi-qiang Li*[1]; Vivian Zhou[1]; Simon Li[1]; Simon Watkins[2]; [1]Crosslight Software Inc., 202-3855 Henning Dr., Burnaby, BC V5C 6N3 Canada; [2]Simon Fraser University, Dept. of Physics, 8888 Univ. Dr., Burnaby, BC V5A 1S6 Canada

A detailed chemical kinetics model for III-V MOVPE has been developed and tested in conjunction with actual growth data from a novel quartz showerhead vertical reactor. This reactor geometry solves the problem of limited optical access usually inherent in conventional showerhead designs. Emphasis has been put on the surface reactions that are important for the bulk phase GaAs and InAs growth. Good agreement with available experiments on InGaAs was achieved concerning the growth rates of the film and the In incorporation coefficients. We further investigated the effect of gas inlet design on the growth rate and film concentration distribution. Optimal design and operating conditions are presented that lead to more uniform films and higher source utilization efficiency over large-area substrates. InGaAs is selected as a model system, however, a variety of other material systems will be discussed.

Safety

(25) Operation Safety Considerations for Commercial MOVPE Reactors: *J. Kaeppeler*[1]; T. Grantham[2]; D. Schmitz[1]; B. Schulte[1]; [1]AIXTRON AG, Kackertstr. 15 - 17, Aachen 52072 Germany; [2]Thomas Swan Scientific Equipment, Anderson Rd., Buckingway Business Park, Swavesey, Cambridge CB4 5FQ UK

MOVPE application for industrial production of semiconductor materials requires stringent work safety considerations. Risk assessment procedures for the tools are a vital part of the design process at equipment suppliers. The presented work shows the detailed safety assessment of an MOVPE reactor under consideration of all design and operational aspects. Semi S2 standard related requirements of mechanical, electrical and material failures are taken into account. Interaction analysis of chemicals and construction materials and necessary safety precautions are presented. Additionally reactor vessel as most sensitive part of the entire equipment, because it is de-signed for convenient substrate loading, undergoes a worst-case reaction test. Filled with a mixture of 31% H_2 in air an explosion test has been performed on a typical multiwafer reactor cell of the AIXTRON/Thomas Swan type. The result was recorded by pressure transient measurement and high-speed camera. Detailed analysis of the proof of safety measures will be presented.

(26) Environment, Health and Safety Issues for Sources Used in MOVPE Growth of Compound Semiconductors: *Deodatta Vinayak Shenai*[1]; Randall J. Goyette[1]; Gregory Dripps[1]; [1]Rohm and Haas Electronic Materials, L.L.C., Metalorganics, 60 Willow St., N. Andover, MA 01845 USA

As Metalorganic Vapor Phase Epitaxy (MOVPE) is becoming well-established production technology, there are equally growing concerns associated with its bearing on personnel and community safety, environmental impact and maximum quantities of hazardous materials permissible in the device fabrication operations. The safety as well as responsible environmental care has always been of paramount importance in the MOVPE-based crystal growth of compound semiconductors. In this paper, we present the findings from workplace exposure monitoring studies on conventional MOVPE sources such as trimethylgallium, triethylgallium, trimethylantimony and diethylzinc. Also reviewed are the environmental, health and safety hazard aspects for metalorganic sources of 15 elements, their decomposition mechanisms, and the means to minimize the risks (i.e., engineering controls) involved while using these MOVPE sources. The sources include alkyls (or hydrides or a combination thereof) of aluminum, gallium, indium, nitrogen, phosphorous, arsenic, antimony, bismuth, zinc, cadmium, selenium, tellurium, magnesium, silicon and germanium.

(27) Safety Considerations of Operating Large Scale Production MOCVD Reactors with Hydrogen: *Dave Vanderwater*[1]; Werner Goetz[1]; Jared Holzwarth[1]; Ted Mihopoulos[1]; Rick Dalla[1]; Doug Pocius[1]; Anneli Munkholm[1]; [1]Lumileds Lighting, 370 W. Trimble Rd., San Jose, CA 95131 USA

When assessing the risks associated with operating an MOCVD reactor, the possibility of a hydrogen explosion is usually assigned a much lower risk factor than, for example, possible exposure to toxic gasses. Risk is typically determined by two factors: the likelihood of occurrence, and the severity of the incident. The safety interlocks present in any production-scale MOCVD reactor result in a low probability for a hydrogen explosion. However, our estimates of the possible severity of such an explosion indicate that operating with hydrogen may in fact represent a larger risk than generally assumed. In the early days of MOCVD development, when the typical reactor chamber was a simple quartz tube with a volume of just 1-2 liters, the severity of a hydrogen explosion was low. A quartz chamber easily shatters providing a clear path for the explosive energy to be released. Operation of such a reactor with hydrogen did not represent a large risk. Today, production MOCVD chambers are typically fabricated from aluminum or stainless steel, with a volume that can exceed 100 liters; the consequences of a hydrogen explosion are far more severe than incidents with early MOCVD reactors would suggest. It is critical for safe operation of these large scale MOCVD reactor chambers that adequate provisions for release of explosive energy be included in the chamber design. In this presentation, we will estimate the possible result of such an explosion. Modifications to both the equipment, and to the process that can minimize the risk from a hydrogen explosion will be discussed.

(28) Performance of Tunable Diode Laser Absorption Spectrometer for On-Line Measurement of Trace Moisture in Ammonia: Hans H. Funke[1]; Jianlong Yao[1]; *Mark W. Raynor*[1]; Andrew Wright[2]; [1]Matheson Tri-Gas, Inc., Advd. Tech. Ctr., 1861 Lefthand Cir., Longmont, CO 80501 USA; [2]Delta F Corporation, 4 Constitution Way, Woburn, MA 01801 USA

The performance of a commercial tunable diode laser spectrometer (Delta-F 740) developed for on-line monitoring of trace moisture in ammonia has been studied. Instrument calibration, usually carried out by adding humidified nitrogen to a purified ammonia stream, was complicated by the presence of small amounts of nitrogen that resulted in an apparent moisture response of ~10 ppb/percent nitrgoen. Calibration in nitrogen-free ammonia was therefore performed by vaporizing a liquid ammonia stream with a known moisture content and diluting it with purified ammonia. The detection limit for moisture in ammonia was estimated to be 9 ppb based on 3 times the signal/noise ratio. Long-term drifts in the range of +/- 10 ppb additionally affected the instrument sensitivity. The analyzer responded rapidly to changes in moisture concentrations and reached 90% of the final reading within ~5 minutes at the 200 ppb level. Also studied was the effect of pressure on the moisture response.

(29) Environmental Considerations in the MOVPE Growth of (Hg,Cd)Te: Jennifer A.J. Pardoe[2]; *Janet E. Hails*[1]; David J. Cole-Hamilton[2]; Keith Porter[2]; Nicholas Blacker[2]; [1]QinetiQ Ltd., St Andrews Rd., Malvern, Worcs WR14 3PS UK; [2]University of St. Andrews, Sch. of Chmst., St Andrews, Fife KY16 9ST UK

The precursors and reaction products of the MOVPE growth of mercury cadmium telluride (MCT) are at best noxious and at worst exceedingly toxic. MCT finds uses in thermal imaging arrays, infrared detectors and many other infrared devices. The MOVPE process is now approaching commercialisation, hence the use of these compounds is becoming more of an environmental issue. Effluent from the growth chamber is passed through two scrubbers, containing activated charcoal, placed in series. Exhaustion of the first scrubber is monitored by a UV detector (Hg sensor) placed between the scrubbers; unfortunately such detectors cannot be run continuously. We have therefore devised a colourimetric detection system for these noxious compounds. This comprises a silica tube containing several chemical detector compounds which change colour when in contact with their specific organometallic; a colour change thus indicates that the first scrubber is exhausted. Other environmental aspects of MCT MOVPE have also been investigated. © Copyright QinetiQ Ltd 2004.

(30) Developments in Abatement Technology for MOCVD Processing: *Joseph D. Sweeney*[1]; Tadaharu Watanabe[2]; Paul Marganski[1]; Nobuyasu Tomita[2]; Karl Olander[1]; Gary Orlando[2]; Robert Torres[2]; [1]ATMI, R&D, 7 Commerce Dr., Danbury, CT 06810 USA; [2]Matheson Tri-Gas, R&D, 1861 Lefthand Cir., Longmont, CO 80501 USA

A new gas adsorbent has been developed for use in dry scrubbing abatement systems. The adsorbent is specifically designed to remove toxic species, such as arsine and phosphine, from the effluent of MOCVD reactors, and combines the strengths of two different materials. One material provides high sorptive capacity with a low heat of reaction, while the other material is a high-efficiency polisher that serves to maintain the bed outlet concentration below threshold limit values. The combination of the two materials has yielded an adsorbent with an overall sorptive capacity 2-5 times greater than commonly used materials such as impregnated carbon or copper oxide. The significant improvement in capacity enables longer uptime of the abatement system, reduces overall waste, and lowers cost-of-ownership relative to other adsorbents.

(31) Measurement of Vapour Pressure of In Based Metalorganics for MOVPE: M. Fulem[2]; K. Ruzicka[1]; V. Ruzicka[1]; E. Hulicius[2]; *T. Šimecek*[2]; J. Pangrác[2]; S. Rushworth[3]; L. Smith[3]; [1]Institute of Chemical Technology, Dept. of Phys. Chmst., Technická 5, CZ-166 28, Prague 6 Czech Republic; [2]Academy of Sciences of the Czech Republic, Inst. of Physics, Cukrovarnická 10, CZ-162 53 Prague 6 Czech Republic; [3]Epichem Limited, Power Rd., Bromborough, Wirral, Merseyside CH62 3QF UK

Vapour pressure measurement of In based precursors (trimethylindium (TMIn), trimethylindium-N,N-dimethyldodecylamine and pure N,N-dimethyldodecylamine) are performed by a static method in the technologically important temperature range using MKS Baratron gauges. Pressures from 1 Pa to 1300 Pa are measured with the accuracy of about 1% or 0.1 Pa (whichever is greater). New materials supplied by Epichem are used for this work. Knowledge of vapour pressure data of TMIn in different forms is important for establishing optimum conditions of MOVPE processes when switching between these sources. Published data on the measured vapour pressures are uncertain or unknown. Presence of dissolved gasses, impurities or gasses desorbed from the inner surface of the apparatuses might have caused the scatter of the published data. Our results will be compared with available literature data and presented as parameters of the Antoine equation.

(32) Efficient Removal of UDMH from Dilute Nitride MOCVD Exhaust Streams: Andrew Seeley[1]; Derek Baker[1]; *Michael R. Czerniak*[1]; [1]BOC Edwards, EMS, Kenn Business Park, Kenn Rd., Clevedon, N. Somerset BS21 6TH UK

UDMH (unsymmetrical dimethyl hydrazine (CH3)2N2H2) is often used in the deposition of dilute nitride semiconductors because it provides a source of nitrogen with a low thermal decomposition temperature. The problems with using this material, however, are its significant toxicity (0.01 ppm compared to ammonia's 25 ppm) and also the fact that it blocks the action of conventional dosed wet scrubbers sometimes used on nitride applications, resulting in their efficiency in removing arsine (the source of arsenic) diminishing, and arsine being similarly toxic (TLV of 0.05 ppm). Efficient removal of UDMH, AsH3 and hydrogen (which, though not toxic poses a potential safety hazard) by means of a combined thermal oxidation reaction and wet scrubber in series is described at input gas flow rates exceeding those typically encountered in practice. The detection technique employed was Fourier Transform Infra Red Spectroscopy (FTIR), and the calibration and resolution techniques will be described. For input UDMH flows of up to 445 sccm, Destructive Reaction Efficiencies (DRE's) of >99.9% were demonstrated, corresponding to the background detection resolution of 0.4 ppm.

(33) Safety Benefits of Using Sub-Atmospheric Pressure Hydride Gas Sources for MOCVD: *Mark W. Raynor*[1]; Virginia H. Houlding[1]; Russell Frye[2]; Karl Olander[2]; [1]Matheson Tri-Gas, Advd. Tech. Ctr., 1861 Lefthand Cir., Longmont, CO 80501 USA; [2]ATMI, Inc., 7 Commerce Dr., Danbury, CT 06810-4169 USA

Sub-atmospheric pressure gas enhanced (SAGE) sources offer a safe alternative to high-pressure cylinders for storage and delivery of toxic and flammable arsine and phosphine for MOCVD processes. With this technology, the hydride gas is adsorbed onto a high surface area medium and is stored, withdrawn and delivered to the tool at sub-atmospheric pressures. Consequently, any gas release from a SAGE cylinder or delivery system is diffusion rather than pressure controlled. This paper discusses and compares SAGE and high-pressure gas sources with respect to (a) risk reduction, (b) gas purity and (c) other operational benefits. Gas release tests will be presented and compared to theoretical release rates from high-pressure cylinders via restrictive flow orifices. Delivery of high purity gases from SAGE sources will be demonstrated by gas analysis and test device performance data. Additional benefits, such as the development of bulk SAGE sources to minimize cylinder change-outs and improve process repeatability, will also be discussed.

(34) Safety Considerations in the Design and Operation of MOCVD Production Equipment: *Paul Fabiano*[1]; [1]Veeco Instruments, TurboDisc Operations, 394 Elizabeth Ave., Somerset, NJ 08873 USA

Safe operation of MOCVD epitaxial equipment has been a primary concern to manufacturers since the inception of commercial tool fabrication twenty years ago. Initial approaches dealt with materials of construction, focusing on the use of stainless steel reactors in place of quartz, and ensuring compatibility with chemicals such as arsine and ammonia. Later improvements such as interlocks built in to the software and control systems, and thorough failure analysis of system designs, have allowed an excellent safety history in the operation of MOCVD equipment. With the move towards a silicon-style production environment, tool manufacturers are continuing to focus on the prevention of hazardous events, and the use of software systems to ensure safe operation. This paper will look at recent third-party studies commissioned by Veeco to evaluate likely failure modes in specific areas of the equipment and corresponding forms of prevention. The steps taken on Turbodisc tools to ensure safe operation will also be discussed.

Thursday AM - June 3, 2004

Plenary Session

Thursday AM   Room: Kihei
June 3, 2004   Location: Westin Maui Hotel

Session Chairs: P. D. Dapkus, University of Southern California, Los Angeles, CA 90089 USA; W. Stolz, Philipps-University, Marburg D-35032 Germany

8:20 AM Invited

Growth of 1-Dimensional Nanostructures in MOVPE: *Werner Seifert*[1]; [1]University of Lund, Solid State Physics Sweden

The quantum effect, associated with nano-scale devices, is an important aspect of microelectronic device design. Within the last decennium, semiconductor quantum dots (QD), i.e., zero-dimensional nanostructures, grown by self-assembly in the Stranski-Krastanow growth mode, have attracted much attention because of their interesting formation mechanism as well as because of their practical importance in nanodevices. Using self-assembled QDs as the functional building blocks in devices like QD-lasers, memory devices, resonant tunneling devices (RTD) and others has already been demonstrated. Another group of nanostructures, exploiting quantum effects, and growing similarly by a self-organization mechanism, are one-dimensional semiconductor structures in form of nano-wires (nano-rods, nano-whiskers). There are several growth mechanisms under debate, the most general is the so-called vapor-liquid-solid (VLS) mechanism, introduced already in the sixtees by Wagner et al. However, whereas the whiskers described by Wagner had diameters in the range of micrometers, it was the pioneering work of Hiruma et al. to scale down the dimensions to a regime where quantum effects start to be important for the physical properties. Due to the small diameter in the range down to about 10 nm, materials with very different lattice parameters can be combined without causing misfit defects. We used this VLS-process with size-selected aerosol-produced Au-particles as catalyst to grow nano-wires in the materials systems GaP, GaAs, InP and InAs. We demonstrate that the Au catalyzes whisker growth locally, whereas the global process is still defined by the kinetics of the specific MOVPE materials system. The following issues will be in the focus of a more extended discussion: - sizes and shapes of the grown whiskers as a function of growth parameters, - specifics of the different materials, - whisker growth directions, - relations between growth directions and internal defect structure, - growth of hetero-interfaces, abruptness of interfaces, - lateral positioning of whiskers in arrays for application in photonic bandgap structures. Including some results from CBE-grown whiskers we can show one-dimensional heterostructures with inbuilt quantum dots for efficient carrier recombination or barriers for carrier transport (1D-0D-1D...). Such nano-wires can be contacted and gated and can be used as single-electron devices. Other applications of such structures for field emitters, high-efficiency nano-LEDs and lasers, resonant-tunneling devices, high-mobility one-dimensional electron gas structures, etc., seem to be realistic and have already been demonstrated for a few examples.

9:00 AM Invited

Molecular Orbital Studies of Chemical Vapor Deposition. Gas Phase Processes in Titanium Nitride and Zinc Oxide CVD: *H. Bernhard Schlegel*[1]; [1]Wayne State University, Dept. of Chmst., Detroit, MI 48202 USA

Molecular orbital calculations based on ab initio and density functional methods can provide accurate structures, energetics and properties of species involved in chemical vapor deposition. Titanium nitride films can be grown from TiCl4 or Ti(NR2)4 and ammonia. We have calculated the equilibrium geometries, heats of reaction, transition structures and barrier heights for ligand exchange reactions, TiX4 + n NH3 TiX4-n(NH2)n + n HX (X = Cl, NR2) and elimination reactions to form imido complexes, TiX3NH2 TiX2NH + HX (X = Cl, NH2). The calculations also show that imido complexes are quite reactive and can dimerize readily; however, further elimination to form nitrido and di-imido complexes is difficult. Zinc oxide films can be grown from diethyl zinc and water vapor. We have studied gas phase hydrolysis, elimination and oligomerization reactions of Zn(C2H5)2 + H2O. The presence of a second molecule of water reduces the barrier height significantly. Zn(C2H5)OH and Zn(OH)2 form very stable dimers and tetramers, but further elimination of C2H6 or H2O from these small oligomers is endothermic and leads to ring opening.

Nitrides Growth II

Thursday AM   Room: Kihei
June 3, 2004   Location: Westin Maui Hotel

Session Chairs: F. A. Ponce, Arizona State University, Tempe, AZ 85287-1504 USA; U. W. Pohl, Technische Universität Berlin, Berlin 10623 Germany

9:50 AM

High-Quality Al0.12Ga0.88N Film with Low Dislocation Density Grown on Facet-Controlled Al0.12Ga0.88N by MOVPE: *Takeshi Kawashima*[1]; *Kazuyoshi Iida*[1]; Atsushi Miyazaki[1]; Masataka Imura[1]; Motoaki Iwaya[1]; Satoshi Kamiyama[1]; Hiroshi Amano[1]; Isamu Akasaki[1]; [1]Meijo University, Faculty of Sci. & Tech., HRC, 21st Century COE "Nano-Factory", 1-501 Shiogamaguchi, Tempaku-ku, Nagoya, Aichi 468-8502 Japan

For the realization of high-efficiency UV-LEDs, thick, crack-free, high-crystalline-quality AlGaN films with low threading dislocation density and a stack configuration without an absorbing layer such as GaN, are essential. In this paper, we report the fabrication of high-quality AlGaN film with low dislocation?\@density, using facet-controlled AlGaN, which does not contain GaN. Al0.12Ga0.88N was grown with a low-temperature buffer layer on (0001) sapphire. Periodic grooves in the <1-100> direction were fabricated by RIE techniques. The facet-controlled AlGaN seed crystals were selectively grown on the terrace region. As a result, we succeeded in growing low-dislocation-density AlGaN without cracks in which the wafer does not contain GaN. By examining the cathodeluminescence image of this AlGaN, the dark spots, which correspond to dislocations, were observed with a density of as low as 5x10^7 cm^-2 over the entire wafer. The peak intensity of photoluminescence from low-dislocation-density AlGaN increased to 28 times that from conventional AlGaN.

10:10 AM

Growth of AlN by Chemical Vapor Reaction Process and its Application to Lateral Overgrowth on Patterned Sapphire Substrates: *Kenji Fujito*[1]; Tadao Hashimoto[1]; Katsuya Samonji[1]; John F. Kaeding[2]; Paul T. Fini[1]; James S. Speck[1]; Shuji Nakamura[1]; [1]University of California, ERATO JST, UCSB Grp., Santa Barbara, CA 93106 USA; [2]University of California, Matls. Dept., Santa Barbara, CA 93106 USA

A high-quality AlN layer is required as a substrate for UV devices and high-power electronic devices. Epitaxial lateral overgrowth (ELO) and similar techniques have been successfully used to reduce threading dislocation density (TDD) in GaN. However, it is difficult in AlN growth to reduce dislocation density via ELO due to the lack of selectivity on SiO_2 or SiN_X masks. The chemical vapor reaction process has an advantage of high growth rate over MOCVD. We have grown AlN on MOCVD-grown AlN templates and obtained a high-quality film that has a TDD of $9.3 \mathrm{x} 10^9$ cm^{-2}. We have also studied lateral overgrowth on grooved AlN templates. Deep grooves that extend into the sapphire substrate were prepared with laser-induced backside wet etching, which enables high-speed etching of transparent materials. We confirmed extended lateral growth over the grooved region by combining these two novel techniques.

10:30 AM

Reduction of Dislocation Density in AlGaN by Using Facet-Control Technique: *H. Miyake*[1]; A. Ishiga[1]; T. Ohnishi[1]; Y. Liu[2]; T. Shibata[3]; M. Tanaka[3]; K. Hiramatsu[1]; [1]Mie University, Elect. & Elect. Engrg., 1515 Kamihama, Tsu, Mie 514-8507 Japan; [2]Mie University, SVBL, 1515 Kamihama, Tsu, Mie 514-8507 Japan; [3]NGK Insulators, Ltd, 2-56 Suda-cho, Mizuho-ku, Nagoya, Aichi 467-8530 Japan

AlGaN is the most promising III-nitride material for ultraviolet LEDs and LDs, because it has direct wide bandgap from 3.4 eV up to 6.2 eV. It is important to obtain AlGaN with low dislocation density in order to realize ultraviolet LED with high-efficiency. Unto this time, we successfully obtained crack-free and also high-quality AlGaN with dislocation density of lower than 10^10 cm-2 by using epitaxial AlN film on sapphire (0001) as a substrate. In this work, we have proposed the new approach of growing low-dislocation-density AlxGa1-xN (x=0.4-0.5) by using AlN epilayer with incline-facets. Dislocation density in the AlGaN was 10^7-10^8 cm-2. Optical properties and dislocation distribution were examined by cathodoluminescence (CL). we also discussed enhancement of lateral growth rate of AlGaN on the AlN with incline facets.

10:50 AM Break

Dots III

Thursday AM   Room: Kula
June 3, 2004   Location: Westin Maui Hotel

Session Chairs: D. Huffacker, University of New Mexico, Albuquerque, NM 87131 USA; M. Leys, IMEC vzw, Leuven B-3001 Belgium

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9:50 AM
Formation of Self-Assembled InAs Quantum Dots on InP for Long-Wavelength Laser Applications: *Jin Soo Kim*[1]; Jin Hong Lee[1]; Sung Ui Hong[1]; Won Seok Han[1]; Ho-Sang Kwack[1]; Chul Wook Lee[1]; Dae Kon Oh[1]; [1]Electronics and Telecommunications Research Institute (ETRI), Basic Rsch. Lab., 161 Gajeong-dong, Yuseong-gu, Daejeon 305-350 Korea

Self-assembled InAs quantum dots (QDs) in an InAlGaAs matrix grown on InP substrates were investigated by atomic force microscopy, transmission electron microscopy, photoluminescence (PL) and time-resolved PL. Ridge waveguide lasers with seven stacks of InAs QDs as an active layer were also fabricated by using the InAlGaAs-InAlAs material system on InP (001). Room-temperature lasing at the wavelength of 1501 nm was achieved from the InAs QDs, which is the first observation from InAs QDs with the InAlGaAs-InAlAs structure. There were a few reports on the room-temperature laser operation from InAs quantum structures based on InAlGaAs-InAlAs material system on InP (001), however, the active layer was composed of InAs quantum dashes rather than QDs. The characteristic temperature was 135 K in the vicinity of room temperature, which is larger compared to those of InAs quantum dash lasers fabricated on InP (001) substrates.

10:10 AM
InAs and InGaAs Quantum Dot Lasers by MOCVD: *Jeffrey G. Cederberg*[1]; Mark C. Phillips[1]; Michael J. Cich[1]; Steven R. Kurtz[1]; Forrest H. Kaatz[1]; Robert M. Biefeld[1]; [1]Sandia National Laboratories, PO Box 5800, Albuquerque, NM 87185 USA

Semiconductor quantum dots are being investigated to exploit the effects of three-dimensional quantum confinement. Our efforts have investigated the formation InAs and InGaAs quantum dots on GaAs by MOCVD for lasers and optoelectronic devices. InGaAs quantum dot active regions show ground-state transitions between 900 and 1000 nm. The effect of growth temperature, AsH3 partial pressure, and InGaAs thickness on quantum dot formation will be discussed. Absorbance of 350 cm-1 is associated with quantum dots. The net optical gain of these structures is 10 to 20 cm-1. InAs quantum dots show ground state emission between 1000 and 1300 nm. InAs quantum dot growth is sensitive to all the growth parameters resulting in a narrow window for formation. Results from InAs quantum dot lasers will be presented. Sandia National Laboratories is a multiprogram laboratory operated Lockheed Martin Company for the Department of Energy under contract DE-AC04-94AL85000.

10:30 AM
Alternative Precursor Growth of Quantum Dot Based VCSELs and Edge Emitters for Near Infrared Wavelengths: Ilia N. Kaiander[1]; Friedhelm Hopfer[1]; Thorsten Kettler[1]; *Udo W. Pohl*[1]; Dieter Bimberg[1]; [1]Technische Universität Berlin, Inst. für Festkörperphysik, Hardenbergstr. 36, Berlin 10623 Germany

We demonstrate InGaAs/GaAs quantum dot edge emitters and the first QD VCSEL grown using MOCVD, lasing at 1.24 and 1.1 µm, respectively. Tertiarybutylarsine is used instead of hazardous arsine leading to monodispersed QDs. Tenfold closely stacked InGaAs QDs covered with InGaAs QWs for wavelength adjustment are embedded in the active zone GaAs matrix of conventional ridge waveguide edge emitters. A wavelength of 1243 nm is achieved with 75% internal quantum efficiency and 72 A/cm2 transparency current density for the ridge waveguide structure at room temperature. The VCSEL has a 4λ cavity with 3 QD layers placed in each of the three central antinodes to obtain a large modal gain. We processed selectively oxidized high reflectance AlOx/GaAs DBR mirrors and applied intracavity contacts. A maximum cw output power of 0.7 mW at room temperature is achieved, with a peak differential efficiency of 43% and 280 mA threshold current.

10:50 AM Break

Nitrides Growth III

Thursday AM   Room: Kihei
June 3, 2004   Location: Westin Maui Hotel

Session Chairs: S. Yi, Agilent Technologies, Palo Alto, CA 94304 USA; M. Lampalzer, Philipps-University Marburg, Marburg D-35032 Germany

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11:30 AM
Growth and Characterization of AlInN on AlN Template: *Takao Fujimori*[1]; Hitoshi Imai[1]; Akihiro Wakahara[1]; Hiroshi Okada[1]; Akira Yoshida[1]; Tomohiko Shibata[2]; Mitsuhiro Tanaka[2]; [1]Toyohashi University of Technology, Dept. of Elect. & Elect. Engrg., 1-1 Hibarigaoka, Tempakucho, Toyohashi, Aichi 441-8580 Japan; [2]NGK Insulators, Ltd., 2-56 Suda-cho, Mizuho, Nagoya, Aichi 467-8530 Japan

AlInN is very attractive and useful for realizing a nonstrain AlInN/GaN hetero-structures, because the a-axis lattice constant of $Al_{0.83}In_{0.17}N$ matches to that of GaN by the Vegard's law. However, the physical properties of AlInN have not been clarified yet. In order to investigate the optical properties of AlInN avoiding the influence of substrate, the AlInN layer was grown by metalorganic vapor phase epitaxy using the AlN/ α-Al_2O_3 epitaxial template which possesses wider bandgap than AlInN. The crystalline quality of the grown AlInN layers was characterized by X-ray diffraction and reflection high-energy electron diffraction. As a result, the growth of single crystal AlInN was confirmed in all samples. The optical properties of the samples were investigated by chathodoluminescence, transmittance and reflectance spectroscopy. The absorption edge shows large tail, indicating the presence of large compositional inhomogeneity. The bandgap of AlInN with the In composition of 17% is thought to be around 4eV.

11:50 AM
Characterisation of Quaternary AlGaInN Thick Layers and Quantum Wells Grown by MOVPE: Victoria Perez-Solorzano[1]; Albert Gröning[1]; Ralf Härle[1]; Heinz Schweizer[1]; *Michael Jetter*[1]; [1]Universität Stuttgart, 4. Physikalisches Inst., Pfaffenwaldring 57, Stuttgart 70550 Germany

Built-in electric fields related to strain and spontaneous polarization play an important role in nitride based devices. The introduction of quaternary AlGaInN layers allows to control the fields and to engineer the strain and band gap independently. In this contribution we present x-ray diffraction (XRD), cathodoluminescence (CL) and photoluminescence (PL) studies of AlGaInN quantum wells and 100 nm thick layers. The AlGaInN layers were grown in a low pressure MOVPE on sapphire, with a 1 µm thick GaN buffer, with growth temperatures between 760°C and 840°C. The Al content was varied between 0% and 40%, while the In content was kept constant. The XRD measurements of the 100 nm thick AlGaInN showed a clear reduction of the compressive strain with increasing Al content and increasing temperature. In samples grown at 840°C the strain even changes from compressive to tensile. From the comparison between the PL and CL spectra we can estimate the reduction of the electric field. Also first device structures will be presented.

12:10 PM
High-Temperature-Grown High-Quality Quaternary AlInGaN Quantum Well Structure for Ultraviolet Applications: *Yang Liu*[1]; Takashi Egawa[1]; Hiroyasu Ishikawa[1]; Hao Jiang[1]; Baijun Zhang[1]; Maosheng Hao[1]; [1]Nagoya Institute of Technology, Rsch. Ctr. for Nano-Device & Sys., Gokiso-Cho, Showa-Ku, Nagoya 466-8555 Japan

A set of AlInGaN epilayers with same alloy composition (Al: 9%, In: 2%) was grown at different temperatures from 780 to 940ºC by MOVPE. A clear temperature dependent growth mode transition (from 3-dimensional to 2-dimensional growth) was observed for the first time. Both structural and optical quality of AlInGaN also improved notably with increasing growth temperature. Further investigation indicated that the poor crystalline quality of low-temperature-grown AlInGaN was due to the improper incorporation of Al and the facile formation of non-radiative recombination centers. For demonstration, high performance AlInGaN MQWs structure had been grown at a high temperature, from which a strong photoluminescent emission at 348nm with very narrow FWHM value of 67meV were observed at room temperature. Such FWHM value is far smaller than other published data (>120meV) of AlInGaN MQWs, indicating high crystalline quality and smooth interfaces in MQWs region.

SAE

Thursday AM Room: Kula
June 3, 2004 Location: Westin Maui Hotel

Session Chairs: R. F. Hicks, University of California, Los Angeles, CA 90095 USA; A. Persson, Lund University, Lund 221 00 Sweden

11:30 AM
A Study of Regrowth Interface and Material Quality for a Novel InP Based Architecture: *James W. Raring*[1]; Erik J. Skogen[2]; Larry A. Coldren[2]; Steven P. DenBaars[1]; [1]University of California, Matl. Dept., Santa Barbara, CA 93106 USA; [2]University of California, Elect. & Computer Engrg., Santa Barbara, CA 93106 USA

Monolithic integration of photonic integrated circuits is at the forefront of research in the InP based material system. Innovative device architectures utilizing unique growth/processing schemes must be employed to maintain rapid progression. This work examines a new technology, coupling the use of a quantum-well-intermixing (QWI) processing platform and an offset quantum-well regrowth. By intermixing the centered-quantum-well base structure to render it non-absorbing, and then regrowing offset wells, the saturation power in semiconductor-optical-amplifiers can be greatly increased. Achieving a high material quality regrowth on a surface subjected to heavy processing and defect diffusion during the intermixing process is vital to the performance of the offset quantum-wells. Using photoluminescence we will show the effects of pre-regrowth surface preparation and QW/interface offset distance on the material quality of the offset wells. We have demonstrated for the first time that good material quality can be achieved when regrowing on surfaces with intermixed material beneath.

11:50 AM
Fabrication and Characterization of GaAs Two-Dimensional Triangular Air-Hole Arrays Using Selective Area MOVPE: *Junichiro Takeda*[1]; Masaru Inari[1]; Akihiro Tarumi[1]; Junichi Motohisa[1]; Takashi Fukui[1]; [1]Hokkaido University, Rsch. Ctr. for Integrated Quantum Elect., N13 W8 Kitaku, Sapporo 060-8628 Japan

Two-dimensional triangular air-hole arrays are promising for application to two-dimensional photonic crystal (PhC) slabs, which forms full photonic bandgaps for both TE and TM modes. In this study, we successfully grew GaAs triangular air-hole arrays with vertical facets by using selective area MOVPE on GaAs (111)B masked substrates. Growth was done under growth temperature of 850°C and AsH$_3$ partial pressure of about 5.0x10^{-5} atm. Initially, six-fold symmetric air-holes appeared following to hexagonal opening pattern. As growth proceeds, lateral overgrowth (LOG) from three <-211> corners becomes prominent because of many steps or kinks at the corners. On the other hand, LOG from three <2-1-1> corners was pinned by the formation of (111)A facets. As a result, we obtained uniform 1µm~400nm pitch triangular air-hole arrays having vertical sidewalls. Similar air-hole arrays were obtained on (111)A masked substrates under at 550°C. The growth mechanisms and optical properties of PhCs will be discussed.

12:10 PM
High-Quality Grating Regrowth Interface in the InP/InGaAsP Material System Using TBA and TBP: *Erik J. Skogen*[1]; Jonathon S. Barton[2]; Larry A. Coldren[1]; Steven P. DenBaars[2]; [1]University of California, ECE Dept., Santa Barbara, CA 93106 USA; [2]University of California, Matls. Dept., Santa Barbara, CA 93106 USA

A key aspect to the realization of wavelength-agile phonic-integrated-circuits is the formation of high index contrast InP/InGaAsP gratings. A matrix of reactive-ion etch and MOCVD regrowth experiments were used to study the quality of the regrowth interface in InP/InGaAsP grating regions as compared to regions without gratings (InP), using photoluminescence measurements. The modified regrowth procedure consists of a warm-up under tertiarybutylphosphine (TBP) and tertiarybutlyarsine (TBAs) overpressure, and elimination of a high temperature pre-growth bake. The goal was to reduce the group-V exchange on the surface during warm-up, which can lead to highly strained interface layers. The photoluminescence intensity of the regions with gratings was strongly affected by the modification in the etch process and MOCVD regrowth program. This process was used in the fabrication of widely tunable sampled-grating (SG) distributed Bragg reflector (DBR) lasers, which exhibited excellent characteristics in terms of injection efficiency, modal loss, and carrier induced tuning.

Thursday PM - June 3, 2004

Plenary Session

Thursday PM Room: Kihei
June 3, 2004 Location: Westin Maui Hotel

Session Chairs: Koh Matsumoto, Nippon Sanso Corporation, Minato-ku, Tokyo 105-8442 Japan; M. G. Craford, Lumileds Lighting, San Jose, CA 95131 USA

2:00 PM Invited
Growth and Design of Deep UV (270nm-290nm) Light Emitting Diodes Using AlGaN Alloys: *A. A. Allerman*[1]; M. H. Crawford[1]; A. J. Fischer[1]; K. H.A. Bogart[1]; S. R. Lee[1]; D. M. Follstaedt[1]; P. P. Provencio[1]; D. D. Koleske[1]; [1]Sandia National Laboratories, Albuquerque, NM 87185 USA

Solid-state light sources emitting between 270 and 340nm would enable technological advances in many areas such as fluorescence-based biological agent detection, non-line-of-sight communications (NLOS), water purification, and industrial processing including ink drying and epoxy curing. In this paper, we present our recent progress in the development of LEDs with emission between 270 to 290nm for biological agent detection and NLOS communications. We will discuss growth and design issues, including characterization of the AlN nucleation layer, transport in Si-doped AlGaN buffers, optimization of AlGaN quantum well active regions, and hole injection. The LEDs are designed for bottom emission so that improved thermal heat sinking can be achieved by flip chipping. To date, we have demonstrated 1.3 mW of output power at 290 nm from 1mm x 1mm LEDs operated at 300 mA (35A/cm2) and 9.4V. Shorter wavelength LEDs emitting at 275 nm have achieved 0.53 mW output powers. Sandia is a multiprogram laboratory operated by Sandia Corporation, for the United States Department of Energy under Contract DE-ACO4-94AL85000. This work is support by DARPA under the SUVOS program managed by J. Carrano.

2:40 PM Break

Dilute Nitrides I

Thursday PM Room: Kihei
June 3, 2004 Location: Westin Maui Hotel

Session Chairs: F. Dimroth, Fraunhofer ISE, Freiburg 79110 Germany; C. Wang, MIT Lincoln Laboratories, Cambridge, MA 02420 USA

3:20 PM
Considerable Improvement of Optical Property of GaInNAs/GaAs Quantum Well: *Takashi Ishizuka*[1]; Takashi Yamada[1]; Yasuhiro Iguchi[1]; Tadashi Saito[1]; Tsukuru Katsuyama[1]; Shigenori Takagishi[1]; [1]Sumitomo Electric Industries, Ltd., Transmission Devices R&D Labs., 1-1-1, Koya-kita, Itami, Hyogo 664-0016 Japan

GaInNAs is an attractive material for long wavelength laser diodes. But it is difficult to obtain high quality GaInNAs crystal. Generally, annealing after the growth of GaInNAs is necessary to improve the optical property. We have found that the addition of antimony(Sb) before the growth of GaInNAs by MOVPE drastically improved the optical property without annealing. GaInNAs/GaAs single quantum well structures were grown using TEGa, TMIn, TBAs, DMHy, and TMSb(trimethylantimony). The growth temperature was 510°C. TMSb wasn't supplied during the growth of GaInNAs, but was supplied before the growth of GaInNAs. PL intensity and FWHM of GaInNAs without annealing were equivalent to those of GaInNAs with annealing. AFM measurement showed the roughness of surface became smoother. These results suggest the flow of TMSb before the growth of GaInNAs is more suitable, and TMSb in the growth by MOVPE has good effects of improvement of interface between GaInNAs and GaAs.

3:40 PM

Improved Performance of MOVPE Grown GaInNAs Quantum Wells by Control of Interfacial Strain: *Ki-Sung Kim*[1]; Jae-Ryung Yoo[1]; Sung-Jin Lim[1]; Ki-Hong Kim[1]; Taek Kim[1]; Yong-Jo Park[1]; [1]Samsung Advanced Institute of Technology, Photonics Lab., San 14-1, Nongseo-ri, Giheung-eup, Yongin-si, Gyeonggi-do 449-712 Korea

A comprehensive study to achieve optically efficient GaInNAs QWs grown by low-pressure metalorganic vapor phase epitaxy (MOVPE) has been accomplished. In order to extend emission wavelength over 1.3um effectively, GaInNAs QW structures with multiple barriers of GaNAs/InGaAs were proposed. Significant improvement of PL efficiencies and easy controllability of emission wavelengths were obtained. It is believed that the wavelengths emitted from our employed QW structures are correlated to the amount of strain, determined by the strain competition between InGaAs(compressive) and GaNAs(tensile) layer. As N contents increased in the QWs, the emission wavelength was able to extend up to 1.38um without deteriorating spectral width. The role of multi-barriers as well as some important growth parameters (Indium composition in QW, V/III ratio, growth rate) will be discussed in detail.

4:00 PM

Optical Investigation of the Novel Material System (GaIn)(NP)/GaP: *Bernardette Kunert*[1]; Jörg Koch[1]; Torsten Torunski[1]; Kerstin Volz[1]; Wolfgang Stolz[1]; [1]Philipps University Marburg, Central Tech. Lab., Matl. Scis. Ctr., Hans Meerwein Strasse, Marburg 35032 Germany

Recently, diluted III-V-Nitrides have attracted an immense interest, because incorporating a small amount of nitrogen in conventional GaAs- and GaP-based III-V semiconductors results in drastic changes in band structure formation. It is well known that N atoms in GaP cause highly localized isoelectronically states which lead to an impurity band with increasing N concentration. In this study, we have extended the MOVPE growth investigations to the novel highly strained (GaIn)(NP)/GaP material system. Examination by transmission electron microscopy (TEM), atomic force microscopy (AFM) and high-resolution X-ray diffraction confirm the crystalline perfection of the (GaIn)(NP) MQW structures under optimised conditions. We will discuss MOVPE growth conditions as well as temperature dependent photoluminescence, photoluminescence excitation and absorption measurements depending on the In- and N-concentration. The band structure characteristics as a function of composition are clarified and discussed.

4:20 PM

Minority Carrier Lifetimes in Dilute Nitride Bipolar Transistors: Roger E. Welser[1]; Richard S. Setzko[1]; *Kevin S. Stevens*[1]; Eric M. Rehder[1]; Charles R. Lutz[1]; Daily S. Hill[1]; Peter J. Zampardi[2]; [1]Kopin Corporation, 695 Myles Standish Blvd., Taunton, MA 02780 USA; [2]Skyworks Solutions, 2427 W. Hillcrest Dr., Newbury Park, CA 91320 USA

We have recently developed an InGaP/GaInAsN/GaAs double heterojunction bipolar transistor (HBT) technology that substantially improves upon existing GaAs-based HBTs. Band-gap engineering with dilute nitride GaInAsN alloys is utilized to reduce the HBT turn-on voltage and base transit time. Furthermore, these GaInAsN-based HBTs are fully compatible with existing high-volume MOVPE and IC fabrication processes. Using growth algorithm optimization and compositional grading, we achieve minority carrier characteristics with dilute nitrides that approach conventional GaAs HBTs. In this work, we characterize the impact of both carbon and nitrogen doping on minority carrier lifetime. Lifetimes are extracted from bipolar transistor device structures via base thickness and DC current gain measurements. Minority carrier lifetime is observed to be inversely proportional to both carbon and nitrogen doping. While we can replicate poor as-grown lifetimes consistent with those reported in photovoltaic dilute nitride materials, our best material to date exhibits nearly 30x higher lifetime after current soaking.

Devices II

Thursday PM Room: Kula
June 3, 2004 Location: Westin Maui Hotel

Session Chairs: M. Hansen, Cree Inc., Santa Barbara, CA 93117 USA; K. Onabe, University of Tokyo, Tokyo 113-8656 Japan

3:20 PM

MOVPE Grown Quantum Cascade Lasers Operating at ~9µm Wavelength: *A. B. Krysa*[1]; J. S. Roberts[1]; R. P. Green[2]; L. R. Wilson[2]; H. Page[3]; M. Garcia[3]; C. M. Tey[4]; J. W. Cockburn[2]; [1]University of Sheffield, EPSRC Natl. Ctr. for III-V Tech., Dept. of Elect. & Elect. Engrg., Mappin St., Sheffield S1 3JD UK; [2]University of Sheffield, Dept. of Physics & Astron., Hounsfield Rd., Sheffield S3 7RH UK; [3]Thales Research and Technology, Domaine de Corbeville, 91404 Orsay Cedex France; [4]University of Sheffield, Dept. of Elect. & Elect. Engrg., Mappin St., Sheffield S1 3JD UK

Since the first experimental demonstration of the Quantum Cascade Laser in 1994, MBE has been considered to be the only viable growth technique. However, we have recently developed a MOVPE technology for the growth of similar InP/InGaAs/InAlAs QCLs [1]. Here, we report MOVPE grown QCLs which include carrier extraction using a double phonon resonance design. High-resolution X-Ray diffraction data and cross- sectional TEM images indicate a high degree of uniformity between the periods of the QCL structures, precise layer thickness as well as high reproducibility between similar growth runs. Lasing was observed at ~9µm, with pulsed mode threshold current densities as low as 840A/cm2 at 12K and 3.5 kA/cm2 at RT, with peak powers in excess of 1W at RT. These performance levels are comparable to similarly designed state of the art MBE grown QCLs. [1] R.P. Green, A. Krysa, J.S. Roberts, D.G. Revin, L.R. Wilson, E.A. Zibik, W.H. Ng and J.W. Cockburn, Appl. Phys. Lett. 83 1921 (2003).

3:40 PM

MOCVD-Grown InGaN-Channel HEMT Structures with Electron Mobility of Over 1000 cm^2/Vs: *Naoya Okamoto*[1]; Katsuyuki Hoshino[1]; Naoki Hara[1]; Masahiko Takikawa[2]; Yasuhiko Arakawa[1]; [1]University of Tokyo, Nanoelect. Collaborative Rsch. Ctr., 4-6-1 Komaba, Meguroku, Tokyo 153-8505 Japan; [2]Fujitsu Laboratories Ltd., 10-1 Morinosato-Wakamiya, Atsugi, Kanagawa 243-0197 Japan

We demonstrate MOCVD-grown AlGaN/InGaN/GaN HEMT structures with two-dimensional electron gas (2DEG) mobility of over 1000 cm^2/Vs at room temperature (RT). InGaN-channel HEMTs are very promising as electron devices for millimeter-wave power applications, because it is possible to suppress the short channel effect by the strong carrier confinement. To date, the mobility in InGaN-channel structures was reported to be 730-800 cm^2/Vs at RT. In this work, we achieved the highest 2DEG mobility of 1110 cm^2/Vs with the sheet carrier density of $1.31x10^{13}$ cm^{-2} by using an ultra-thin InGaN channel (3 nm). Furthermore, excellent electron confinement was observed, compared to conventional AlGaN/GaN heterostructure, despite the use of a very thin InGaN channel. Our proposed ultra-thin InGaN-channel structures let a part of 2DEG penetrate into GaN buffer layer, thereby the component of alloy disorder scattering is reduced.

4:00 PM

Control of Epitaxial Defects for Optimal AlGaN/GaN HEMT Performance and Reliability: *Daniel S. Green*[1]; Shawn R. Gibb[1]; Brook Hosse[1]; Chris Palmer[1]; Joseph A. Smart[1]; [1]RF Micro Devices, Infrastructure Product Line, 10420-A Harris Oaks Blvd., Charlotte, NC 28269 USA

High quality GaN epitaxy continues to be challenged by the lack of matched substrates. Threading dislocations that result from heteroepitaxy are responsible for leakage currents, trapping effects and have an unknown influence on device reliability. We have studied the impact of AlN nucleation conditions on the distribution of threading dislocations on SiC substrates. Variation of the nucleation temperature, V/III ratio, thicknesses, and growth rate are seen to have a dramatic effect on the balance between edge, screw and mixed character dislocation densities. Material electrical and structural properties have been assessed by AFM, XRD, CV, Hall and resistivity measurements. The ratio between dislocation characteristics has been established primarily through comparison of symmetric and asymmetric XRD rocking curve widths. The effect of each dislocation type on gate and drain leakage current, RF power and reliability at 2 GHz, the targeted band for cell phone infrastructure applications, will be discussed.

4:20 PM

Solar Cells with (BGaIn)As and (InGa)(NAs) as Absorption Layers: *Gunnar Leibiger*[1]; Claudia Krahmer[1]; Volker Gottschalch[1]; Nasser Razek[2]; Helmut Herrnberger[2]; Axel Schindler[2]; [1]Universität Leipzig, Fakultät für Chemie & Mineralogie, Inst. für Anorganische Chemie, Linnestr. 3, 04103, Leipzig Germany; [2]Leibniz-Institut für Oberflächenmodifizierung e.V , Permoserstr. 15, 04303, Leipzig Germany

(BGaIn)As and (InGa)(NAs) mixed crystals allow both the lattice matched growth on GaAs with band-gap energies smaller than 1.42 eV (Eg of GaAs) and are therefore attractive new materials for application in thin film solar cells. (BGaIn)As (2.7% boron) and (InGa)(NAs) (1.6% nitrogen) layers have been grown lattice matched on GaAs using MOVPE at low growth temperatures (550-560°C). Dimethylhydrazine, triethylboron Trimethylgallium, trimethylindium, arsine, and tertiarybutylarsine have been used as precursors. N- and p-type doping has been investigated with diethylzinc and disilane as doping precursors. Subsequently, GaAs-solar cells have been grown and tested for the incorporation of (BGaIn)As and (InGa)(NAs). The influence of the incorporation of both materials on the cell properties is discussed. Additionally, solar cells have been grown on Ge-substrates. Corresponding structures are compared to solar cells, which were bonded to Ge substrates under UHV-conditions at low temperatures. First results for tandem cells (BGaInAs/GaInP and InGaNAs/GaInP) are presented.

Growth Issues Poster Session - 4:40 to 6:00 PM

Thursday PM Room: Lahaina
June 3, 2004 Location: Westin Maui Hotel

Session Chair: S. Nakamura, University of California, Santa Barbara, CA 93106 USA

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(1) Defect Study of MOVPE-Grown InGaP Layers on GaAs: *A. Knauer*[1]; P. Krispin[2]; M. Weyers[1]; [1]Ferdinand-Braun-Institut fuer Hoechstfreqenztechnik, Albert-Einstein-Strasse 11, Berlin D-12489 Germany; [2]Paul-Drude-Institut fuer Festkoerperelektronik, Hausvogteiplatz 5-7, Berlin D-10117 Germany

Defects in n-type InGaP layers grown with MOVPE at various conditions were studied by deep-level transient spectroscopy. The occurrence and depth distribution of an electron trap E1 at about 0.75 eV below the conduction band edge were investigated in dependence on growth conditions, on lattice mismatch, on storage time, and on thickness of a GaAs cap layer. Further the influence of InGaP growth interruptions under PH3 or AsH3 and of introduced 5 nm thick GaAs-layers on the formation and distribution of E1 has been studied. It is demonstrated that the E1-related defect is generated after InGaP growth starting from the surface. The maximal trap density of E1 as well as its diffusion velocity is determined by the MOVPE growth conditions. The E1 distribution shifts even at room temperature over time into the epitaxial layer, probably due to a vacancy diffusion process.

(2) A Combined Fluid Dynamic and 3D Kinetic Monte Carlo Investigation of the Selective Deposition of GaAs and InP: *Carlo Cavallotti*[1]; Alessandro Mencarelli[1]; Maurizio Rondanini[1]; Maurizio Masi[1]; Sergio Carrà[1]; [1]Politecnico di Milano, Dept. Chimica, Materiali e Ingegneria Chimica, via Mancinelli 7, Milano I-20131 Italy

The selective deposition of GaAs and InP was investigated using a fully integrated multiscale model. Local gas phase composition, temperature, and flow fields were calculated solving mass, energy and momentum conservation equations at the reactor scale with 2D FEM. The growth on patterned wafers was described with a 2D microscale model that includes adsorption and diffusion on mask and features. Reactor and microscopic models are linked consistently imposing the continuity of gas phase fluxes. The morphology evolution was investigated with 3D KMC using gas phase fluxes calculated with the microscopic scale model. The model is generally in good agreement with experimental data except for high mask/feature ratios, in which case the growth rate is overestimated both for GaAs and InP. We attribute the overestimation to the diffusion of adsorbed species from feature to mask, which would explain the nucleation of GaAs experimentally observed on the mask in these conditions.

(3) Piezoreflectance and Contactless Electroreflectance Spectra of an Optoelectronic Material: GaInNP Grown on GaAs Substrates: Cheng-Hsien Wu[1]; Yan-Kuin Su[1]; Ying-Sheng Huang[2]; Hung-Pin Hsu[2]; Shuo-Hsien Hsu[1]; Chi-Cheong Sio[1]; [1]National Cheng Kung University, Inst. of Microelect., Dept. of Elect. Engrg., Univ. Rd. No. 1, Tainan 701 Taiwan; [2]National Taiwan University of Science and Technology, Dept. of Elect. Engrg., No.43, sec.3, ji lueng Rd., Taipei 106 Taiwan

We report a detailed study of piezoreflectance (PzR) and contactless electroreflectance (CER) on Ga0.44In0.56NxP1-x epitaxial layers at room temperature. The polarized PzR spectra show anisotropic character along the [110] and [1-10] directions. Ordering-induced superlattice-like microstructure shown in high resolution transmission electron microscope images confirms the spontaneous ordering in Ga0.44In0.56NxP1-x epitaxial layers. The obtained PzR and CER spectra are fitted with the theoretical line shape functional form. The valence-band maximum, crystal field/strain splitting and spin-orbit splitting to conduction band transition energies are accurately determined. With nitrogen incorporation, the PzR and CER features red-shifts, indicating bandgap reduction. The experimentally observed bandgap energy reduction of GaInP incorporation nitrogen is of the same order as for nitrogen in binaries. However, the bowing coefficient b is determined to be -10.5 eV.

(4) Hetero-Epitaxy Growth of $B_{12}P_2$ on Various Substrates by MOCVD: *Dalong Zhong*[1]; John J. Moore[1]; Terrence L. Aselage[2]; Arun Madan[3]; [1]Colorado School of Mines, MME Dept., 1500 Illinois St., Golden, CO 80401 USA; [2]Sandia National Laboratories, 1515 Eubank SE, Albuquerque, NM 87123-0613 USA; [3]MVSystems, Inc., 17301 W. Colfax Ave., Ste. 305, Golden, CO 80401 USA

Icosahedral boron phosphide, $B_{12}P_2$, is a refractory solid and a wide bandgap semiconductor. Its self-healing of radiation damage has been demonstrated. Consequently, it could be a promising material to be used as a novel radiation tolerant, high temperature semiconductor to construct solid-state devices such as detectors, sensors and beta-cells — direct nuclear-to-electric energy conversion devices for beta sources. We have recently developed an inductively heated MOCVD process to synthesize high-quality $B_{12}P_2$ from B_2H_6-PH_3-H_2 precursor systems. The growth rate is of approximately 30-40 nm/min. This paper presents the growth of $B_{12}P_2$ on various substrates, including <100> Si wafer, quartz, and different types of single crystal SiC wafers made by CREE, Inc. The composition, crystallographic orientation, surface morphology, and microstructure of $B_{12}P_2$ films were characterized by AES, XRD, Roman Spectroscopy, SEM, and TEM. This paper will demonstrate that $B_{12}P_2$ has been successfully synthesized, its hetero-epitaxy growth was high quality on both Si nd SiC substrates, and the orientation of the film on SiC was strongly dependent on the degree of substrate's off-axis.

(5) Optimized 9x2-Inch Reactor Configuration for the Growth of Al-Containing Antimonides: *Frank Dimroth*[1]; Andreas W. Bett[1]; Christoph Giesen[2]; Michael Heuken[2]; [1]Fraunhofer ISE, SWT, Heidenhofstrasse 2, Freiburg 79110 Germany; [2]Aixtron AG, Kackertstrasse 15-17, Aachen 52072 Germany

The growth of Al-containing antimonides has been proven to be specifically challenging. New precursors like the DMEAA (dimethylethylamine alane) or TTBAl (tritertiarybuthylauminium) are used due to their low decomposition temperatures. Unfortunately, these precursors suffer from severe prereactions with other metalorganics. Furthermore the low vapour pressures of these sources limits the economical use in multiwafer MOVPE systems. A new 9x2-inch substrate configuration has been developed to meet the demands of the growth of Al-containing antimonides in an AIX2600-G3 MOVPE system. This is the first multiwafer MOVPE reactor that was specifically designed for the growth of antimonides. Major advantages of this reactor are reduced prereactions, high MO efficiency, excellent layer homogeneity and reproducibility. This paper will discuss the problematic of prereactions and highlight the improvements of the new reactor configuration. Also results of GaSb thermophotovoltaic cells with AlGaAsSb barriers, grown on the 9x2-inch configuration will be presented.

(6) In-Situ Investigations of Surface Kinetics During Nitridation and Growth of GaAsN/GaAs: *Florian Poser*[1]; Veit Hoffmann[1]; Stefan Weeke[1]; Christian Kaspari[1]; Markus Pristovsek[1]; Wolfgang Richter[1]; [1]Technische Universität Berlin, Inst. für Festkörperphysik, Sekr. PN 6-1, Hardenbergstr. 36, Berlin D-10623 Germany

GaAsN is a potential key material for optoelectronic devices to reach the important wavelengths of 1.3 and 1.55 μm. VCSEL made of GaInAsN have been already realised, but neither the growth kinetics nor the chemical surface reactions of the arsenic/nitrogen exchange are completely understood. Therefore we have investigated surface processes on GaAsN/GaAs during nitridation and growth using the newly developed in-situ multichannel reflectance-anisotropy spectroscopy (RAS) together with multichannel spectral ellipsometry (SE). The RAS spectra exhibit strong changes in the surface anisotropy when exposing the sample to the alternative nitrogen precursor tertiary-butyl-hydrazine (tBHy). As these changes were almost similar for GaAs as well as for GaAsN surfaces, a high surface coverage with reactive nitrogen species can be deduced. In a first approach the activation energies were calculated by varying the growth parameters and correlating these results with standard ex-situ techniques like XRD, AFM and PL.

(7) Intrinsic Carbon Doping of (AlGa)As for (InGa)As Laser Structures with Emission Wavelengths ~ 1.17 μm: Volker Gottschalch[1]; *Gunnar Leibiger*[1]; Gabriele Benndorf[2]; Helmut Herrnberger[3]; [1]Universität Leipzig, Fakultät für Chemie & Mineralogie, Inst. für Anorganische Chemie, Linnestr. 3, 04103 Leipzig Germany; [2]Universität Leipzig, Fakultät für Physik, Inst. für Experimentelle Physik II, Linnestr. 5, 04103 Leipzig Germany; [3]Leibniz-Institut für Oberflächenmodifizierung e.V, Permoserstr. 15, 04303 Leipzig Germany

The intrinsic carbon doping of GaAs and (AlGa)As during MOVPE allows the growth of well-defined doping profiles with high hole concentrations. This method has been used e. g. for growing tunnel junctions in tandem solar cells, Bragg mirrors in VCSEL-structures, and (AlGa)As-cladding layers in laser diodes. We have studied the intrinsic carbon doping of (AlGa)As-cladding layers in (InGa)As double-quantum well laser diodes (λ ~ 1.17 μm) for typical growth temperatures between 500 and

600°C using the precursors TMGa, TMAl, AsH3, and TBAs. The influence of Al-composition, hole concentration and mobility on growth temperature and V/III-ratio is discussed. Epitaxial layers were characterized with high-resolution x-ray diffraction, Hall-measurements, photoluminescence, ellipsometry, transmission electron microscopy , atomic force microscopy, and rutherford backscattering. MQW structures have been grown strained and lattice matched on GaAs in addition to the single-layer structures. We have compared the laser performance of structures with zinc- and carbon-doped cladding layers.

(8) New MOVPE Process for Horizontal Reactors with Reduced Parasitic Deposition: *Hilde Hardtdegen*[1]; Nicoleta Kaluza[1]; Roger Steins[1]; Roland Schmidt[1]; E.V. Yakovlev[2]; R. A. Talalaev[2]; Yu. N. Makarov[2]; [1]Research Center Juelich, Inst. of Thin Films & Interfaces, Juelich 52425 Germany; [2]Semiconductor Technology Research GmbH, Erlangen 91002 Germany

In the past there have been a number of reports which deal with the influence of parasitic deposition on growth in MOVPE reactors. The deposits influence the true surface temperature and also behave as a catalytic surface, which depletes the gas phase of the chemical species contributing to growth. In both cases the run to run variation of surface reactor coverage hinders reproducible growth and results in a drift in growth rates. In this paper we report on a new MOVPE process for horizontal reactors. Usually the group III and group V gases are injected separately into the reactor: the group III sources through the upper channel, the group V sources through the lower (closer to the substrate). By inverting this injection, parasitic deposition is effectively reduced leading to higher reproducibility and higher uptimes without maintenance. A comparison between the standard and the new process for GaN growth will be made. Results of modelling and experiments will be presented.

(9) Na in (Hg,Cd)Te - Friend or Foe?: *Janet E. Hails*[1]; Jean Giess[1]; Michael Houlton[1]; Andrew Graham[1]; David J. Cole-Hamilton[2]; [1]QinetiQ Ltd., St Andrews R, ., Malvern, Worcs WR14 3PS UK; [2]University of St Andrews, Sch. of Chmst., St. Andrews FY16 9ST UK

We have previously reported that the pre-treatment of GaAs substrates, with a sodium containing compound, can be used to reduce the hillock density on the surface of mercury cadmium telluride (MCT, Hg$_{1-x}$Cd$_x$Te) grown by MOVPE to less than 5 cm^{-2}. This paper seeks to establish the mechanism by which this technologically important result is achieved. The effect of Na on precursor-substrate interactions, its role in the MCT MOVPE process, its probable surfactant behaviour and the mechanism of its incorporation will be discussed. Data showing the p-type doping behaviour of Na in nominally undoped, as-grown MCT will be presented. SIMS profiles show that sodium is mobile, migrating to the layer surface, on annealing in an inert, Hg rich atmosphere. In contrast annealing under an Hg rich, H$_2$ atmosphere pins the Na within the MCT and leads to layers which are strongly n-type. This difference will be addressed. © Copyright QinetiQ Ltd 2004.

(10) Applications of Thin GaN Layers in GaAs Heterostructures Grown Using DMHy Precursor: Jaakko Sormunen[1]; Juha Riikonen[1]; Markku Sopanen[1]; Harri Lipsanen[1]; [1]Helsinki University of Technology, Optoelect. Lab., Tietotie 3, PO Box 3500, Espoo FIN-02015 Finland

We have studied thin cubic GaN layers in GaAs heterostructures. DMHy is a preferable nitrogen source for MOVPE of GaN on GaAs because it decomposes readily at relatively low temperatures. According to our previous results, the growth temperature of GaN should be around or below 600°C to get smooth layers despite the large lattice mismatch. In this work, GaN/GaAs superlattices with 5 nm of GaN per period were grown. X-ray diffraction and morphology measurements showed the SL to be of good quality. This type of novel structure might be applicable to p-type resonant tunneling devices. Furthermore, the use of an epitaxial GaN layer for the surface passivation of GaAs was tested. The photoluminescence of near-surface InGaAs QWs with GaAs barrier thickness of 5 nm was enhanced by at least two orders of magnitude when passivated with 3 MLs of GaN, thus showing GaN to effectively passivate the GaAs surface.

(11) In-Situ Monitoring and UHV-Characterization of MOVPE-Grown InSb(100): Kristof Möller[1]; Zadig Kollonitsch[1]; Ulf Seidel[1]; Christoph Giesen[2]; Michael Heuken[2]; Frank Willig[1]; *Thomas Hannappel*[1]; [1]Hahn-Meitner-Institute, Solarenergy Rsch. Dept. 4 (SE-4), Glienicker Str. 100, Berlin D-14109 Germany; [2]AIXTRON AG, Kackerstr. 15-17, Aachen D-52072 Germany

InSb(100) was grown in an AIXTRON 200 MOVPE-reactor with trimethylindium (TMIn) and triethylantimony (TESb) as precursors. In-situ monitoring was carried out by reflection anisotropy/difference spektroscopy (RAS/RDS). RA spectra were used for improving the growth parameters. Specular surfaces were grown at a temperature of 750 K with deposition rates up to 2 µm/h. For the first time RA spectra of different surface reconstructions of InSb(100) were recorded. A patented MOVPE-UHV transfersystem was used to characterize the InSb(100) surface reconstructions via photo electron spectroscopy (PES) and LEED. RA spectra could be corraleted with three different surface reconstructions, notably (1 x 3), c(4 x 4) and a very Sb-rich (2 x 1). The latter one has not been reported yet neither for MBE-prepared nor for MOVPE-prepared InSb(100) and will be discussed in detail.

(12) Preparation and Characterization of Ultra-Thin PZT Films Grown by Plasma-Assisted CVD: *Ken Nishida*[1]; Ken Shirakata[1]; Minoru Osada[2]; Mosato Kakihana[3]; Takashi Katoda[1]; [1]Kochi University of Technology, Dept. of Elect. & Photonic Sys. Engrg., Miyanokuchi 185, Tosayamada, Kochi 782-8502 Japan; [2]National Institute for Materials Science, Advd. Matls. Lab., 1-1 Namiki, Tsukuba, Ibaraki 305-0044 Japan; [3]Tokyo Insutiute of Technology, Matl. & Structured Lab., 4259 nagatuda, Midoriku, Yokohama 226-8503 Japan

The ferroelectric material lead zirconate titanate (PZT) is expected for nonvolatile memories and other applications. In this study, ultra-thin ferroelectric PZT films were grown using plasma-assisted CVD method with growth equipment specially designed for in-situ monitoring by Raman spectroscopy. The PZT thin films were made on Pt(100)/MgO(100) substrates. Pb(DPM) $_2$, Zr(DPM)$_4$, Ti(O-iC$_3$H$_7$)$_4$ and high purity oxygen were used as the sources. When these sources were introduced simultaneously, the PZT films which contain ZrO$_2$ at initial stage of growth were grown. However, when the supply of Zr was delayed, ZrO$_2$ was suppressed. We succeeded in the growth of monolayer PZT films even with a thickness of 46.5 nm. The reason for this favorable result is considered that the optimum interface between the substrate and the film was prepared before the growth of monolayer PZT because ZrO$_2$ nucleus was suppressed by delaying supply of Zr source.

(13) Growth and Characterization of p-Type InGaAs on InP Substrates by LP-MOVPE Using a New Carbon Dopant Source CBrCl3: *Kazuo Uchida*[1]; Kazuma Takahashi[1]; Shogo Kabe[1]; Shinji Nozaki[1]; Hiroshi Morisaki[1]; [1]University of Electro-Communications, Dept. of Elect. Engrg., 1-5-1 Chofugaoka, Chofu, Tokyo 182-8585 Japan

LP-MOVPE growth of lattice-matched p-type InGaAs on InP substrates using a new dopant precursor carbon trichloro-bromide (CBrCl3) will be reported. CBrCl3, an intermediatary compound between CCl4 and CBr4, has been successfully employed in MOVPE growth of p-type GaAs. [1] The Hall measurement indicates that high p-type doping level \@RT up to 1E19 cm-3 has been achieved by using CBrCl3. However, a strong amphoteric behavior of carbon that is very sensitive for growth conditions has been found. In particular, the x-ray rocking curve analysis reveals that very small variation in magnitude and sign of the lattice mismatch between InGaAs and InP determines the occupation site of carbon and the conduction type of samples. Details including the compensation mechanism in p-type InGaAs by CBrCl3 will be discussed in the conference. [1]K. Uchida, et al, J. Crystal Growth 248 (2003) 124.

(14) Growth of Epitaxial ZnO on Si(111) Using Y2O3 Buffer Layer: *Li Chang*[1]; Chih-Wei Lin[1]; [1]National Chiao Tung University, Dept. of Matls. Sci. & Engrg., 1001, Tahsueh Rd., Hsinchu 300 Taiwan

Epitaxial ZnO can be deposited on Si(111)using Y2O3 buffer layer which can be easily formed in epitaxy with Si and is thermodynamically more stable than SiO2. Deposition of ZnO was carried out in an atmospheric pressure CVD reactor using Zn(C5H7O2)as Zn source. The substrate and O2 gas temperature were all heated at 500 C. Microstructual characterization by XRD and TEM shows that ZnO is oriented in [0001] and the ZnO/Y2O3 interface is sharp and flat with ZnO basal plane parallel to Y2O3 {111} plane. In the initial stage of growth, it is shown that the typical ZnO grain size have a thickness of 10 nm and a width of 25 nm. Further growth results in a columnar structure in the ZnO films.

(15) Liquid Injection MOCVD of SBTN Using an all Alkoxide Precursor System: *Lesley M. Smith*[1]; Anthony C. Jones[2]; Hywel O. Davies[1]; Neil L. Tobin[2]; Paul R. Chalker[3]; Paul A. Marshall[3]; Richard J. Potter[3]; John L. Roberts[2]; [1]Epichem Ltd., Rsch., Power Rd., Bromborough, Wirral, Merseyside CH62 3QF UK; [2]University of Liverpool, Dept. of Chmst., Liverpool L69 7ZD UK; [3]University of Liverpool, Dept. of Matls. Sci. & Engrg., Liverpool L69 3BX UK

Thin films of strontium bismuth tantalate niobate (SBTN) have applications in non-volatile ferroelectric memories. MOCVD is an attractive technique for the deposition of these materials, but progress has been restricted due to lack of suitable precursors. Conventional precursors include Sr(thd)2 (thd = 2,2,6,6-tetramethylheptane-3,5-dionate), Bi(thd)3, BiMe3 and Ta(OEt)5 or Ta(OPri)4(thd), but these are generally incompatible, having very different physical properties and deposition characteristics. To alleviate the mis-match between the Sr and Ta or Nb sources, we have developed the “single-source” precursors Sr[Ta(OEt)5(dmae)]2 and Sr[Nb(OEt)5(dmae)]2 Sr[Ta0.5Nb0.5(OEt)5(dmae)]2 (dmae = OCH2CH2NMe2). Bi-alkoxides, Bi(OR)3, are potentially suitable co-precursors, with similar decomposition behaviour to the Sr-Ta and Sr-Nb heterometal alkoxides, but the majority are involatile polymers. The sterically hinderd ligand mmp (OCMe2CH2OMe) inhibits polymerisation and leads to a volatile monomeric complex, Bi(mmp)3. In this paper we describe the liquid injection MOCVD of SBTN using the all-alkoxide precursor combination, Sr[Ta(OEt)5(dmae)]2 and Sr[Nb(OEt)5(dmae)]2 and Bi(mmp)3.

(16) InN Growth and Annealing Investigations with In-Situ Spectroscopic Ellipsometry: *Massimo Drago*[1]; Christoph Werner[1]; Torsten Schmidtling[1]; Udo W. Pohl[1]; Wolfgang Richter[1]; [1]TU-Berlin, Solid State Physics, Hardenbergstrasse 36, Berlin 10623 Germany

Growth of InN is a challenging issue due to a very narrow growth parameter window. In-situ spectroscopic ellipsometry was used to optimise InN growth on c-plane sapphire using a low-temperature nucleation layer. Higher interband transitions around 5 eV served as a benchmark for the crystal quality. Roughening of the layer was found to lead to a decreased amplitude in this energy region, allowing for direct feedback during the search for optimum growth conditions. Parameters like temperature and total pressure have been optimised. To further improve layer quality, InN stability was studied under different gas atmospheres in the possible growth temperature range (400-600 ° C). During annealing the layer undergoes roughening at 550°C in nitrogen atmosphere and at even lower temperatures in hydrogen or ammonia ambient. Based on these results an improved growth procedure is proposed.

(17) Measurement of Surface Reaction Rate Constants and Reactor-Scale Simulation of Growth Rate and Composition in InGaAsP MOVPE: *Masakazu Sugiyama*[1]; Ho-jin Oh[2]; Ik Tae Im[3]; Yoshiaki Nakano[4]; Yukihiro Shimogaki[2]; [1]University of Tokyo, Dept. of Elect. Engrg., 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656 Japan; [2]University of Tokyo, Dept. of Matls. Engrg., 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656 Japan; [3]Iksan National College, Dept. of Auto. Engrg., 194-5 Ma-dong, Iksan 570-752 Korea; [4]University of Tokyo, Rsch. Ctr. for Advd. Sci. & Tech., 4-6-1 Komaba, Meguro-ku, Tokyo 153-8904 Japan

Surface reaction rate constants (k_s) of InGaAsP film precursors were measured by the 'multi-scale analysis' which utilizes (1) a reactor-scale growth rate profile under diffusion-limited kinetics (the measurement of mass diffusivities, D) and (2) a micrometer-scale growth rate profile in selective area growth (measurement of D/k_s). The values of ks were incorporated in the reactor-scale simulation of the growth rate and the composition of InGaAsP films. The activation energy of ks for the Ga precursor was larger than that for the In precursor. Therefore, in the simulation, the Ga/In ratio decreased with decreasing surface temperature. This prediction was consistent with the results of experiments. The measurement of ks is a step not only to more accurate MOVPE simulations but also to more fundamental understanding of surface reaction mechanisms.

(18) Growth Parameter Optimization for High Nitrogen Content GaInNAs by MOVPE: *Outi Reentilä*[1]; Marco Mattila[1]; Jaakko Sormunen[1]; Markku Sopanen[1]; Harri Lipsanen[1]; [1]Helsinki University of Technology, Optoelect. Lab., Tietotie 3, PO Box 3500, Espoo 02015 Finland

GaInNAs/GaAs quantum wells have excellent properties for novel SESAM structures. For operation at 1.55 µm, relatively high nitrogen composition in GaInNAs is needed. In this work we compare results from low-pressure and atmospheric-pressure MOVPE using TMGa, TMIn, TBAs and DMHy as precursors. The growths were performed in a vertical showerhead reactor and a horizontal reactor. The highest nitrogen content was achieved at a growth temperature of 530 °C. The TBAs/III ratio had a different effect on nitrogen composition at low and atmospheric pressures. At atmospheric pressure the ratio should be as low as possible to get high nitrogen content. However, below the ratio of two the crystal quality deteriorates. At low pressure the optimum TBAs/III ratio is larger and the growth rate should be low to obtain high nitrogen content.

(19) Routine Growth of InP Based Device Structures Using Process Calibration with Optical In-Situ Techniques: *Peter Wolfram*[1]; E. Steinmetz[2]; Willi Ebert[1]; Norbert Grote[1]; J.-T Zettler[2]; [1]Fraunhofer Institute for Telecommunications, Heinrich-Hertz-Institut, Matls. Tech., Einsteinufer 37, Berlin 10587 Germany; [2]LayTec GmbH, Hardenbergstr. 36, Berlin 10623 Germany

The complexity of MOVPE grown structures for InP based optoelectronic, optical and electronic devices requires extensive calibration and assessment of the various layer parameters involved to guarantee the device specifications. Since in many cases the common evaluation methods are either destructive or not directly applicable to the real wafer, we applied spectroscopic Reflectance(R) and Reflectance Anisotropy Spectroscopy (RAS) for in-situ monitoring the bulk composition of InGaAsP (through R) and the related As-P surface stoichiometry (through RAS). We determined the respective high-temperature refractive index and analysed the characteristic chance of surface response during growth from (1x2)-like to (2x4)-like for increasing As content of the growth surface. A clear correlation of the bulk refractive index and the surface stoichiometry during growth to the resulting quaternary composition has been found and was used for routine process calibration before device growth, including also the measurement of the actual growth rates of the InGaAsP layers.

(20) Material Properties of Graded Composition InGaP Buffer Layers Grown on GaP by Organometallic Vapor Phase Epitaxy: *Stanislav Hasenohrl*[1]; Jozef Novak[1]; Ivo Vavra[1]; [1]Institute of Electrical Engineering, Slovak Academy of Sciences, Optoelect., Dubravska cesta 9, Bratislava 841 04 Slovak Republic

Graded $In_xGa_{1-x}P$ buffer layers were grown on GaP substrate in order to prepare optically transparent substrate for optoelectronic structures. In our contribution we will present results from the optimization of the growth process. The main criterion for the final buffer layer design was to achieve full relaxation of the misfit strain. Technological parameters of low pressure Aixtron AIX 200 equipment were chosen to minimize surface roughening and to achieve low threading dislocation density. The subject of our investigation was the influence of growth temperature, reactor pressure, growth rate and grading rate on buffer properties. Layer composition was determined using X-ray diffraction. Photoluminescence measurements served to find the composition at which the bandgap changes from indirect to direct one. Surface morphology was characterized by atomic force microscopy and scanning electron microscopy. Transmission electron microscopy in plan view and cross-sectional view configuration was used for revealing the buffer microstructure.

(21) Nitrogen Induced Ordering Effects in Novel Dilute-Nitride Material GaInPN/GaAs Grown by MOCVD: Shuo-Hsien Hsu[1]; *Jyun-De Wu*[1]; Cheng-Hsien Wu[1]; Yan-Kuin Su[1]; Shoou-Jinn Chang[1]; Kuang-I Lin[1]; [1]National Cheng Kung University, Dept. of Phyics, Tainan 701 Taiwan; [1]National Cheng Kung University, Inst. of Microelect., Dept. of Elect. Engrg., Tainan 701 Taiwan

In this study, we report the optical characterization and spontaneous ordering effect of novel dilute-nitride material Ga0.46In0.54P1-xNx (x from 0 to 0.02) which were grown by metal organic vapor phase epitaxy on GaAs (100) substrates. The optical properties and the spontaneous ordering effect were characterized by Photoluminescence (PL), polarized micro-Raman spectra and high-resolution x-ray rocking curve (XRC). Incorporating proper amount of nitrogen into Ga0.46In0.54P can be lattice-matched to GaAs. As incorporating nitrogen, the PL peak red shifts, indicating that the band gap reduction and the line width broadening increases due to alloy scattering. We combined PL and micro-Raman spectra to distinguish the ordering induced band gap changes from the compositional changes. However, with the increasing nitrogen content, the non-radiative centers and deep level defects were induced by ordering effect, which indicates the results in poor PL performance. By analyzing the different polarization Raman signal, the degree of ordering on different nitrogen content is also discussed.

(22) Temperature Dependence of Hall-Effect and Persistent Photoconductivity Measurement in InGaAsN: Shuo-Hsien Hsu[1]; Bing-Yang Chen[1]; Yan-Kuin Su[1]; Shoou-Jinn Chang[1]; Cheng-Hsien Wu[1]; Kuang-I. Lin[1]; [1]National Cheng Kung University, Dept. of Phys., Tainan 701 Taiwan

In our study, the electrical properties of InGaAsN films have been investigated by the temperature dependence Hall-effect and photoconductivity. The films of InGaAs and InGaAsN were grown by metalorganic chemical vapor phase deposition on GaAs (100) substrates. The crystal quality has been confirmed by High Resolution X-Ray Diffraction (HR-XRD) and photoluminescence (PL). Compared to the nitrogen-free samples, the mobility of the InGaAsN sample quenched significantly with a small amount of nitrogen incorporation due to scattering of the nitrogen induced lattice defects. In the temperature range from 120K to 400K, the free carrier concentration of InGaAsN sample is not affected by increasing temperature. Furthermore, the persistent photoconductivity (PPC) has been also observed in this material. Indicating that the PPC depends on the different temperature and varied nitrogen content. The relation between saturated trend on free carrier concentration of temperature dependence Hall measurement and PPC phenomenon is also discussed.

(23) Study of Ohmic Contacts and Interface Layers of Carbon Doped GaAsSb/InP Heterostructures for DHBT Application: *S. Neumann*[1]; S. Topaloglu[1]; J. Driesen[1]; Z. Jin[1]; W. Prost[1]; F.-J. Tegude[1]; [1]University Duisburg Essen, Solid-State Elect. Dept., Lotharstrasse, Duisburg 47057 Germany

The $GaAs_{0.51}Sb_{0.49}$:C base layer in InP double heterojunction transistor (DHBT) has recently demonstrated the potential for ultra high speed combined with high breakdown voltage and very high current density. The growth of $GaAs_xSb_{1-x}$ lattice matched to InP is possible far away from thermal equilibrium. In addition, Sb segregation and carry over and the limited growth temperature complicates the MOVPE growth. We investigate the MOVPE growth of $GaAs_xSb_{1-x}$/InP heterostructures in the presence of nitrogen carrier gas. The formation of interlayers between the InP/$GaAs_xSb_{1-x}$/InP heterostructures influence the processing and lead to a non linear contact resistance on the highly doped GaAsSb layer. On single layers (non-)alloyed Ti/Pt/Au and Pt/Ti/PT/Au contacts were studied to improve the ohmic contact. We observed a specific contact resistance with record values smaller 10^{-8} Ohmcm^2. HRXRD measurement and simulation of superlattice and DHBT structures were realized to investigate the formation of interlayers in detail, where as DC characterization of realized DHBTs shows a high heterojunction quality.

(24) Optical and Structural Properties of Zn(1-x)Mg(x)O on n-GaN Epi-Layer by Metal Organic Chemical Vapor Deposition: *Sun-Hong Park*[1]; Seon-Hyo Kim[1]; Kyung-Bo Kim[2]; [1]Pohang University of Science and Engineering, Matl. Sci. & Engrg., san 31, hyo-ja dong, Po-Hang, kyung-buk 790-784 S. Korea; [2]NINEX, R&D Ctr., 449-12, Mogok-dong, Pyung-Tak, Kyongki-do 459-040 S. Korea

Growth Zn(1-x)Mg(x)O and Zn(1-x)Mg(x)O/GaN thin films by metal organic chemical vapor deposition on a sapphire (a-Al2O3) substrate was conducted toward LED application. Structural and optical properties of ZnMgO film on n-GaN epi layer have been studied X-ray diffraction, transmission electron microscopy and photoluminescense. The synthesis of ZnO films was performed over a substrate temperature of 400-700°C and at chamber pressures of 0.1-10 torr. The band gap of ZnMgO films extended up to 3.6eV by adding Mg component. Zn, Mg and O elements in the ZnMgO film on GaN were investigated by EPMA(Electron Micro Probe Analyser) and XPS (X-ray Photoelectron spectroscopy). The Photoluminescence spectroscopy data of ZnMgO film also shows dominating exciton emission peak and very weak deep level emission.

(25) MOCVD Preparation and Termination of Si(100) Surfaces: *Thomas Hannappel*[1]; William E. McMahon[2]; Jerry M. Olson[2]; [1]Hahn-Meitner-Institute, SE4, Glienicker Str. 100, Berlin D-14109 Germany; [2]National Renewable Energy Laboratory, 1617 Cole Blvd., Golden, CO 80401 USA

Clean As- and P-terminated Si(100)-films were prepared with H2 carrier gas and AsH3 and PH3 in an MOCVD apparatus. In-situ reflectance difference spectra (RDS) were measured in the MOCVD reactor. After contamination-free transfer of the samples to UHV Auger electron spectroscopy, low energy electron diffraction, and scanning tunneling microscopy were accomplished. Clean, oxygen- and carbon-free Si(100) surfaces were achieved by annealing samples at T<900°C while supplying hydrogen, PH3, or AsH3. Extended annealing under AsH3 led to strongly facetted surfaces, whereas AsH3 flow of moderate concentration and temperature led to flat surfaces. RD spectra almost identical to RD spectra of As-terminated, one-domain Si(100) surfaces prepared in an MBE system were obtained when annealing samples under AsH3. LEED and STM of As-terminated surfaces showed two-domain 2x1/1x2 reconstructions. Annealing under moderate PH3 supply bore a new, two-domain 6x3/3x6 surface reconstruction and at high PH3 supply the appearance of a new phase, SiP.

(26) Crystal Growth and Characterization of InSbN by MOPVE: *Toshiyuki Ishiguro*[1]; Yuta Kobori[1]; Yoshihito Nagawa[1]; Yasuo Iwamura[1]; Shigeo Yamaguchi[1]; [1]Kanagawa University, Elect., Elect & Info. Engrg., 3-27-1 Rokkakubashi, Kanagawa-ku, Yokohama 221-8686 Japan

It has been reported that the lattice-mismatch of 14% between InSb and GaAs has a significant effect on the electrical properties of InSb film grown on GaAs substrate. We have focused on the crystal growth of InSbN from the standpoint of controlling the strain between GaAs and InSbN, which can be lattice-matched to GaAs. The XRD measurement showed that two peaks emerged simultaneously, which originate from cubic InSbN. Since InSb and InN are difficult to be miscible with each other, the two peaks are considered to be produced by the difference in the content of In. Using the value of lattice constants c (=0.6116nm) at the higher angle peak, the maximum nitrogen content in InSbN was estimated to be 0.24. Hall measurement showed that the electron mobility was 700 cm^2/Vs at room temperature.

(27) Effect of Material Composition on Mg Doping Profiles: *Toshikazu Onishi*[1]; Kenichi Inoue[1]; Toshiya Fukuhisa[2]; Masaaki Yuri[1]; Kazutoshi Onozawa[1]; [1]Matsushita Electric Industrial Co., Ltd., Semiconductor Device Rsch. Ctr., 1 Kotari-yakemachi, Nagaokakyo, Kyoto 617-8520 Japan; [2]Matsushita Electric Industrial Co., Ltd., ULSI Process Tech. Dvlp. Ctr.

Zn has been widely used as a p-type dopant in laser diodes for optical disk applications, in spite of its high diffusion coefficient. In obtaining higher doping concentrations, Mg appears to be advantageous because of its relatively low diffusion coefficient. However, Mg has not been practically used because of such issues as strong memory effects. We found that Mg-doped AlGaInP alloys can be grown by MOVPE without significant memory effects. Abrupt Mg profiles are obtained in ternary and quaternary alloys like GaInP and AlGaInP. On the other hand, strong memory effects are observed in GaAs and AlGaAs alloys. Mg profiles are not affected by the type of Mg precursors: Cp_2Mg or $EtCp_2Mg$. These results show that the material of epilayer has a great effect on the Mg doping profiles. The presence of GaInP plays an important role to suppress the memory effects.

(28) Use of a Triple Wavelength Laser Based Reflectometer to Monitor the Development of Narrow (Cdte) and Wide (Zno) Band-Gap Materials Grown by MOCVD: *Vincent Barrioz*[1]; Stuart J.C. Irvine[1]; Carl L. Griffiths[2]; [1]University of Wales Bangor, Dept. of Chmst., Bangor, Gwynedd LL57 2UW UK; [2]ORS Ltd, Intec House, Parc Menai, Bangor, Gwynedd LL57 4FG UK

The band-gap of the growing films, in MOCVD, will have a strong influence on the performance of a single wavelength in situ monitoring device. In this investigation, a newly developed triple wavelength laser reflectometer has been tested during the growth of narrow band-gap (CdTe) and wide band-gap (ZnO) layers onto GaAs and Sapphire substrates respectively, under different growth conditions. The triple wavelength monitoring instrument used the following wavelengths in its current form, 532 nm, 635 nm and 980 nm. Various growth parameters have been predicted from the observed interferograms, including film growth rate, film thickness, optical properties of the films, and their surface roughness. The composition of the film may also be investigated using this monitoring instrument depending on the quality of the interferograms. The new instrument, using fibre optics, will be introduced showing the advantages and flexibility of using a multi-wavelength laser reflectometer in advanced MOCVD monitoring.

(29) Growth of ZnO Films by MOVPE Using Isopropylzinc and Alcohols: *Yasuhisa Fujita*[1]; Ryuichi Nakai[1]; [1]Shimane University, Interdisciplinary Faculty of Sci. & Engrg., 1060 Nishikawatsu, Matsue 690-8504 Japan

ZnO is expected as a material for high performance light emitting devices in the ultra-violet or blue region, because it has a high exciton binding energy of 60 meV. However, the MOVPE process has not been optimized for the growth of high quality ZnO films. To prevent the defect formation such as oxygen vacancy, low temperature growth and reduction of the pre-reactions between Zn and O-precursors in vapor phase are important. In this work, ZnO films were grown by MOVPE using isopropyl zinc as a zinc source and iso-propanol or tertiary-butanol as oxygen sources. The growth temperature and pressure were 300~500°C and 76Torr. The samples were characterized by photoluminescence, Hall measurements, X-ray diffraction and Raman spectroscopy. When tertiary-butanol was used for oxygen source in high VI/II conditions, the distinctive 3.30eV emission peak and 1500cm^{-1} peak were observed in photoluminescence and Raman spectra, respectively.

(30) Selective MOVPE Growth of Tilted Arrayed Waveguides from [011] Direction: *Yasumasa Kawakita*[1]; Akira Kawai[1]; Suguru Shimotaya[1]; Kazuhiko Shimomura[1]; [1]Sophia University, Dept. of Elect. & Elect. Engrg., 7-1,Kioi-cho,Chiyoda-ku, Tokyo 102-8554 Japan

GaInAs/InP MQW arrayed-waveguide wavelength demultiplexer with linearly varying refractive-index distribution has been achieved by low-pressure selective MOVPE. An asymmetric mask, which had a wide width mask at one side of the array, was used and the waveguides with different thickness across the array were realized. The arrayed waveguides were formed along the [011] direction on (100)-oriented n-InP substrate under the growth condition of 640 °C and 100 torr. To connect the arrayed waveguides to the input/output star couplers based on Rowland circle geometry, the tilted arrayed waveguides from [011] direction were necessary for focus of light. In this paper, we investigated the cross-sectional profiles of tilted waveguides and found that its profiles were changed from trapezoidal profile with (111)B facet to inverted trapezoidal profile with (111)A facet by increasing the tilted angle from [011] direction. To avoid the coalescence of adjacent waveguide, less than 4.7-degree tilted angle was required.

(31) Thermodynamic Analysis of InN and InxGa1-xN MOVPE Using Various Nitrogen Sources: *Yoshinao Kumagai*[1]; Jun Kikuchi[1]; Yuriko Matsuo[1]; Yoshihiro Kangawa[1]; Ken Tanaka[1]; Akinori Koukitu[1]; [1]Tokyo University of Agriculture and Technology, Dept. of Applied Chmst., Koganei, Tokyo 184-8588 Japan

NH_3 is generally used as a nitrogen source for the MOVPE growth of nitrides. For indium containing nitrides, however, NH_3 is not an optimal reagent because the equilibrium constant for the formation of InN is very small compared with those of AlN and GaN. This fact causes the low In incorporation under high growth temperature, compositional unstable growth in $In_xGa_{1-x}N$ and In droplet formation. In this paper, thermodynamic analysis on the $In_xGa_{1-x}N$ MOVPE using hydrazine (N_2H_4), mono-methyl-hydrazine (MMHy), 1,1-di-methyl-hydrazine (1,1-DMHy) or 1,2-di-methyl-hydrazine (1,2-DMHy) as a more reactive nitrogen source is performed. Equilibrium partial pressures, driving force for deposition and vapor-solid distribution relationship are calculated for various growth conditions. It is shown that the driving force for deposition drastically increases in the order of $NH_3 << N_2H_4 <$ MMHy < 1,1-DMHy ~ 1,2-DMHy. Also, the composition unstable region is found to be suppressed in the systems except NH_3.

(32) C-Doped GaAsSb Base HBT Without Hydrogen Passivation Grown by MOVPE: *Yasuhiro Oda*[1]; Noriyuki Watanabe[2]; Masahiro Uchida[2]; Kenji Kurishima[1]; Takashi Kobayashi[1]; [1]NTT Photonics Laboratories, NTT Corporation, High-Speed Devices & Tech. Lab., 3-1, Morinosato Wakamiya, Atsugi-shi, Kanagawa Pref. 243-0198 Japan; [2]NTT Advanced Technology Corporation, Semiconductor Crystalline Matls. Dept., Elect. Div., 3-1, Morinosato Wakamiya, Atsugi-shi, Kanagawa Pref. 243-0198 Japan

Hydrogen passivation of C-doped GaAsSb during both MOVPE growth and annealing under hydride atmosphere was investigated in detail. It is well known that C accepters are easily passivated by hydrogen in III-V materials. We found a way to suppress hydrogen passivation in C-doped GaAsSb grown by MOVPE and examined its mechanism. We also found that hardly any hydrogen atoms are incorporated into C-doped GaAsSb by the hydride-exposure annealing. These results are very advantageous for fabricating C-doped GaAsSb base HBTs without hydrogen passivation. In fact, we successfully fabricated an InP/GaAsSb/InP D-HBT whose hydrogen concentration in the base ([C]: 8×10^{19} cm^{-3}) was under the detection limit of our SIMS measurement. We demonstrate that this HBT has relatively high performance (β ~40, f_T ~300 GHz, f_{max} ~200 GHz, and BV_{CEO} ~6V) at an injection current of 6mA/μm^2 without any dehydrogenation processes.

Friday AM - June 4, 2004

Plenary Session

Friday AM Room: Kihei
June 4, 2004 Location: Westin Maui Hotel

Session Chairs: C. Wang, MIT Lincoln Laboratories, Cambridge, MA 02420 USA; S. Irvine, University of Wales Bangor, Bangor, Gwynedd LL57 2UW UK

8:20 AM Invited

In-Situ Monitoring Tools for MOVPE Systems: *J.-T. Zettler*[1]; K. Haberland[1]; E. Steinmetz[1]; [1]LayTec GmbH, Helmholtzstr. 13-14, D-10587 Berlin Germany

In-situ monitoring tools for MOVPE are typically based on optics - because photons can penetrate the gas-phase easily and can sense the actual growth status even for complex or very fast wafer rotation configurations. The physical wafer-related parameters that can be detected today in-situ are: wafer temperature, growth rate, material composition, doping level and - if present - wafer curvature and surface roughness. In addition, complete finger-printing of device growth (e.g., stop-band wavelength and cavity dip of laser structures) by means of spectroscopic in-situ sensors is increasingly used. This talk will focus on the physics background of the optical in-situ methods presently in use: emissivity corrected pyrometry, spectroscopic reflectance, reflectance-anisotropy spectroscopy and laser beam deflection. Based on this we will discuss how the optimum wavelength range of a sensor can be chosen with respect to the material grown in the actual MOVPE process. We will compare the different techniques regarding their applicability to process development, process calibration, process monitoring and control. Here the accuracy and reproducibility of the different methods will be discussed and the related sensitivity limits will be estimated. It will be demonstrated that the over-all performance of a specific in-situ sensor depends not only on the sensor's degree of sophistication but also on the application conditions at the very different types of MOVPE growth systems. Finally, we will review very recent results on actually challenging in-situ applications like the effect of wafer curvature and wafer doping on the true wafer temperature, absolute wafer temperature calibration for process transfer between different MOVPE systems and the quantitative analysis of in-situ optical data measured on structured and masked substrates.

Nitrides Growth IV

Friday AM Room: Kihei
June 4, 2004 Location: Westin Maui Hotel

Session Chairs: F. A. Ponce, Arizona State University, Tempe, AZ 85287-1504 USA; U. W. Pohl, Technische Universität Berlin, Berlin 10623 Germany

9:10 AM

Growth Modes in Metal-Organic Vapour Phase Epitaxy of InGaN on GaN: *Rachel A. Oliver*[1]; Menno J. Kappers[1]; Colin J. Humphreys[1]; G. Andrew D. Briggs[2]; [1]University of Cambridge, Dept. of Matls. Sci. & Metall., New Museums Site, Pembroke St., Cambridge CB2 3QZ UK; [2]University of Oxford, Dept. of Matls., Parks Rd., Oxford OX1 3PH UK

The successful optimisation of InGaN quantum well lasers and light-emitting diodes for emission wavelengths across the visible spectrum depends on the growth of films with variable indium content. Increasing the indium content of InGaN epilayers may be achieved in MOVPE via a number of routes, including reduction of growth temperature, increase of NH_3 pressure or increase of indium precursor flow. However, these strategies have significant effects on the film morphology and hence on device performance. We have used atomic force microscopy to examine the effect of the growth conditions in InGaN epilayer growth on GaN, aiming to understand what controls the growth mode and to enable the growth of self-assembled nanostructures suitable for employment as quantum dots. We also consider how the growth mode may be modified by in-situ annealing or the use of surfactants to further promote quantum dot formation.

9:30 AM

Migration Enhanced MOCVD of AlInGaN-Based Heterostructures on Large Area Substrates: *Remis Gaska*[1]; Qhalid Fareed[1]; Jianping Zhang[1]; Asif Khan[2]; Michael Shur[3]; [1]Sensor Electronic Technology, Inc., 1195 Atlas Rd., Columbia, SC 29209 USA; [2]University of South Carolina, Elect. Engrg., Columbia, SC 29208 USA; [3]Rensselaer Polytechnic Institute, Elect., Compu. & Sys. Engrg., Troy, NY 12180 USA

We will present our latest data on Migration Enhanced Metal Organic Chemical Vapor Deposition (MEMOCVD) epitaxial technique for growth of AlN/GaN/InN based films and heterostructure layers on up to 3? diameter SiC and 4? diameter sapphire substrates. Using this new technique, we achieved a better mobility of pre-cursor species on the surface and, thus, better atomic incorporation and improved surface coverage. These improvements yield a better surface morphology, reduced density of growth defects and increased carrier lifetime in the epitaxial layers. The MEMOCVD technique allows for, low-temperature growth of high quality InN-on-GaN heterostructures (with temperatures similar to those used in MBE) and for high-temperature growth of uniform Heterostructure Field Effect Transistor epitaxial wafers with less than 3% sheet resistance variation across 4? diameter wafers. We also used the MEMOCVD technology for the fabrication of Deep UV LEDs with peak emission wavelengths in 247 nm - 365 nm range.

9:50 AM

Enhanced Morphology of Planar Nonpolar m-Plane GaN Grown by Hydride Vapor Phase Epitaxy: *Benjamin Allen Haskell*[1]; Hideo Sasano[1]; Paul T. Fini[1]; Steven P. DenBaars[1]; James S. Speck[1]; Shuji Nakamura[1]; [1]University of California, Engrg. Matls. Dept., Santa Barbara, CA 93106-5050 USA

Nonpolar (1-100) m-plane GaN has been found to grow heteroepitaxially on (100) γ-$LiAlO_2$ by several groups. Previous attempts to grow m-plane GaN by hydride vapor phase epitaxy (HVPE) yielded films unsuitable for subsequent device regrowth due to high densities of faceted voids intersecting the free surface. We report here on the first growth of planar m-plane GaN films on $LiAlO_2$ and elimination of bulk defects. GaN films were grown in a three-zone horizontal HVPE reactor at substrate temperatures of 860-890°C, with growth rates of 50-240 μm/hour. The m-plane GaN films were optically transparent and mirror-like, exhibiting a finely striated surface morphology as observed by atomic force microscopy. RMS roughness was 0.89 nm over 25 μm^2 areas, comparable to planar a-plane GaN films. The smooth surface morphology achieved now allows for the fabrication of m-plane GaN templates and free-standing substrates for subsequent nonpolar device regrowth.

10:30 AM Break

Characterization I

Friday AM Room: Kula
June 4, 2004 Location: Westin Maui Hotel

Session Chairs: W. Richter, Technische Universität Berlin, Berlin D-10623 Germany; R. Biefeld, Sandia National Laboratory, Albuquerque, NM 87185 USA

9:10 AM
Microscopic Properties of InGaN Alloys: *Fernando A. Ponce*[1]; Abigail Bell[1]; Michael Stevens[1]; Sridhar Srinivasan[1]; Hiromasa Omiya[1]; H. Marui[2]; S. Tanaka[2]; [1]Arizona State University, Dept. of Physics & Astron., POB 871504, Tempe, AZ 85287-1504 USA; [2]Nichia, 491 Oka, Kaminaka, Anan, Tokushima 774-8601 Japan

This paper presents a correlation of the properties of In$_x$Ga$_{1-x}$N epilayers based on a systematic study of thick layers grown by MOVPE. We find that the microstructure varies significantly with indium composition. For low indium content, $x<0.08$, the film composition is uniform and unperturbed by dislocations. For intermediate values, $0.10<x<0.20$, secondary phases nucleate at threading dislocations. For $x>0.20$, spontaneous phase separation occurs resulting in a polycrystalline, inhomogeneous layer. A correlation between optical properties and microstructure has been established. It is observed that the misfit strain is affected by threading dislocations. Mechanisms of misfit strain relaxation are presented for In$_x$Ga$_{1-x}$N layers grown on various substrates. The implications of the bulk characteristics on the properties of quantum wells have been explored using electron holography and time-resolved cathodoluminescence techniques.

9:30 AM
Development of Crystal Tilt During Early Stages of MOCVD Growth of InAs on (100) GaAs as Revealed by Electron Backscatter Diffraction: G. Suryanarayanan[1]; Anish A. Khandekar[2]; *Thomas F. Kuech*[4]; Susan E. Babcock[3]; [1]University of Wisconsin, Matls. Sci. Program, 1509 Univ. Ave., #201A MSE Bldg., Madison, WI 53706 USA; [2]University of Wisconsin, Dept. of Chem. Engrg., 1415 Engrg. Dr., Madison, WI 53706 USA; [3]University of Wisconsin, Dept. of Matls. Sci. & Engrg. & Matls. Sci. Program, 1509 Univ. Ave., Madison, WI 53706 USA; [4]University of Wisconsin, Dept. of Chem. Engrg. Matls. Sci. Program, 1415 Engrg. Dr., Madison, WI 53706 USA

Electron backscatter diffraction (EBSD) was used to map local crystal orientation within pre-coalesced InAs epitaxial islands grown on planar and patterned (100) GaAs substrates in order to understand the origin of the multiple tilts observed in thicker coalesced films by x-ray diffraction. Trimethylindium and arsine precursors were used for MOCVD growth with a V/III ratio of 80 at 700°C. EBSD of diamond-shaped InAs islands of lateral dimensions 1-10 µm and heights 100-400 nm showed a distinct crystal orientation within each of the four quadrants that comprised each island. Each quadrant was tilted 3-5° relative to the GaAs substrate and 3-8° with respect to other quadrants. These results show that the tilt observed in continuous films develops early in the growth process and within each island. Parallel studies of InAs grown by Lateral Epitaxial Overgrowth on stripe-patterned substrates with one micron-scale window widths show reduced tilt, dislocation density reduction, and defect rearrangement.

9:50 AM
Real-Time Reflectance Anisotropy Spectroscopy During III-V-MOVPE Using a Multichannel Approach: Christian Kaspari[1]; *Florian Poser*[1]; Stefan Weeke[1]; Markus Pristovsek[1]; Wolfgang Richter[1]; [1]Technische Universität Berlin, Dept. of Physics, Hardenbergstraße 36, Berlin 10623 Germany

In-situ monitoring with Reflectance Anisotropy Spectroscopy (RAS) has considerably improved our understanding of the MOVPE process. However, for fast processes on a sub-second time scale like quantum dot formation or growth of strained layers, conventional scanning RAS systems with a monochromator can only measure single transients at a fixed wavelength. The full spectral information can only be extracted by successive transient measurements at different wavelengths. However, this procedure is not always feasible (e.g. irreversible processes). To overcome this problem we developed a multichannel RAS system (minimum 30 ms/spectrum) which simultaneously measures at eight wavelengths using a diode array with eight separate lock in-amplifiers. This system shares the optical setup with a conventional scanning system, allowing for simultaneous operation of both systems and thus easy benchmarking. We study the deoxidation of several III-V-semiconductors, InAs quantum dot formation and group V hetero-exchange during GaAsN growth.

10:30 AM Break

Novel Materials II

Friday AM Room: Kihei
June 4, 2004 Location: Westin Maui Hotel

Session Chairs: S. Stockman, Lumileds Lighting, San Jose, CA 95131 USA; T. Fukui, Hokkaido University, Sapporo, Hokkaido 060-8628 Japan

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11:10 AM
Surface, Interface and Bulk Optical Properties of MOVPE-Grown InN: *Tobias Ludwig Schenk*[1]; Massimo Drago[1]; Torsten Schmidtling[1]; Wolfgang Richter[1]; [1]Technical University of Berlin, Solid State Physics, PN6-1, Hardenbergstr. 36, Berlin 10623 Germany

The optical properties of InN are still a matter of strong discussion and closely related to the layer quality. Due to the large lattice mismatch between layer and commonly used substrates the films have poor quality up to peeling off. Therefore, our work focuses on growing InN on top of GaN templates. Interface and interlayer were optimized by exploiting measurements of the optical properties. In-situ spectroscopic ellipsometry (SE) gave direct feedback and was augmented by wide-range ex-situ SE for complete inclusion of the important interband critical points of both nitrides. Based on the well-known optical properties of the GaN template an optical model of the layer stack is constructed in order to deduce the dielectric function of bulk and surface InN. These results will be compared not only to former experiments of InN deposition directly on sapphire but also to the GaN growth mechanisms.

11:30 AM
Growth Condition Dependence on Nucleation and Evolution of InN Thin Films by MOVPE: *Michael C. Johnson*[1]; Edith D. Bourret-Courchesne[1]; Steven L. Konsek[2]; Wei-Qiang Han[2]; [1]Lawrence Berkeley National Laboratory, Matls. Scis. Div., 1 Cyclotron Rd., MS2R0200, Berkeley, CA 94720 USA; [2]University of California, Dept. of Physics, 366 LeConte Hall, Berkeley, CA 94720 USA

Nucleation and crystallinity evolution for InN thin films deposited using metalorganic vapor phase epitaxy were investigated. Substrate materials, buffer layers, and growth temperatures (ranging from 460°C to 600°C) were studied to obtain a fundamental understanding of nucleation and epitaxial thin film deposition of InN using trimethylindium and ammonia. It was found that InN is extremely sensitive to growth conditions giving InN deposition a small growth parameter space. Growth temperature and ammonia flow-rate have a major effect on the structural quality of the films. The deposited films were characterized using Scanning Electron Microscopy and Atomic Force Microscopy to investigate morphology, X-Ray Diffraction to investigate crystallinity, and Low-Temperature Photoluminescence to investigate optical properties. Similar to GaN optical performance, a photoluminescence emission peak is observed at 0.8 eV although the films have a very high structural defect density. Additionally, it is proposed that the presence of hydrogen from the ammonia decomposition is detrimental and thermodynamically inhibiting for InN deposition.

11:50 AM
MOCVD Growth of GaPN on Si: *J. M. Olson*[1]; John Geisz[1]; W. E. McMahon[1]; T. Hannappel[2]; K. M. Jones[1]; H. Moutinho[1]; M. M. Al-Jassim[1]; [1]National Renewable Energy Laboratory, 1617 Cole Blvd., Golden, CO 80401 USA; [2]Hahn-Meitner Institute, Berlin Germany

Although GaP is closely lattice matched to silicon, epitaxial GaP on Si usually exhibits a large (004) x-ray line width (>200arcsec). However, the alloy GaP$_{0.98}$N$_{0.02}$ is lattice matched to silicon and line widths less than 20 arcsec have been achieved. Here, we examine some of the factors that affect the structural and electronic quality of GaPN epilayers on Si. We show, for example, that the oval defect density is dependent on the high temperature thermal treatment of the Si(001) surface prior to nucleation. Increasing the annealing time in H$_2$ at 1000°C from 2min to 10min decreases the oval defect density in the GaPN epilayer from 10^{5}cm^{-2} to less than 10 cm^{-2}. On the other hand, the addition of AsH$_3$ or PH$_3$ to the annealing atmosphere yields low oval defect densities even for 2min annealing times. These and other factors are presented and discussed.

Characterization II

Friday AM Room: Kula
June 4, 2004 Location: Westin Maui Hotel

Session Chairs: W. Richter, Technische Universität Berlin, Berlin D-10623 Germany; R. Biefeld, Sandia National Laboratory, Albuquerque, NM 87185 USA

11:10 AM
Use of SiC Band Gap Temperature Dependence for Absolute Calibration of Emissivity Corrected Pyrometers in III-Nitride MOVPE: *Roger Steins*[1]; Nicoleta Kaluza[1]; Hilde Hardtdegen[1]; M. Zorn[2]; K. Haberland[3]; J.-T. Zettler[3]; [1]Research Center Juelich, Inst. of Thin Films & Interfaces, Juelich 52425 Germany; [2]Ferdinand-Braun-Institut für Höchstfrequenztechnik, Albert Einstein-Str. 11, Berlin 12489 Germany; [3]LayTec Gesellschaft für In Situ and Nansosensorik mbH, Helmholzstr. 13-14, Berlin 10587 Germany

Real time in-situ measurement and control of the true substrate temperature during the MOVPE of GaN is crucial for obtaining reproducible layer quality. Typically, emissivity corrected pyrometry is used for reaching exactly the same run-by-run wafer temperature in a given MOVPE system. However, especially for process transfer to other reactors, the accurate calibration of the pyrometer to the absolute temperature is still an issue. The determination of an Al/Si eutectic temperature or the melting point of Al layers is usually employed. However our experience is that the calibration accuracy is influenced by Al-layer purity and thickness. Also in rf-heated MOVPE systems the melting temperature can be erroneous when the highly conductive Al-layer is heated by induction. In this paper we will demonstrate a new method for temperature calibration by using the in-situ measured band-gap shift of SiC in conjunction with real-time emissivity corrected pyrometry. The complete procedure for temperature calibration and real-time wafer temperature measurement on transparent substrates will be presented.

11:30 AM
In-Situ Stress Measurements During MOVPE Growth of High Al-Content AlGaN on SiC: *Jeremy D. Acord*[1]; Srinivasan Raghavan[1]; David W. Snyder[3]; Joan M. Redwing[2]; [1]Pennsylvania State University, Matls. Sci. & Engrg., 5 Hosler Bldg., Univ. Park, PA 16802 USA; [2]Pennsylvania State University, Matls. Sci. & Engrg., 108 Steidle Bldg., Univ. Park, PA 16802 USA; [3]Pennsylvania State ARL, Electro-Optics Ctr., 559A Freeport Rd., Freeport, PA 16229 USA

Deposition of AlxGa1-xN (x>0.3) for UV devices is challenging due to defect formation and film cracking which are commonly observed in thick layers. Cracking is generally attributed to film/substrate lattice constant and thermal expansion mismatch, however, growth-related stresses due to developing film morphology may also play a role. In-situ stress measurements were used to investigate effects of growth conditions on stress evolution during MOVPE growth of AlGaN on SiC. An initial compressive stress was measured during AlGaN growth on thin AlN buffer layers which evolved with film thickness into a tensile growth stress. The compressive stress is attributed to epitaxial mismatch between film and buffer layer, and the tensile stress to increasing lateral grain size with thickness. Increasing the V/III ratio during AlN buffer growth from 750 to 10,600 increased the AlGaN initial compressive stress from 1.9 to 8.5 GPa, which reduced the final tensile stress of the film.

11:50 AM
In-Situ Measurements of Strain and Stresses in GaN Heteroepitaxy: *A. Dadgar*[1]; R. Clos[1]; G. Strassburger[1]; J. Blaesing[1]; T. Riemann[1]; A. Diez[1]; J. Christen[1]; A. Krost[1]; [1]Otto-von-Guericke-Universitaet Magdeburg, FNW/IEP, Universitaetsplatz 2, Magdeburg 39106 Germany

In heteroepitaxy stress, either intrinsic or thermal, is a common problem. We have investigated in detail stress during GaN heteroepitaxy on sapphire and silicon. While some well known sources as strained layers do result in tensily or compressively stressed layers other sources of stress are not as well known. Growth in heteroepitaxy is usually initiated from separate islands which does lead to an island-size dependent tensile stress from gap closure between the islands. Doping with Si is another source of dislocation density and doping concentration dependent stress. We find that, independent of the stress state of the material Si induces tensile stress most likely by promoting the movement of edge type dislocations and by this reducing the correlated lattice planes. For a detailed analysis of stress during GaN epitaxy we have developed a curvature measurement technique and found an analytical solution for the correct determination of stress which is important for large curvatures.

Friday PM - June 4, 2004

Closing Ceremony

Friday PM Room: Kihei
June 4, 2004 Location: Westin Maui Hotel

12:10 PM Final Remarks

Index