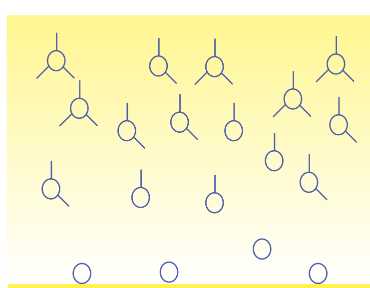
1998

The Ninth International Conference on Metal Organic Vapor Phase Epitaxy (ICMOVPE IX)

Final Program

ICMOPVE IX Technical Program Information

ICMOVPE IX



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AMERICAN ASSOCIATION FOR CRYSTAL GROWTH

May 31-June 4, 1998

Sheraton Grande Torrey Pines

La Jolla, California

ICMOVPE IX SCHEDULE OF EVENTS

DATE & TIME	FUNCTION	LOCATION
Sunday, 5/31/98		
12:00Noon-7:00pm	Workshop Registration	Grand Ballroom Lobby
5:00pm-7:00pm	Welcoming Reception, Sponsored by Aixtron AG	Parterre Garden
7:00pm-9:00pm	Bavarian Reception Sponsored by EMF Ltd. and MOCHEM	Palm Terrace Pavilion
Monday AM, 6/1/98		
7:00am-5:00pm	Workshop Registration	Grand Ballroom Lobby
7:00am-8:00am	Authors Coffee	Canyon
7:00am-5:00pm	Slide Preview	Shores
8:00am-8:20am	Plenary	Grand Ballroom D&E
9:30am-12:20pm	Growth of Device Structures	Grand Ballroom A&B
9:30am-12:20pm	Nitrides: Growth, Defects, Characterization and Devices - Session I	Grand Ballroom D&E
10:30am-11:00am	Coffee Break, Sponsored by Morton International	Grand Ballroom C
12 Noon-5:00pm	Exhibits	Grand Ballroom C
12:30pm-1:45pm	Luncheon (Ticketed)	Ballroom Terrace
Monday PM 6/1/98		
2:00pm-5:30pm	Growth and Doping Mechanisms	Grand Ballroom A&B
2:00pm-5:30pm	Surface, Physics and Chemistry During Growth	Grand Ballroom D&E
3:20pm-3:40pm	Coffee Break, Sponsored by Morton International	Grand Ballroom C
6:00pm-9:00pm	Evening Excursion	Stephen Birch Aquarium-Museum
Tuesday AM, 6/2/98		
7:00am-12:00 Noon	Workshop Registration	Grand Ballroom Lobby
7:00am-8:00am	Authors Coffee	Canyon
7:00am-12:00 Noon	Slide Preview	Shores
7:00am-12:00 Noon	Exhibits	Grand Ballroom C
8:20am-9:20am	Plenary	Grand Ballroom D&E
9:30am-12:20pm	Low Dimensional Structures	Grand Ballroom A&B
9:30am-12:20pm	Infrared Materials and Devices	Grand Ballroom D&E
10:30am-11:00am	Coffee Break, Sponsored by Morton International	Grand Ballroom C
Tuesday PM, 6/2/98		
1:00pm-6:00pm	Afternoon Excursions	Bus Departure Area
5:00pm-7:00pm	Shades and Caps Party, Sponsored by AIXTRON AG	Palm Terrace Pavilion
7:30pm-8:00pm	Late News Papers	Grand Ballroom D
8:00pm-10:00pm	Poster Presentations	Grand Ballroom D
8:00pm-10:00pm	Poster Session	Scripps Ballroom
Wednesday AM, 6/3/98		
7:00am-5:00pm	Workshop Registration	Grand Ballroom Lobby
7:00am-8:00am	Authors Coffee	Canyon
7:00am-5:00pm	Slide Preview	Shores
7:00am-4:00pm	Exhibits	Grand Ballroom C
8:20am-9:20am	Plenary	Grand Ballroom D&E
9:30am-12:20pm	Quantum Wells, Wires and Dots	Grand Ballroom A&B
9:30am-12:20pm	Selective Area Growth	Grand Ballroom D&E
10:30am-11:00am	Coffee Break, Sponsored by Morton International	Grand Ballroom C
12:30pm-1:45pm	Luncheon (Ticketed)	Ballroom Terrace

ICMOVPE IX SCHEDULE OF EVENTS

DATE & TIME	FUNCTION	LOCATION
Wednesday PM, 6/3/98		
2:00pm-5:30pm	High Power, High Temperature Semiconductor Materials and Devices	Grand Ballroom A&B
2:00pm-5:30pm	Nitrides: Growth, Defects, Characterization and Devices - Session II	Grand Ballroom D&E
3:20pm-3:40pm	Coffee Break, Sponsored by Morton International	Grand Ballroom C
7:00pm-7:30pm	Reception, Sponsored by Emcore Corporation	Grand Ballroom CD&E
7:30pm-9:30pm	Conference Banquet	Grand Ballroom CD&E
Thursday AM, 6/4/98		
7:00am-12:00Noon	Workshop Registration	Grand Ballroom Lobby
7:00am-8:00am	Authors Coffee	Canyon
7:00am-10:00am	Slide Preview	Shores
8:20am-9:20am	Plenary	Grand Ballroom D&E
9:30am-12:20pm	Nitrides: Growth, Defects, Characterization and Devices - Session III	Grand Ballroom A&B
9:30am-12:20pm	In-Situ Probes, Real Time Monitoring and Process Control	Grand Ballroom D&E
10:30am-11:00am	Coffee Break, Sponsored by Morton International	Grand Ballroom C
12:30pm-2:00pm	Luncheon (Ticketed)	Palm Terrace Pavilion

Scope

The Ninth International Conference on Metal Organic Vapor Phase Epitaxy (ICMOVPE IX) is being held May 31 through June 4, 1998 at the Sheraton Grande Torrey Pines Hotel, La Jolla, CA USA. The conference builds upon the strong tradition of previous conferences by presenting the latest advances in the science, technology and applications of MOVPE and related growth techniques. The objective of the conference is to bring together a wide spectrum of specialists from Industry, Commerce, Academia and National Laboratories to present their most recent progress in the fundamental and applied aspects of MOVPE technology. The program is designed to provide a wide range of opportunities for formal and informal discussions of and presentations on all topics of interest.

Session Topics

- Nitrides: Growth, Defects, Characterization and Devices: Sessions I, II & III
- Surface Physics and Chemistry During Growth
- Infrared Materials and Devices
- Selective Area Growth
- In-Situ Probes, Real Time Monitoring and Process Control
- Growth of Device Structures
- Growth and Doping Mechanisms
- Low Dimensional Structures
- Quantum Wells, Wires and Dots
- High Power, High Temperature Semiconductor Materials and Devices

Conference Committee

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Technical Sessions

The Ninth International Conference on Metal Organic Vapor Phase Epitaxy Technical Program will commence at 8:00 AM on Monday, June 1, 1998. Sessions will be held in the Grand Ballroom of the Sheraton Grande Torrey Pines Hotel. Session by paper titles and abstracts are included in this brochure.

Policy on audio and video recording of technical presentations/sessions

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Late News Papers

Will be included in the workshop prior to the poster session Tuesday evening. Late news presentations will begin at 7:30 PM and run until 8:00 PM.

Poster Papers

Poster setup will begin Tuesday, 2:00 PM. The posters will follow the late news papers session. Authors are requested to stand at their posters Tuesday evening between 8:00 PM-10:00 PM. Posters must be removed by 10:00 AM Wednesday.

Authors Coffee

Monday through Thursday, authors and session chairmen will meet in the Canyon Room from 7:00 AM - 8:00 AM. Authors and session chairmen are required to attend on the day of their presentation. Please refer to the Workshop Program and Schedule of Events for times and days of presentations.

Slide Preview Area

Authors are invited to preview their slides at the Slide Preview Area located in the Shores meeting room during the following hours:

Monday, June 1, 1998	7:00 AM - 5:00 PM
Tuesday, June 2, 1998	7:00 AM - 12:00 Noon
Wednesday, June 3, 1998	7:00 AM - 5:00 PM
Thursday, June 4, 1998	7:00 AM - 10:00 AM

Publication of the Workshop Papers

Papers accepted for The Ninth International Conference on Metal Organic Vapor Phase Epitaxy will be reviewed in a special issue of the Journal of Crystal Growth. Submit your manuscripts Monday-Wednesday at the Elsevier desk located in the Canyon Room.

Publication Chairs:

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E-Mail: rmbiefe@sandia.gov

Corporate Sponsors

The organizers and attendees of the conference wish to acknowledge their appreciation to the following companies for their generous support of ICMOVPE IX. Specific events and student attendance are being supported by their contributions. Please stop by to visit their tabletop exhibits during the conference.

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AIXTRON is the world-leading manufacturer focusing exclusively on MOCVD equipment for compound semiconductors. AIXTRON offers: • Efficient manufacturing with lowest cost of ownership. • Worldwide service network with representation in over 15 countries.

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BIO-RAD

Bio-Rad manufactures a range of semiconductor materials characterization equipment including Electrochemical CV Profilers , Hall Measurement equipment, DLTS systems and is introducing the new Rapid Photoluminescence Mapping system.

COMPOUND SEMICONDUCTOR MAGAZINE

Compound Semiconductor is a news magazine which covers the latest commercial and research developments relating to III-V, II-VI and IV-IV semiconductors. It is available only by subscription, but free samples will be available at the exhibit.

LOGO TO BE SENT VIA EMAIL.

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Crystar is a leading provider of high quality Sapphire substrates to the expanding Gallium Nitride based market.

Substrate tolerances and surface finish are keys to Gallium Nitride device production and yield. Crystar sets the standards for flatness and surface finish. Our strong product development team uses industry standard measurement techniques, such as AFM, X-ray rocking curves and surface analysis to study surface and crystalline quality of substrates.

ELSEVIER ADVANCED
Technology, publishers of III-Vs Review magazine, are presenting their range of market and technical information sources dedicated to the semiconductor industry worldwide. Free sample copies of III-Vs Review and information on the Advanced Semiconductors Buyer's Guide will be available.

EMF LIMITED
EMF Limited is a vertically integrated company supplying III-V precursors (TMAl, TMG, TMI, TEG, DEZn, TBA and TBP), custom epiwafers in both GaAs and InP alloys and specialist optoelectronic devices. The company is unique in its ability to provide training and technology transfer packages for both epiwafers and devices.

EMCORE
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Epichem's primary product offering is a line of ultra-high-purity metalorganics. Its proprietary adduct purification technology yields volatile compounds, including those of aluminum, gallium, indium, arsenic, phosphorus, zinc, sulfur, antimony, nitrogen and magnesium. Epichem's new facility in Massachusetts (USA) provides dual production capability and assures customers of uninterrupted delivery of chemical metalorganic needs. Value added services include emergency response, leading edge analytical instrumentation, technical and customer support, R&D, local sales support and custom packaging, JIT delivery or local stocking and safety, health and environmental support.

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Matheson Semi-Gas brand of Gas Source, Distribution, Gas Management, On-Board Gas Jungles and Bulk Specialty Gas Equipment, SDS® Safe Delivery Source for Ion Implantation; High Purity Process Gases and CVD Precursors; Nanochem® brand Purification Systems, and TGC™ Total Gas Management Systems Engineering Services; Site Management Services; Gas Safety Detectors and Monitors; Gas Effluent Treatment Systems.

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was founded in 1993 under the name of sgs Mochem Products in Marburg - right in the center of Germany. The company develops and manufactures chemicals specifically designed for semiconductor technologies.

MOCHEM emphasizes the application proof quality of its products to enable and improve the process technology and reduce the costs. The company is recognized as No. 1 supplier for TBA & TBP sources in Europe & north America.

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Morton International is a leading manufacturer of high purity metalorganic precursors for metalorganic vapour phase epitaxy (MOVPE) and related film growth technologies used in the manufacture of compound semiconductors. With significant capital investments in a new world class manufacturing and research facility, state-of-the-art analytical instrumentation, advanced purification and a focus on global manufacturing expansion, Morton is committed to a long-term leadership position in the markets it serves.

NIMTEC INC

NIMTEC, located in Chandler, AZ, is a subsidiary of Japan Energy that sells ACROTEC brand semiconductor material products. We provide high quality InP and CdTe bare wafers, epi GaAs and InP wafers and high purity In, Cd and Te. For inquiries, please contact us at 1-800-NIMTEC-1 or nimteccs@ix.netcom.com

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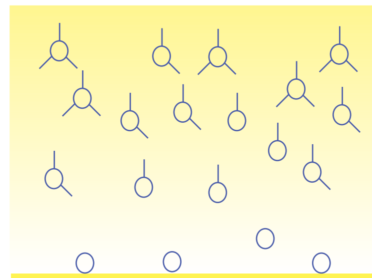

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ICMOVPE IX
Technical Program
Daily Listing of Sessions & Papers

Starts: Monday, 8:00 AM, June 1, 1998

Ends: Thursday, 12:30 PM, June 4, 1998

The Ninth International Conference on Metal Organic Vapor Phase Epitaxy (ICMOVPE IX)

May 31 - June 4, 1998

		Grand Ballroom D & E	Grand Ballroom A & B	Scripps Ballroom
Monday	AM	Plenary 8:00AM-9:20AM Nitrides: Growth, Defects, Characterization and Devices: Session I 9:30AM-12:20PM	Growth of Device Structures 9:30AM-12:20PM	
Monday	PM	Surface Physics and Chemistry During Growth 2:00PM-5:30PM	Growth and Doping Mechanisms 2:00PM-5:30PM	
Tuesday	AM	Plenary 8:20AM-9:20AM Infrared Materials and Devices 9:30AM-12:20PM	Low Dimensional Structures 9:30AM-12:20PM	
Tuesday	PM	Late News 7:30PM-8:00PM		Poster Session 8:00PM-10:00PM
Wednesday	AM	Plenary 8:20AM-9:20AM Selective Area Growth 9:30AM-12:20PM	Quantum Wells, Wires and Dots 9:30AM-12:20PM	
Wednesday	PM	Nitrides: Growth, Defects, Characterization and Devices: Session II 2:00PM-5:30PM	High Power, High Temperature Semiconductor Materials and Devices 2:00PM-5:30PM	
Thursday	AM	Plenary 8:20AM-9:20AM In-Situ Probes, Real Time Monitoring and Process Control 9:30AM-12:20PM	Nitrides: Growth, Defects, Characterization and Devices: Session III 9:30AM-12:20PM	

ICMOVPE IX
Technical Program

Monday AM - June 1, 1998

Plenary Session

Monday AM — Room: Grand Ballroom D & E
June 1, 1998 — Location: Sheraton Grande Torrey Pines

Session Chairs: T. F. Kuech, University of Wisconsin, Dept. of Chemical Engineering, Madison, WI 53706 USA; R. Moon, Hewlett Packard Laboratories, Palo Alto, CA 94304-1392 USA

8:00AM WELCOME INTRODUCTION: Thomas F. Kuech, Ronald Moon.

8:20 AM INVITED PAPER
InGaN-Based Blue Laser Diodes with a Lifetime of 10,000 Hours: SHUJI NAKAMURA[1]; [1]Nichia Chemical Industries Ltd., R&D Department, 491, Oka, Kaminaka, Anan, Tokushima 774 Japan

We previously reported InGaN multi-quantum-well (MQW)-structure laser diodes (LDs), which have AlGaN/GaN modulation-doped strained-layer superlattices (MD-SLSs), within the critical thickness range, as cladding layers instead of thick AlGaN layers in order to prevent cracking of the AlGaN layers. Epitaxially laterally overgrown GaN (ELOG) on sapphire was used to reduce the number of threading dislocations of the GaN epilayer. Using both the MD-SLSs and the ELOG substrates, LDs with an estimated lifetime of more than 10,000 hours were developed. In the structures, sapphire substrates were used. Using a sapphire substrate, it is difficult to obtain cleaved mirror facets which are used for the cavities of conventional LDs. Also, the thermal conductivity of the sapphire is relatively small in order to dissipate the heat generated by the LDs. Here, the LDs grown on GaN substrates which are easily cleaved and have a high thermal conductivity, are described.

8:50 AM INVITED PAPER
Real-Time Monitoring of MOCVD Device Growth by Reflectance-Anisotropy-Spectroscopy and Related Optical Techniques: J.-THOMAS ZETTLER[1]; [1]Institut für Festkörperphysik, Technische Universität Berlin, Sekr. PN 6-1, Hardenbergstr. 36, Berlin D-10623 Germany

Reflectance-Anisotropy-Spectroscopy (RAS/RDS), invented at Bellcore [1] ten years ago, has been widely used for basic growth studies both in MBE and MOVPE [2]. Due to its sensitivity to the uppermost atomic monolayer RAS became a very versatile tool for studying surface stoichiometry, surface reconstruction and surface morphology especially under gas phase conditions. Meanwhile, however, the performance and adaptability to standard MOVPE systems has been enhanced significantly (rotating samples can now be dealt with, reflectance and RA data are analyzed simultaneously, the time per spectrum was reduced to only a few seconds, etc.) and RAS sensors now can also be used for MOVPE device growth monitoring and control. Therefore, following a brief introduction into the basic surface physics and surface chemistry causing the optical signatures, this talk will concentrate on device related applications. Examples will be given concerning the real-time measurement of both n-type and p-type GaAs doping levels and the real-time measurement of ternary compound composition for reaching lattice matched growth (InGaAs/InP and InGaP/GaAs). A visualization of the optical surface response during the growth of a complete GaAs/InGaP HBT device is demonstrated that is able to indicate on a monolayer level either consistency to or deviations from the intended growth process.

9:20 AM Break into Parallel Sessions

Growth of Device Structures

Monday AM — Room: Grand Ballroom A & B
June 1, 1998 — Location: Sheraton Grande Torrey Pines

Session Chairs: J. J. Coleman, University of Illinois, Urbana, IL 61801 USA; K. Heime, RWTH Aachen, 52056 Aachen Germany

9:30 AM
A Novel Super-Lattice AlAs/AlInAs Lateral-Oxide Current Confinement Structure for InP-Based Laser Devices: NORIYUKI OHNOKI[1]; Tatsuya Uchiyama[1]; Fumio Koyama[1]; Kenichi Iga[1]; [1]Tokyo Institute of Technology, Precision & Intelligence Lab. Iga Lab., 4259 Nagatsuta Midori-ku , Yokohama, Kanagawa 226 Japan

The buried heterostructure (BH) has been used for current confinement of semiconductor lasers but the regrowth process is needed in the laser fabrication and the current leaking between active region and current blocking layer sometimes deteriorates temperature characteristics. In this paper, we propose a novel super-lattice AlAs/AlInAs lateral-oxide current confinement structure for InP-based semiconductor lasers, VCSELs and opto-electronic devices. We have realized an oxide current confined AlGaInAs/AlGaInAs compressive strain MQW laser emitting at 1550nm with the threshold current of 45mA. The lasers can be fabricated by a single step MOCVD growth and oxidation. A tensile-strained AlAs layer on InP substrate has a large hetero-barrier and works as an electron stopping layer in a p-type region. The optimized super-lattice AlAs/AlInAs layers have no defects in spite of AlAs layers over the critical thickness, whose AlAs layers are carbon-δ-doped for low turn-on voltage, and in both sides of which narrow gap layers are inserted for low resistance. By this technique the broad laser with the super-lattice structure exhibited the threshold current density of 133 A/cm^2/well and To =80-90 K.

9:50 AM
High-Power, Single-Mode, Al-Free InGaAs(P)/InGaP/GaAs Distributed Feedback (DFB) Diode Lasers: L. J. MAWST[1]; H. Yang[1]; M. Nesnidal[1]; A. Al-Muhanna[1]; D. Botez[1]; [1]University of Wisconsin-Madison, Dept. of Electrical and Computer Engineering, 1415 Engineering Dr., Madison, WI 53706 USA

The selective etching and oxide-free regrowth properties of the Al-free InGaAs(P)/InGaP/GaAs material system have been exploited to demonstrate a novel, single-mode diode laser; the Simplified Antiresonant Optical Waveguide (S-ARROW) laser. The device is fabricated using a three-step MOCVD growth process, incorporating a lower (i.e. below the quantum well active layer) grating for single frequency operation and an S-ARROW structure for spatial mode stability. Initially, a second-order DFB grating is holographically defined and wet etched into an InGaP cladding layer, followed by a GaAs “fill-in” and quantum well active layer regrowth. Planarization of the active region over the grating has been studied by TEM and photoluminescence. The S-ARROW structure is then defined above the active layer by the selective etching of a high-refractive index layer and subsequent growth of InGaP, thereby creating a large spot-size (7micron-wide) single-mode waveguide. Devices operate single-frequency and single-spatial mode to 157mW CW.

10:10 AM

Mass-Transport Effect on InP Corrugation Shape Control of DFB-LDs under Atmospheric Pressure MOVPE: TOMOAKI KOUI[1]; Yasutaka Sakata[1]; Yoshihiro Sasaki[1]; Takashi Matsumoto[2]; Keiro Komatsu[1]; [1]NEC, ULSI Device Development Laboratories, 2-9-1, Seiran, Otsu, Shiga 520-0833 Japan; [2]NEC, Optoelectronics and High Frequency Device Research Laboratories, 34, Miyukigaoka, Tsukuba, Ibaraki 305-8501 Japan

The mass-transport (MT) effect is very important to control the corrugation shape of DFB-LDs. Quite uniform InGaAsP epitaxial growth has been achieved by atmospheric-pressure MOVPE(AP-MOVPE) with dual-fluid-layer structure reactor. However, MT-mechanism for AP-MOVPE has not yet been investigated. This paper discusses MT-effect under group-V atmosphere using AP-MOVPE, for the first time. The MT-layer was found to be piled with the specific crystal orientation, unlike low-pressure MOVPE case, in the concave-region of the corrugation during heating-up time to growth temperature(T_{growth}). The piling rate(R_{pile}) for several temperatures was calculated from holding-time-dependence of the quantity of MT-layer. So, it was derived that R_{pile} at 625ϒC was three times larger than that at 575ϒC. Then, threshold temperature is estimated to be 550ϒC, where MT starts to occur. Based on the above consideration, quick heat-up sequence (less than 15 seconds from 550ϒC to T_{growth} of 625ϒC) was adopted to realize well-controlled corrugation shape for 1.3um-strained MQW-DFB-LDs, and excellent device characteristics, such as I_{th}=24.7mA and η_s=0.36W/A \@70ϒC, were attained.

10:30 AM Break

11:00 AM

Etching of InP-Based MQW Laser Structure in an MOCVD Reactor by Chlorinated Compounds: DANIELE BERTONE[1]; Giuliana Morello[2]; Roberta Campi; [1]CSELT, Transmission and Optical Technologies, via Reiss Romoli, 274, Torino 10148 Italy

Four different chlorinated compounds: 2-chloropropane, dichlorometane, chloroform and carbon-tetrachloride have been used to etch 1.55um InGaAsP/InP MQW laser structures partially masked with SiNx. Etching experiments were performed in a homemade MOCVD reactor with Ar or Ar+H2 as carrier gas, using PH3 or TBP to prevent thermal decomposition. Etching temperature (540-590°C) as well as the chlorocarbon flow, were varied to obtain the best trade-off between etch rate and surface morphology. Working pressure was maintained constant at 76 Torr. The resulting best conditions were found using dichlorometane or 2-chloropropane, at a temperature of 555°C under Ar flow. The etch-rate (4um/h) is also depending on the presence of PH3 or TBP. These experimental conditions were applied to etch mesa stripes in a SCH-MQW laser structure, followed by lateral InP:Fe regrowth in the same step. Preliminary measurements on the fabricated SI-BH MQW laser show Ith<6mA and differential quantum efficiency >20%.

11:20 AM

GaAs-Based VCSEL-Structures with Strain-Compensated (GaIn)As/Ga(PAs)-MQWH Active Regions Grown by Using TBAs and TBP: C. Ellmers[1]; S. Leu[1]; R. Rettig[1]; M. Hofmann[1]; W. STOLZ[1]; W. Rühle[1]; [1]Philipps-University, Material Science Center and Department of Physics, Hans-Meerwein-Str., Marburg, 35032 Germany

Strain-compensated (GaIn)As/Ga(PAs)-MQWH active regions increase the possibilities for the design of the gain region in VCSELs. In particular, the number of wells can be increased for optimum dynamical properties. These specific structures have been grown by MOVPE using the less hazardous group-V-sources TBAs and TBP. We report on growth optimization, characterization of the VCSEL structures, and ultrafast emission dynamics after femtosecond optical excitation. The improved decomposition characteristics of the alternative compounds yield a small variation in the cavity thickness of only +- 0.35% across the 2'' wafer. The high quality of the VCSEL structures having a 2 λ cavity with 4 stacks of 3 (GaIn)As/Ga(PAs)-MQWH and AlAs/GaAs-Bragg mirrors is revealed by the large normal mode coupling of 10.6 meV. Excellent pulse response after femtosecond optical excitation with a pulse width of 3.9 psec and a peak delay of 4.8 psec is obtained. These results demonstrate the advantages of the strain-compensated material system for VCSEL structures grown by MOVPE using TBAs and TBP.

11:40 AM

Very High Compositional Homogeneity of 1.55 µm Strain-Compensated GaInAsp MQW Structures by MOVPE under N2 Atmosphere: S. JOCHUM[1]; E. Kuphal[1]; V. Piataev[1]; H. Burkhard[1]; [1]Deutsche Telekom AG, Technologiezentrum, Darmstadt D-64307 Germany

In order to improve the compositional homogeneity, MOVPE growth under N2 as a carrier gas has been applied for the first time to strain-compensated GaInAsP MQW structures on InP. Various GaInAs(P) layers and MQW structures have been grown by low pressure MOVPE in a horizontal reactor with substrate rotation using standard precursors. By replacing H2 with N2 the material homogeneity could be considerably improved in all aspects like wavelength, composition and layer thickness due to the lower heat conductivity of the N2., e.g. the standard deviation s(l) of the wavelength over 40 mm of a 50-mm-water of strain-compensated l=1.55µm laser structures with 10 QWs could be reproducibly reduced from 6.5 nm (H2) to 0.75 nm (N2), which is a factor of about "8". To our knowledge, this is the best homogeneity value reported so far for GaInAsP grown in any type of MOVPE reactor with any precursors. Details of the growth parameters and results will be presented along with the static and dynamic characteristics of DFB lasers and laser arrays produced from these structures.

12:00 PM

Growth of Strain Compensated InGaAs for 1.3 µm Emission on GaAs Using Metalorganic Chemical Vapor Deposition: WON-JIN CHOI[1]; In Kim[1]; P. Daniel Dapkus[1]; Jack L. Jewell[2]; [1]University of Southern California, Department of Electrical Engineering, University Park, Los Angeles, CA 90089-0271 USA; [2]Picolight, Inc., Boulder, CO

We present a study of MOCVD growth of strain compensated InGaAs quantum wells for application to 1.3 µm lasers on GaAs substrates. We examine the growth of GaAsP/InGaAs and GaP/InGaAs quantum well structures with high In composition for this application. The introduction of tensile strain barriers allows us to extend the wavelength of emission from InGaAs quantum wells on GaAs to 1.28 µm with high efficiency. In this paper, we describe the structures used to achieve this emission as well as the growth procedures used. The active region structure consists of GaAsP (or GaP) tensile strained barriers and an InGaAs compressive strained single quantum well, sandwiched by lattice matched GaInP on GaAs. We report the dependence of the emission efficiency and linewidth on In composition for these structures. The PL intensity is decreased by only a factor of 4 at 1.3 µm from lower composition materials and a linewidth of 79.8meV is observed at room temperature. Device results will also be reported.

Nitrides: Growth, Defects, Characterization and Devices - Session I

Monday AM Room: Grand Ballroom D & E
June 1, 1998 Location: Sheraton Grande Torrey Pines

Session Chairs: T. F. Kuech, University of Wisconsin, Madison, WI 53706 USA; S. Nakamura, Michia Chemical Industries Ltd., Anan, Tokushima 774 Japan

9:30 AM

Spiral Growth of Group-III Nitrides and Its Influence on the Properties of InGaN/GaN Single and Multi Quantum Wells: STACIA KELLER[1]; Umesh K. Mishra[1]; Steven P. DenBaars[1]; [1]University of California, Electrical & Computer Engineering Department, Engineering I Building, Santa Barbara, CA 93106 USA

Spiral growth was found to be the dominant growth mechanism for nitride films grown under low group-III precursor flow rates typical for the deposition of InGaN/GaN hetrostructures by metal-organic chemical vapor deposition. The growth spirals formed around threading dislocations with screw component. Spiral height and diameter (analyzed by atomic force microscopy) strongly depended on the growth conditions. The spiral growth strongly affected the structural and optical properties of InGaN/GaN single and multi quantum wells. Thus, single quantum wells containing spiral disks showed more efficient luminescence and significantly longer radiative recombination lifetimes (1.5 ns vs 300 ps). In addition, growth condition dependent variations of the structural properties of multi quantum wells could be correlated to spiral growth related effects. The spiral disk formation will be discussed as a possible contribution to the development of spatial inhomogeneities in InGaN layers.

9:50 AM

Optical Emission Characteristics of Thin InGaN Layers Grown on GaN and the Implications for Growing High Quality Quantum Wells by MOCVD: JUNKO T. KOBAYASHI[1]; Nobuhiko P. Kobayashi[1]; Xingang Zhang[2]; P. Daniel Dapkus[1]; Daniel H. Rich[2]; [1]Compound Semiconductor Laboratory, Department of Materials Science and Electrical Engineering / Electrophysics, VHE313, University of Southern California, Los Angeles, CA 90089-0241 USA; [2]Photonic Materials and Devices Laboratory, Department of Materials Science and Engineering, University of Southern California, Los Angeles, CA 90089-0241 U.S.A

The optical emission from InGaN quantum wells is often spectrally broad because of In segregation particularly for higher In concentration. In this paper we examine the formation of thin layers of InGaN grown by MOCVD by use of cathodoluminescence to elucidate the extant and mechanisms for the segregation. The thickness dependence and the spatial inhomogeneity of cathodoluminescence from thin InGaN films (10 ~ 100 Å) grown on GaN in an atmospheric pressure showerhead reactor will be discussed. Our results indicate that there is a layer with low In composition at the initial stage of InGaN growth whose composition does not depend on the growth temperature. Furthermore, the inhomogeneity of spectral peak position across the wafer increases as the growth temperature decreases. We will describe the detailed results of our CL study of photoemission along with a complimentary study of the structural properties by SEM and AFM to elucidate the issues in growing high quality InGaN quantum wells.

10:10 AM

Structural and Optical Properties of AlInN and AlGaInN on GaN Grown by Metalorganic Vapor Phase Epitaxy: SHIGEO YAMAGUCHI[1]; Michihiko Kariya[1]; Shugo Nitta[1]; Hisaki Kato[1]; Tetsuya Takeuchi[1]; Christian Wetzel[1]; Hiroshi Amano[1]; Isamu Akasaki[1]; [1]Meijo University, Dept. of Electrical and Electronic Engineering, Tempaku-ku, Shiogamaguchi, 1-501, Nagoya, Aichi 468 Japan

We report the study of structural and optical properties of AlInN and AlGaInN nitride semiconductors. We have recently, for the first time, observed photoluminescence from AlInN. AlInN and AlGaInN have attracted a small amount of attention compared to GaInN and AlGaN in spite of the fact that those mixed crystals have the possibility of, e.g., lattice-matched cladding layer to GaN and GaInN. This is mainly because of the difficulty in growth. We have grown AlInN and AlGaInN epitaxial films on GaN with the low-temperature deposited AlN buffer layer by metalorganic vapor phase epitaxy. X-ray diffraction, absorption and photoluminescence measurements have shown that AlInN and AlGaInN films are not in the phase separation and constituted in the wurtzite structure and that the luminescence and absorption spectra in AlInN and AlGaInN peak around 480 to 650nm with InN molar fraction of 0.19 to 0.44.

10:30 AM Break

11:00 AM

Step-Flow MOVPE of GaN on SiC Substrate: TOSHIO NISHIDA[1]; Tetsuya Akasaka[1]; Masami Kumagai[1]; Hiroaki Ando[1]; Naoki Kobayashi[1]; [1]NTT Basic Research Laboratories, Material Science Research Laboratory, 3-1, Morinosato Wakamiya, Atsugi-shi, Kanagawa Pref. 243-0198 Japan

Step-flow MOVPE of GaN on SiC substrates is confirmed by AFM observation. Compared to the growth on sapphire substrates, there are no spiral steps and no 2D nuclei within 10-micron-square area, showing step-flow mode is dominant. The surface mostly consists of 140-nm-wide atomic terraces and 0.5-nm-high doubly stacked monolayers (DSM). This DSM dissolves into a pair of monolayers at the adjacent {11-20} DSM steps, due to the asymmetry between these two monolayers. By the homogeneity of step-flow growth, FWHMs of about 100 arcsec in X-ray locking curve and sharp photoluminescence (FWHM:20 meV) from 1-nm-thick GaN/$Al_{0.15}Ga_{0.85}N$ quantum well are obtained. We also found, in finite area selective epitaxy (FAE), steps originate from a single 2D nucleus, which shows heterointerface flatness will be drastically improved by the combination of SiC substrates and FAE.

11:20 AM

Selective Area MOCVD Growth of GaN on Sapphire and Silicon Substrate Using Oxidized AlAs as a Mask: NOBUHIKO P. KOBAYASHI[1]; Junko T. Kobayashi[1]; Won-Jin Choi[1]; P. Daniel Dapkus[2]; [1]Compound Semiconductor Laboratory, Department of Materials Science and Engineering, Unversity of Southern California, 3651 Watt Way, VHE 313, MC 0241, Los Angeles, CA 90089-0241 USA; [2]Compound Semiconductor Labaratory, Dapartment of Electrical Engineering and Materials Science, University of Southern California, 504 Powell Hall, Los Angeles, CA 90089-0271 USA

We present a novel and flexible approach for selective area growth of GaN by MOCVD using oxidized AlAs (AlOx) as a growth mask. In this, we take advantage of its chemical and mechanical compatibility with sapphire and silicon substrates. The most significant feature of this approach is that it allows us to carry out either positive selective area growth on Si substrates, i.e., the growth takes place on the area covered with a mask, or negative selective area growth on sapphire substrates, i.e. the growth takes place on the area not covered with a mask, depending on the competitive reactions that occur on the AlOx mask and the substrate. Selectively grown GaN using an AlOx mask is examined in terms of growth morphologies, structural properties and optical properties.

11:40 AM

Growth Mechanisms and Extended Defect Reduction in Lateral Epitaxial Overgrowth of Gallium Nitride by Metalorganic Chemical Vapor Deposition: H. MARCHAND[1]; J. P. Ibbetson[1]; P. Fini[2]; P. Kozodoy[1]; X. H. Wu[2]; S. Keller[1]; S. P. DenBaars[2]; J. S. Speck[2]; U. K. Mishra[1]; [1]University of California, Electrical and Computer Engineering Dept., Santa Barbara, California 93106 USA; [2]University of California, Materials Department, Santa Barbara, CA 93106 USA

Lateral epitaxial overgrowth is a very promising technique to reduce the density of extended defects in gallium nitride films, which should be beneficial for both electronic and optoelectronic devices. We have grown GaN on 2"-diameter SiO_2-patterned GaN/Al_2O_3 substrates by LP-MOVPE using a close-space vertical reactor. Patterns consisted of 5-10 µm-wide stripes with a 0.01-0.5 fill factor (ratio of stripe width to pattern period). The overgrown material in high fill factor patterns has a rectangular shape with a flat top surface and vertical sidewalls, while the low fill-factor (<0.1) patterns result in inclined sidewalls. The width of the overgrowth is inversely proportional to the fill factor for a constant stripe width. The highest fill factor patterns are essentially coalesced after only 30 minutes of growth. Preliminary microscopy studies show that no dislocations reach the surface of the overgrown material on 2 µm by 2 µm areas, which places an upper limit of 10^7 cm^{-2} for the dislocation density, compared to $5x10^8$ cm^{-2} for bulk GaN. Structural, optical, and electrical properties of the overgrown material are discussed in relation to the growth parameters.

12:00 PM

Selective-Area and Lateral Epitaxial Overgrowth of III-N Materials by Metalorganic Chemical Vapor Deposition : RUSSELL D.

DUPUIS[1]; Joongseo Park[1]; Paul A. Grudowski[1]; Christopher J. Eiting[1]; Zuzanna Liliental-Weber[2]; [1]The University of Texas at Austin, Microelectronics Research Center, PRC/MER 1.606D-R9900, Austin, TX 78712-1100 USA; [2]Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, CA 94720 USA

The characteristics of GaN films obtained by lateral epitaxial overgrowth (LEO) using metalorganic chemical vapor deposition (MOCVD) are described. The layers are deposited on thin GaN "substrate" films that have been grown on (0001) sapphire substrates. The surface kinetics of the MOCVD process result in lateral growth of single-crystal GaN over the mask. The lateral-to-vertical relative growth rate depends upon the orientation of stripe openings, the ratio of the "open" stripe width to the ?masked? stripe width, and the growth conditions (growth rate, temperature and V/III ratio). The specific orientations of the facets on the sidewalls of the laterally growing stripes are also dependent upon the growth conditions. We describe the dependence of the lateral growth rate on the growth conditions and the masked-to-open ratio. The morphology and luminescence intensity of the GaN layers indicate that improved materials are grown over the oxide mask. TEM analysis confirms no threading dislocations are present in this material.

Monday PM - June 1, 1998

Growth and Doping Mechanisms

Monday PM — Room: Grand Ballroom A & B
June 1, 1998 — Location: Sheraton Grande Torrey Pines

Session Chairs: K. Gaskill, Naval Research Laboratory, Washington, DC 20375 USA; S. Minigawa, Samsung Electro-Mechanics Co., Ltd., Suwon, Kyungki, Korea 442-743

2:00 PM

Annealing Effect on C-Doped InGaAs Grown by Metalorganic Chemical Vapor Deposition: NORIYUKI WATANABE[1]; Sarin Kumar[1]; Shoji Yamahata[1]; Takashi Kobayashi[1]; [1]NTT, System Electronics Laboratories, 3-1, Morinosato Wakamiya, Atsugi, Kanagawa 243-01 Japan

When C-doped InGaAs is used as the base layer of InP/InGaAs HBTs, it is important to remove hydrogen atoms by thermal treatment in inactive gas because they deactivate C acceptors. We systematically study the annealing effect and discuss the hydrogen removal mechanism and thermal stability of C-doped InGaAs. Hydrogen concentration exponentially decreases with increasing annealing time at temperatures below 500ϒC, resulting in an increase in hole concentration. The activation energy for hydrogen elimination is nearly equal to the reported value for the C-H dissociation energy. This indicates that the hydrogen removal process is governed by the dissociation of C-H bonds. On the contrary, at 550ϒC, hole concentration and photoluminescence intensity decrease by over-5-minute annealing even though hydrogen atoms are completely removed. These results indicate that thermal treatment at higher temperature (⊕550ϒC) deteriorates both the electrical and optical quality of C-doped InGaAs, possibly due to point defect reaction with carbon at arsenic sites.

2:20 PM

Si and C Delta-Doping for Device Applications: G. LI[1]; M. B. Johnston[2]; A. Babinski[1]; S. Yuan[1]; M. Gal[2]; S. J. Chua[3]; C. Jagadish[1]; [1]MOCVD, Department of Electronic Materials Engineering, Australian National University, Canberra, ACT 0200 Australia; [2]Department of Physics, School of Physics, The University of New South Wales, Sydney, NSW 2052 Australia; [3]Opto-electronics and Photonics, Institute of Materials Research and Engineering, 10 Kent Ridge Crescent, Singapore 119 260

Controllable n-type and p-type doping is of great importance to fabrication of electronic and opto-electronic devices. The most widely used dopants in (Al,Ga)As grown by MOVPE are Si for n-type and Zn or C for p-type. In order to obtain a high Si doping concentration, 700^C or an even higher growth temperature is normally required, while a low growth temperature is essential to achieve a high p-type doping concentration. In this work, we report the growth conditions at one moderate temperature of 630°C for very high dopant densities of both Si and C delta-doped layers in (Al,Ga)As. Using the optimised growth conditions, very high free carrier densities up to 6e18 and 3e19 cm^(-3), respectively for Si and C delta-doped (Al,Ga)As, were obtained. The key parameters to achieve high doping concentrations and the mechanism responsible for the control of impurity incorporation during delta-doping will be discussed. High quality Si and C delta-doped nipi structures, Si delta-modulation doped In0.2Ga0.8As/GaAs quantum wells, and high performance Zn-free C delta-doped In0.2Ga0.8As/GaAs GRINSCH lasers will be demonstrated to verify those MOVPE-grown delta-doped layers in (Al,Ga)As.

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Si-Doping in GaAs Grown by Metalorganic Vapor Phase Epitaxy Using Bisdiisopropylaminosilane: HIROSATO OCHIMIZU[1]; Hitoshi Tanaka[1]; [1]FUJITSU LABORATORIES LTD., Compound Semiconductor LSIs Laboratory, 10-1 Morinosato-Wakamiya, Atsugi, Kanagawa 243-0197 Japan

We have developed a well-controlled Si doping process in GaAs epilayers using bisdiisopropylaminosilane ($Si[N(i\text{-}C_3H_7)_2]_2H_2$) by MOVPE. Disilane, a commonly used Si source, shows a large growth temperature dependence in doping characteristics with lowering the reactor pressure and increasing the gas-flow velocity. Based on the deliberate consideration of the source material chemistry, we have employed a much reactive aminosilane and have obtained very small temperature dependence in doping characteristics. For disilane, carrier concentration exhibits a marked temperature dependence with an activation energy of 1.4 eV between 570 ϒC and 730 ϒC. The reactor pressure was kept at 80 mbar. For aminosilane, it is slightly dependent on the growth temperature with an activation energy of 0.1 eV. This improvement is very significant for better uniformity and reproducibility of the epitaxial layers. The aminosilane is a preferable Si doping source in GaAs.

3:00 PM

Modeling Study of Silicon Incorporation from $SiBr_4$In GaAs Layers Grown by Chemical Beam Epitaxy: BIN Q. SHI[1]; Charles W. Tu[1]; [1]University of California, San Diego, Dept. of Electrical and Computer Engineering, La Jolla, CA 92093-0407 USA

We report here a modeling study of silicon tetrabromide ($SiBr_4$) doping of GaAs in a chemical beam epitaxy (CBE) setup with triethylgallium (TEGa) and tris(dimethylamino) arsine (TDMAAs) as group-III and group-V precursors. This study utilizes the numerical model we developed for CBE growth of GaAs with TEGa and TDMAAs. With a proper combination of reaction mechanisms derived from surface-science desorption studies, the growth model enables us to predict well the growth rate without adjustable parameters. We assume that silicon incorporation is limited by the rate of $SiBr_4$ chemisorption onto the growth surface and use the surface coverage and growth rate output by the growth model to calculate the doping concentration. The calculation leads us to postulate that the high doping efficiency of $SiBr_4$ may also be owing to its high trapping probability resulted from its very large molecular weight.

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Oxygen Related Defects in $In_{0.5}(Al_xGa_{1-x})_{0.5}P$ Quaternary Alloys Grown by MOVPE: J. G. CEDERBERG[1]; B. Bieg[1]; J.- W. Huang[2]; M. J. Peanasky[2]; S. A. Stockman[2]; T. F. Kuech[1]; [1]University of Wisconsin, Department of Chemical Engineering, 1415 Engineering Dr., Madison, WI 53706 USA ; [2]Hewlett-Packard, Optoelectronics Division, 370 West Trimble Road, San Jose, CA 95131 USA

$In_{0.5}(Al_xGa_{1-x})_{0.5}P$ is an attractive material for the manufacture of high brightness LEDs and other light emitting devices. Unfortunately, this alloy suffers from unintentional oxygen incorporation, reducing the luminescence efficiency. We have investigated the intentional incorporation of oxygen-related defects into $In_{0.5}(Al_xGa_{1-x})_{0.5}P$, where x was varied from 1 to 0.30, using the oxygen source diethylaluminum ethoxide. This investigation correlated the physical oxygen concentration as determined by Secondary Ion Mass Spectroscopy (SIMS) to defects detected in the upper half of the bandgap by DLTS. Our investigations have associated a level at ~0.9 eV with the oxygen-based defect. We have also identified other deep levels that are most likely native defects intrinsic to the alloy system and exhibit a DLTS emission spectrum that is dependent on the thermal and electrical conditions applied, leading to hysteretic effects in the emission spectrum. Photoluminescence (PL) measurements show a reduction in the band edge emission with increasing oxygen content in the film with additional luminescence features appearing in the infrared spectral region at 0.99 and 1.19 eV in these samples.

4:00 PM

Growth of Ru Doped Semi-insulating InP by LP-MOCVD: ARMIN DADGAR[1]; Oleg Stenzel[2]; Lutz Koehne[1]; Alexander Naeser[1]; Matthias Strassburg[1]; Wolfgang Stolz[3]; Dieter Bimberg[1]; Herbert Schumann[2]; [1]Technische Universitaet Berlin, Institut fuer Festkoerperphysik, Hardenbergstr. 36, Berlin 10623 Germany; [2]Technische Universitaet Berlin, Institut fuer Anorganische und Analytische Chemie, Str. des 17. Juni 135, Berlin, Berlin 10623 Germany; [3]Phillips Universitaet Marburg, WZMW, Hans-Meerwein-Str., Marburg, Hessen 35032 Germany

Ruthenium doping has been successfully applied for the growth of semi-insulating (s.i.) InP. In contrast to the 3d-transition metal (TM) Fe, the isovalent 4d-TM Ru exhibits a four orders of magnitude lower diffusion coefficient and no interdiffusion with p-type dopants. Additionally Ru compensates electrons as well as holes, a prerequisite for superior compensation under double injection conditions. The growth of Ru doped InP layers has been performed using bis(η^5-2,4-dimethylpentadienyl)ruthenium(II) for Ru doping, different P-precursors (PH_3, TBP, DTBP) and H_2 or N_2 carrier gas. In first experiments a strong dependence of the layer resistivity with the amount of hydrogen present during growth has been observed. It is indicated, that the amount of atomic hydrogen has a larger influence on the electrically active concentration than the carrier gas (H_2 or N_2) since a strong enhancement of the layer resistivity is observed going from PH_3 to TBP and to DTBP.

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Doping Characteristics of n-Type InP Using Phenylsilane and TBP By MOVPE: YOSHINORI YAMAUCHI[1]; Hideaki Horikawa[1]; [1]Oki Electric Industry Co., Ltd., Research & Development Group, 550-5 Higashiasakawa, Hachioji, Tokyo 193 Japan

This paper describes doping characteristics of low-pressure MOVPE-grown n-type InP layers using phenylsilane as an organometallic precursor for the Si in order to realize all organometallic source epitaxy. We have experimentally verified that electron concentrations of Si increased with decreasing the V/III ratio and increasing the growth temperatures. The electron concentraion was proportional to the mole fraction of phenylsilane from $1x10^{17}$ to $2x10^{19}$ cm^{-3} with smooth surfaces. The electron concentration was saturated at $2x10^{19}$ cm^{-3}. The compensation ratios(Na^-/Nd^+) for the samples with the electron concentration below $1x10^{18}$ cm^{-3} were lower than 0.2 and the ratios for the samples with the higher concentrations increased to 0.3, which agreed well with the result of Si doped layers prepared using disilane. Significant memory effects and incorporation were not observed by SIMS measurement. These results show that phenylsilane is a promising replacement for hazardous n-type doping gases of silane and disilane.

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Post-Growth Zn Diffusion into InGaAs/InP in a LP-MOVPE Reactor: NORBERT GROTE[1]; Dieter Franke[1]; Rainer Bochnia[1]; Peter Harde[1]; [1]Heinrich-Hertz-Institut für Nachrichtentechnik Berlin GmbH, Materials Technology, Einsteinufer 37, Berlin 10587 Germany

For high quality non-alloyed p-contacts to InGaAs(P), as involved in InP-based lasers, a p-doping level of as high as 10^{20} cm^{-3} is required which cannot be achieved with epitaxial doping. To this end, we have studied Zn-diffusion into n- and p-type InGaAs/InP layers performed in a LP-MOVPE reactor immediately following epitaxial growth. DMZn was used as Zn precursor. The influence of diffusion temperature, DMZn partial pressure and total pressure (< 300 mbar) on the diffusion behaviour was investigated. An inverse temperature dependence of the maximum doping level and diffusion depth was obtained. The achievement of p-concentrations above 10^{20} cm^{-3} by this process has been demonstrated for the first time. From SIMS measurements a high Zn-activation coefficient in InGaAs was deduced. Because of the use of a rotating substrate holder an excellent uniformity of the diffused layer was obtained, as judged from the sheet resistance, which exhibits a standard deviation of only 4% over a 2" wafer. Post-growth surface diffused laser structres were fabricated. Furthermore, results on selective diffusion will be reported.

5:00 PM

Zinc Doping of InP by Metal Organic Vapour Phase Diffusion (MOVPD): A. VAN GEELEN[1]; T. de Smet[1]; T. van Dongen[1]; E. van Gils[1]; [1]Philips Research Laboratories Eindhoven, WZpl.65, AA Eindhoven 5656 The Netherlands

High p-doping of InP is desirable for buried heterostructure lasers and photodiodes.The maximum hole concentration in zinc doped InP grown by MOVPE is limited to 3xl0^l8 cm-3. On the other hand, the zinc ampoule diffusion process suffers from poor reproducibility and surface morphology. Diffusion of zinc in InP was carried out in a multi wafer MOVPE reactor. DEZn was used as a precursor. Diffusion temperature, DEEn concentration and diffusion time were optimised to obtain a high hole concentration. In situ annealing was used to activate the zinc. The maximum hole concentration obtained with zinc MOVPD is 5xl0^l8 cm-3. A specular surface is achieved for all zinc concentrations up to 2xl0^l9 cm-3. The zinc diffusion depth can be controlled reproducibly from 0.3 to over 3 5m. Depth and doping uniformity over a two inch wafer are comparable to MOVPE growth. Excellent results for InP/lnGaAs photodiodes were obtained by local zinc MOVPD on a two inch wafer. Finally, a model for the MOVPD process will be presented.

Surface Physics and Chemistry During Growth

Monday PM — Room: Grand Ballroom D & E
June 1, 1998 — Location: Sheraton Grande Torrey Pines

Session Chairs: D. Dapkus, University of Southern California, Los Angeles, CA 90089-0271; N. Mason, University of Oxford, Oxford Oxfordshire OX1 3PU UK

2:00 PM

Surface Phases and Chemistry of GaAs MOVPE: J. RANDALL CREIGHTON[1]; Harry K Moffat[1]; Kevin C Baucom[1]; [1]Sandia National Laboratories, Dept. 1126, PO Box 5800, MS-0601, Albuquerque, NM 87185-0601 USA

We have used reflectance-difference spectroscopy (RDS) and differential reflectometry (DR) on our research rotating disk reactor to explore the surface phases of GaAs(001) for a wide variety of operating conditions. Results of these in-situ optical measurements were interpreted with the aid of benchmarking work in our UHV surface science machine. Reflectometry was also used to measure the deposition rate with high precision, again over a wide range of conditions. We used the surface phase information and the growth rate measurements to formulate a chemical mechanism of GaAs MOVPE that reproduces all of the observed trends, most of them quantitatively. One interesting kinetic regime occurs at lower temperatures and /or higher trimethylgallium (TMGa) concentration. For these conditions the growth rate is highly activated (~34 kcal/mole) and exhibits a sublinear dependence with respect to the TMGa partial pressure. In this kinetic regime the surface exhibits the Type III RDS lineshape, which is due to a methyl terminated arsenic-rich (1 X 2) reconstruction.

2:20 PM

In-Situ Analysis of the Homoepitaxy on GaAs (113) and (115) Surfaces: MARKUS PRISTOVSEK[1]; Housni Menhal[1]; Torsten Schmidtling[1]; Jörg-Thomas Zettler[1]; Wolfgang Richter[1]; Carsten Setzer[2]; Jutta Platen[2]; Karl Jacobi[2]; [1]Technische Universität Berlin, Institut für Festkörperphysik, PN6-1, Hardenbergstr. 36, Berlin D-10623 Germany; [2]Fritz-Haber-Institut der Max-Planck-Gesellschaft, Faradayweg 4-6, Berlin, Berlin D-14195 Germany

The growth on high-index surfaces becomes increasingly important for understanding the formation of nanostructures like facets in V-grooves or quantuum dots. Especially for the GaAs (113), (-1-1-3), (115), and (-1-1-5) surfaces there is still a lack of information. Therefore, we studied these surfaces, applying RAS (reflectance anisotropy spectroscopy) and LEED in MOVPE and MBE. All surfaces exhibit at least two reconstructions: an arsenic-rich and an arsenic-deficient. They were identified by their RAS spectra and for some also by LEED. The activation energies and the reaction orders for the change between the reconstructions were determined by fitting RAS transients obtained during arsenic desorption at different temperatures. These fits and the spectra taken during growth were compared to results of GaAs (001) in order to reveal how the high-index surfaces influence the chemistry and the growth process. Possible consequences and advantages for growing on these surfaces are discussed.

2:40 PM

Simulation of Surface Morphology During OMVPE GaAs Growth: RAJESH VENKATARAMANI[1]; Klavs Jensen[1]; G. B. Stephenson[2]; D. W. Kisker[3]; P. Fuoss[4]; S. Brennan[5]; [1]MIT, Chemical Engineering, 66-501, 25 Ames St., Cambridge, MA 02139 USA; [2]Argonne National Laboratories; [3]IBM; [4]Lucent Technologies; [5]Stanford

Models describing the OMVPE process are developed in order to understand the coupling between gas phase and surface processes. Finite element simulations for modeling the gas phase in OMVPE reactors have been linked to Kinetic Monte Carlo (KMC) simulations of the evolving surface morphology. This coupling allows the examination of how changes in process parameters affect surface morphology. Kinetic mechanisms for both the gas phase and surface are developed for the growth of GaAs from a variety of precursors (TMG, TEG, AsH3, TBAs, TMAs). The models are validated through direct comparison to experimental X-ray scattering studies. Diffuse scattering from the X-ray studies is used as an in-situ probe for monitoring the evolving surface morphology. The KMC simulations are used as a tool to determine the surface mechanisms for the growth of GaAs, which can be contrasted to growth in MBE systems. The developed mechanisms are then used in order to predict surface morphology during doped GaAs growth.

3:00 PM

Mechanisms of Self-Ordering of Nanostructures in Nonplanar OMCVD Growth: GIORGIO BIASIOL[1]; François Lelarge[1]; Klaus Leifer[1]; Eli Kapon[1]; [1]Ecole Polytechnique Fédérale de Lausanne, DP-IMO, EPFL, PH-Ecublens, Lausanne, VD 1015 Switzerland

Despite the wide use of OMCVD on V-grooves in semiconductor quantum wire (QWR) fabrication, the physics of self-limiting growth at the bottom of the grooves is still unknown. We have developed an analytical model that explains quantitatively this self-limiting growth, which results from an equilibrium between the effects of growth rate anisotropy on the different planes composing the groove (that tend to sharpen it) and of adatom migration towards the bottom, due to curvature-related chemical potential differences (that tend to broaden it). During ternary growth, mixing entropy effects add to the curvature-related ones, influencing the self-limiting shape. Monte Carlo simulations confirm this diffusion model, evidencing the importance of orientation-dependent incorporation rates in different growth techniques. Predictions of this model are used to design novel low-dimensionality confined structures, such as vertical quantum wells, QWR superlattices and vertical arrays of quantum dots on inverted pyramids. Comparison with experimental results will be presented and discussed.

3:20 PM Break

3:40 PM

Time-Resolved Reflectance Difference Spectroscopy of InAs and InP Growth Under Alternating Flow Conditions: SIMON P. WATKINS[1]; Richard A. Arès[2]; Jinsheng Hu[1]; [1]Simon Fraser University, Department of Physics, Simon Fraser University, Burnaby, British Columbia V5A 1S6 Canada; [2]Nortel Ltd., Nortel Ltd., Ottawa, Ontario Canada

We report a time-resolved reflectance difference spectroscopy (RDS) study of the growth of InAs and InP during alternating flow conditions typical of atomic layer epitaxy (ALE). The precursors used were trimethylindium (TMI), tertiarybutylarsine (TBA) and tertiarybutylphosphine (TBP). For ALE growth we observe that the InAs surface remains As-rich for an appreciable fraction of the 1 monolayer TMI pulse. This is similar to results obtained for the growth of GaAs by ALE using trimethylgallium. Three distinct RDS spectra are observed, two corresponding to As-rich phases, and one which is In-rich. In both InAs and GaAs the extra As layer appears to play a key role in maintaining self-limiting behaviour. In contrast, under alternating flow conditions, our RDS data indicate no evidence for a double layer of P in InP using TMI and TBP. We propose that this is closely related to the lack of true self-limiting behaviour for this material.

4:00 PM

In-Situ Monitoring and Control of InGaP Growth on GaAs in MOVPE: MARTIN ZORN[1]; Thomas Trepk[1]; Paul Kurpas[2]; Jörg-Thomas Zettler[1]; Arne Knauer[2]; Markus Weyers[2]; Wolfgang Richter[1]; [1]Technical University of Berlin, Solid State Physics, PN 6-1, Hardenbergstr. 36, Berlin D-10623 Germany; [2]Ferdinand-Braun-Institut für Höchstfrequenztechnik, Rudower Chaussee 5, Berlin D-12489 Germany

In order to control the growth of lattice matched InGaP on GaAs we applied in-situ reflectance anisotropy spectroscopy (RAS) and spectroscopic ellipsometry (SE). In the InGaAs on InP material system feedback controlled MOVPE growth of lattice matched InGaAs has been demonstrated recently [1]. For InGaP on GaAs the effect of ordering has to be taken into account additionally. Therefore, first the dependence of the optical data of InGaP on composition, ordering and temperature was determined. Differently ordered InGaP layers have been grown by varying growth parameters like temperature, substrate off-orientation, V/III-ratio and doping level. With these data an optimized photon-energy for feed-back controlled growth of lattice matched InGaP on GaAs is determined, where the correlation between ordering and composition contribution to the optical data is at a minimum. At these conditions a significant shift of the real-time optical data with InGaP composition was found. [1] Proc. 7th European Workshop on Metal-Organic Vapour Phase Epitaxy and Related Growth Techniques, June 1997, Berlin, Germany, G-7

4:20 PM

Effect of Dopants on Surface Structure and Ordering in GaInPHi: S. H. Lee[1]; T. C. Hsu[1]; GERALD B. STRINGFELLOW[1]; [1]University of Utah, Department of Materials Science, 304 EMRO, Salt Lake City, UT 84112 USA

High doping levels inhibit the formation of the CuPt structure during OMVPE growth of GaInP. The mechanism is unknown. The thermodynamic driving force for ordering is due to the 2xn surface reconstruction. In addition, kinetic factors relating to surface steps are important. In this paper Te (EDTe) at a concentration of 1018 cm-3 is demonstrated to completely eliminate ordering. Simultaneouly, the step structure changes dramatically: step bunching is eliminated for vicinal substrates and the spacing of [-110] steps on singular (001) substrates increases by 20X. The surface photoabsorption spectrum is unchanged, indicating no change in the surface reconstruction. The effect of Te is entirely due to an increase in the adatom sticking at steps, which produces the increase in velocity and the elimination of ordering. A qualitative model is suggested.

4:40 PM

The Atomic Structure of Strained $In_xGa_{1-x}As$/GaAs(001) Surfaces: L. LI[1]; B. -K. Han[1]; Q. Fu[1]; D. C. Law[1]; H. Yoon[1]; M. S. Goorsky[1];

R. F. Hicks[1]; [1]University of California, Chemical Engineering and Materials Science Departments, 405 Hilgard Ave., Los Angeles, CA 90095-1592, USA

Strained films of $In_xGa_{1-x}As$ (0.01<x<0.10) were grown on GaAs (001) by MOVPE. The film composition and strain were determined by high-resolution x-ray diffraction. The morphology and atomic structure of the film surfaces were characterized by x-ray photoemission, vibrational spectroscopy, and scanning tunneling microscopy. All the surfaces following MOVPE are composed of atomically flat terraces that are separated by double-height steps. Close-up images of the terraces reveal that they are disordered, consisting of a random mixture of arsenic dimers and alkyl groups adsorbed on an As layer. Annealing in vacuum desorbs the alkyl groups and then the arsenic, generating a variety of new reconstructions, including (2x3), (3x2) and other (nx2) unit cells, where n is an odd integer. Detailed characterization of these structures indicates that they are most likely charged, unlike neutral, unstrained GaAs (001). The structure and electronic properties of the strained film surfaces will be described.

5:00 PM

Self-Limiting Effects of Flow Rate Modulation Epitaxy of GaAs on Patterned Substrate: XUE-LUN WANG[1]; Mutsuo Ogura[1]; Hirofumi Matsuhata[1]; [1]Electrotechnical Laboratory and Japan Science and Technology Corporation, Electron Devices Division, 1-1-4 Umezono, Tsukuba, Ibaraki 305 Japan

We report a novel self-limiting effect of epitaxial growth observed during Flow Rate Modulation Eiptaxy (FME) of GaAs on V-grooved substrate. The growth rate of GaAs at the center of V-groove bottom per FME cycle was found not to increase linearly with the increase of TEGa flow rate, but to be composed of several regions in which the QWR growth stops automatically independent of TEGa flow rate (self-limited) in the growth rate range of 0.6-1.4 ML/cycle. The TEGa flow rate range of these self-limited growth regions becomes to be wider and the growth rate difference between adjacent regions becomes to be larger with increasing QWR growth rate. This is a new self-limiting effect different from that used in the conventional atomic layer epitaxy. A mechanism for this new self-limited growth is proposed based on the change of Ga migration length at V-groove bottom and was investigated experimentally. This new growth technique can be used to fabricate quantum wire and quantum dot structures with size uniformity at an atomic level.

Tuesday AM - June 2, 1998

Plenary Session

Tuesday AM — Room: Grand Ballroom D & E
June 2, 1998 — Location: Sheraton Grande Torrey Pines

Session Chairs: R. Bhat, Corning, NVC 3Z-203, Red Bank, NJ 07701 USA; K. Jensen, Massachusetts Institute of Technology, Dept. of Chemical Engineering, Cambridge, MA 02139 USA

8:20 AM INVITED PAPER

Resonant Self-Organization for Semiconductor Nanostructures: J. TEMMYO[1]; E. Kuramochi[1]; H. Kamada; T. Tamamura[1]; [1]NTT Optoelectronics Laboratories, 3-1 Morinosato-Wakamiya, Atsugi, Kanagawa 243-0198 Japan; NTT Basic Research Laboratories, 3-1 Morinosato-Wakamiya, Atsugi, Kanagawa 243-0198 Japan

Self-processes in crystal growth have been given much attention for fabricating nanostructures. The term "self-process" includes the concpets of self-assembly and self-organization. After Lehn-s definition, self-organization, which indicates an "ordered self-assembly", involves the interaction and integration leading to collective behavior, such as is found in the generation of spatial waves. InAs self-assembled, Stranski-Krastanow islands have been studied during the last few years again. However, we found, in a strained InGaAs/AlGaAs system on a GaAs (311)B substrate during MOVPE growth, a novel phenomenon leading to the formation of well-ordered arrays of nanocrystals with built-in InGaAs quantum disks. The surface rearrangement process resulting in the various quasi-periodic nanopatterns seems to belong to a non-linear Turing-type self-organization phenomenon. We will discuss some semiconductor nanostructures, emphasizing a resonant self-organization for uniform quantum-confined structures.

8:50 AM INVITED PAPER

OMVPE Growth of GaInAsSb/AlGaAsSb Heterostructures for Thermophotovoltaics: CHRISTINE A. WANG[1]; Douglas C. Oakley[1]; Hong K. Choi[1]; Gregory W. Charache[2]; [1]MIT Lincoln Laboratory, Electro-optical Materials and Devices, 244 Wood Street, Lexington, MA 02173 USA; [2]Lockheed Martin Corporation, 2401 River Road, Schenectady, NY 12301 USA

The III-V antimonide-based alloys are useful materials for optoelectronic devices that operate in the mid-infrared. Growth of these alloys for high-performance devices has been dominated by molecular beam epitaxy (MBE) because OMVPE technology is comparatively immature. Recently, however, OMVPE-grown epilayers with improved quality were reported as a result of further developments in alternative organometallic precursors. In this paper, we demonstrate that OMVPE is especially suitable for GaSb/GaInAsSb/AlGaAsSb thermophotovoltaic devices because of the high growth rates that can be achieved. Since the GaInAsSb epilayer thickness of these devices is ~5 µm, the growth time is significant for MBE with typical growth rates of 1 µm/hr. Here, we report the OMVPE growth of GaInAsSb, with cutoff wavelengths in the range between 2 to 2.4 µm, from trimethlyindium, triethylgallium, tertiarybutylarsine, and trimethylantimony. In particular, the effects of alloy composition, temperature, and growth rate on material quality are investigated. The electrical and optical properties are similar to those reported for MBE-grown GaInAsSb layers, and no degradation in properties is observed for layers grown at rates as high as 5 µm/hr. GaSb/GaInAsSb/AlGaAsSb heterostructures exhibit the highest external quantum efficiency and open circuit voltages reported to date for thermophotovoltaic devices at 2.3 µm.

9:20 AM Break into Parallel Sessions

Low Dimensional Structures

Tuesday AM — Room: Grand Ballroom A & B
June 2, 1998 — Location: Sheraton Grande Torrey Pines

Session Chairs: R. Bhat, Corning, Red Bank, NJ 07701 USA; J. Temmyo, NTT Opto-electronics Laboratories, Kanagawa 243-0198 Japan

9:30 AM

Size Control of Self-Assembled InP/GaInP Quantum Islands: JÖRG PORSCHE[1]; Andreas Ruf[1]; Michael Geiger[1]; Ferdinand Scholz[1]; [1]Universität Stuttgart, 4. Physikalisches Institut, Pfaffenwaldring 57, 70569 Stuttgart, Baden-Württemberg Germany

Two types of coherently strained InP-islands were found for the self-organized MOVPE growth of InP on Ga0.51In0.49P. This is in contrast to the well examined InAs/GaAs system. The existence of two classes can be explained by the fact that the larger islands (h=20nm) are energetically favorable whereas the smaller islands (h=5nm) represent the initial non-equilibrium state. Further increase of the size of the larger islands is suppressed by an energy barrier which can be explained by an activation energy for the onset of dislocation formation. The amount of smaller islands was increased for growth conditions with reduced surface diffusion, i. e. low growth temperatures or high growth rates. It is also shown that beside the growth parameters the orientation of the substrate played an important role in the control of the island size. For substrates with high misorientation combined with low growth temperatures we were able to suppress the formation of the larger islands. AFM- and PL-measurements were used to demonstrate this behavior.

9:50 AM

Fabrication of InGaAsP/InP Quantum Dots by Using Self-Organized InAs Islands as Stressors: REKO RANTAMAKI[1]; [1]Helsinki University of Technology, Optoelectronics Laboratory, Otakaari 7A, Espoo, Otaniemi FIN-02150 Finland

Growth parameters, such as temperature, nominal thickness and deposition rate are varied to study the self-organized growth of InAs islands on (100) InP by MOVPE. Growth is performed at atmospheric pressure using TBA and TBP. The unintentional As/P exchange reaction is found to play an important role in the island formation. At 500°C with a deposition rate of 1.1ML/s and nominal layer thickness of 2ML a high density of rather uniform 10nm high InAs islands are obtained. Lateral confinement of carriers in a near-surface InGaAs(P)/InP QW is obtained due to the strain field produced by the optimized InAs islands on the surface. Photoluminescence measurement yields a 40meV deep strain-induced potential. The 25meV wide quantum dot peak is significantly narrower than obtained from InAs islands capped by InP. With this stressor structure a wide quantum dot wavelength range of 1-2µm can be covered.

10:10 AM

High Quality InAs/GaAs Quantum Dots Grown By LP-MOVPE: ISABELLE SAGNES[1]; Bruno Gayral[1]; Isabelle Prevot[1]; Guy Le Roux[1]; Jean Michel Gerard[1]; [1]France Telecom - CNET, DTD/MCM, 196, Avenue Henri Ravera, BP 107, Bagneux, Cedex 92225 France

Room temperature quantum dots (QDs) laser performances, which is known to be limited by carrier photoemission, could be increased by using AlGaAs barriers, larger than the usual GaAs ones. Thanks to its higher QDs growth temperature range, the MOVPE technique allows, contrarily to MBE, the obtention of AlGaAs barriers with good optical properties. In a first step towards the fabrication of room temperature QDs lasers, we report on the successful fabrication of LP-MOVPE InAs QDs with either GaAs or AlGaAs barriers. The influence of growth temperature, V/III ratio and Al content on QDs growth rate, size distribution and density will be discussed. The 2D-3D transition is observed by both high resolution X-ray diffraction and photoluminescence measurements at room and low temperature. In a second step, optimised InAs QDs have been introduced in a high finesse GaAs/AlAs microcavity. This structure shows promising optical emission properties which will be presented.

10:30 AM Break

11:00 AM

GaAs Cap Layer Growth and In-Segregation Effects on Self-Assembled InAs-Quantum Dots Monitored by Optical Techniques: ELISABETH STEIMETZ[1]; Timon Wehnert[1]; Kolja Haberland[1]; Jörg Thomas Zettler[1]; Wolfgang Richter[1]; [1]TU Berlin, Inst. für Festkörperphysik, Hardenbergstr. 36, Berlin 10623 Germany

The real-time monitoring of Quantum Dot (QD) formation in Stranski-Krastanov growth mode by Reflectance Anisotropy Spectroscopy (RAS) and Spectroscopic Ellipsometry (SE) in MOVPE allows the determination of the growth mode transition and the evolution of uncovered InAs- islands after growth[1]. A very important step for QD device fabrication is the overgrowth by a GaAs cap. Temperature dependent Indium segregation effects during cap layer growth and post growth annealing have been monitored already in-situ in MBE [2] and ex-situ via TEM [3]. The suppression of Indium segregation during cap layer growth is one remaining challenge for a routinely InAs-QD-based laser production. We have investigated the influence of different growth conditions (temperature, growth rate and total pressure) on segregation and intermixing with the GaAs cap during growth. Post growth annealing of samples with different cap layer thicknesses allowed us to determine the minimum cap layer thickness to avoid In-segregation. Finally, the influence of the overgrowth procedure on the optical quality (PL, PR) and will be discussed. [1] E. Steimetz, F. Schienle, J.-T. Zettler, W. Richter, J. Cryst. Growth 170 (1997), 208-214 [2] M. Muraki, S. Fukatsu, Y. Shiraki, R. Ito, Appl. Phys. Lett. 6 1(1992) 557-559[3] U. Woggon, W. Langbein, J. M. Hvam, A. Rosenauer, T. Remmele, D. Gerthsen Appl. Phys. Lett. 71(1997) 377-379

11:20 AM

Influence of In Segregation and In-Ga Intermixing on In(Ga)As Quantum Dot Formation: FRANK HEINRICHSDORFF[1]; Alois Krost[1]; Marius Grundmann[1]; Oliver Stier[1]; Dieter Bimberg[1]; Alexander O. Kosogov[2]; Peter Werner[2]; [1]Technische Universität Berlin, Institut für Festkörperphysik, Sekr. PN 5-2, Hardenbergstr.36, Berlin 10623 Germany; [2]Max-Planck-Institut für Mikrostrukturphysik, Weinberg 2, Halle 06120 Germany

The influence of In segregation and In-Ga intermixing on MOCVD grown InGaAs quantum dots (QDs) is studied. Depending on the growth parameters and the layer thickness two distinct types of QDs, which coexist without Ostwald ripening, can be fabricated. Low density, high QDs (h= 6 - 8 nm) with an emission wavelength of ⊕ 1.3 µm are formed under conditions of strong In segregation and enhanced surface diffusion, whereas high density flat QDs (h= 2 - 4 nm) with an emission wavelength of 1.1 µm are found if In segregation and surface diffusion are suppressed. Intermixing of QDs and surrounding barriers is observed upon thermal annealing of QDs and during growth interruptions if the QDs are covered with thin InGaAs layers. The In-Ga intermixing results in a reduction of the QDs in homogenous broadening, sublevel separation, emission wavelength and carrier localization energy, in agreement with a simple diffusion model.

11:40 AM

Size Reduction of Self Assembled Quantum Dots by Annealing: JONAS JOHANSSON[1]; Werner Seifert[1]; Valery Zwiller[1]; Tobias Junno[1]; Lars Samuelson[1]; [1]Division of Solid State Physics, Lund University, Box 118, Lund 221 00 Sweden

Quantum dots in the materials systems InP/GaAs and InP/$Ga_{0.5}In_{0.5}P$ were grown at 600 °C by low pressure MOVPE in the Stranski-Krastanow growth mode and annealed under PH_3/H_2 at growth temperature. AFM investigations of freestanding islands (InP/GaAs) show a continuous decrease in height from 19 to 7 nm after 30 min annealing. No changes in the island density were observed except for the small, not fully developed, islands that vanish during the first two minutes of annealing. Photoluminescence measurements on the overgrown dot samples (InP/$Ga_{0.5}In_{0.5}P$) show a shift of the quantum dot emission peak towards higher energies with an increase in annealing time. The proposed explanation relies on exchange reactions between the islands and the wetting layer, as well as alloying between the wetting layer and the underlying substrate due to interdiffusion.

12:00 PM

InGaAs and InAsP V-Groove Quantum Wires Using Arsenic/Phosphorus Exchange Preparation: MICHAEL KAPPELT[1]; Volker Tuerck[1]; Dieter Bimberg[1]; [1]TU Berlin, Inst. f. Festkoerperphysik, Sekr. PN5-2, Hardenbergstr. 36, Berlin D-10623 Germany

For the first time we present results on InGaAs quantum wires (QWRs) in-situ grown in InP V-grooves by MOCVD utilizing arsenic/phosphorus exchange as preparation method. In order to produce an excellent interface for InGaAs deposition in sharp V-grooves with 5nm tip radius we induce the exchange of phosphorus and arsenic by exposing the as-etched InP V-grooves to arsine in the MOCVD chamber. Then nominally 3 nm InGaAs are grown. No buffer layer is used in order to avoid planarization of the grooves. The structures are capped by 50nm InP. The RT peak emission wavelength of the QWRs is found at 1.32um. Spatially resolved cathodoluminescence (CL) experiments show a very homogeneous intensity distribution. Using only the As/P exchange process in the V-grooved InP substrate leads to direct formation of InAsP QWRs as demonstrated by transmission electron microscopy and CL.

Infrared Materials and Devices

Tuesday AM Room: Grand Ballroom D & E
June 2, 1998 Location: Sheraton Grande Torrey Pines

Session Chairs: C. A. Wang, MIT Lincoln Laboratory, Electro-optical Materials and Devices, Lexington, MA 02173 USA; K. F. Jensen, Massachusetts Institute of Technology, Dept. of Chemical Engineering, Cambridge, MA 02139 USA

9:30 AM
Progress in the Growth of Mid-Infrared InAsSb Emitters by Metal-Organic Chemical Vapor Deposition: R. M. BIEFELD[1]; A. A. Allerman[1]; S. R. Kurtz[1]; K. C. Baucom[1]; [1]Sandia National Laboratory, Dept. 1113, PO Box 5800, MS 0601, Albuquerque, NM 87185-0601 USA

Mid-infrared (3-6 µm) lasers and LEDs are being developed for use in chemical sensor systems and infrared countermeasure technologies. These applications require relatively high power, mid-infrared lasers and LEDs operating near room temperature. The radiative performance of mid-infrared emitters has been limited by nonradiative recombination processes (usually Auger recombination) in narrow bandgap semiconductors. Potentially, Auger recombination can be suppressed in band-structure engineered, strained Sb-based heterostructures. We have demonstrated improved performance for midwave infrared emitters in strained InAsSb heterostructures due to their unique electronic properties that are beneficial to the performance of these devices. To further improve laser and LED performance, we are exploring the MOCVD-growth of novel multi-stage (or cascaded) active regions in InAsSb-based devices. These lasers have multi-stage, type I InAsSb/InAsP quantum well active regions. A semi-metal GaAsSb/InAs layer acts as an internal electron source for the multi-stage injection lasers and AlAsSb is an electron confinement layer. Growth in a vertical, high speed rotating disk reactor was necessary to avoid the previously observed Al memory effects found in conventional horizontal reactors. A single stage, optically pumped laser yielded improved power (> 650 mW/facet) at 80 K and 3.8 µm. A multi-stage 3.8-3.9 µm laser structure operated up to T=180 K. At 80 K, peak power > 100 mW and a slope-efficiency of 48% (4.8% per stage) were observed in our gain guided lasers. In addition, these 10-stage structures are the first cascaded devices grown by MOCVD. The broadband LEDs produced high average powers, > 2 mW (\@ 80K, 3.7 µm) and >0.1 mW (\@ 300K, 4.3 µm). A 3.8-3.9 µm laser structure operated up to T=180 K. The slope-efficiency was strongly dependent on cavity length, and analysis of efficiency data suggest an internal quantum efficiency > 1 and a loss coefficient ⊕ 100 cm⁻¹. The growth of alternate structures is being explored and results on these devices will also be presented.

9:50 AM
Ternary and Quaternary Antimonide Devices for TPV Applications: ISHWARA B. BHAT[1]; Collin Hitchcock[1]; Ronald Gutmann[1]; Hassan Ehsani[1]; Christine Wang; Matthew Freeman; Greg Charache[3]; [1]Rensselaer Polytechnic Institute, ECSE Department & Center for Integrated Electronics and Electronics Manufacturing, 110 8th Street, Troy, NY 12180-3590 USA; Massachussetts Institute of Technology, Lincoln Laboratory, Lexington, MA 02173-0073 USA; Lockheed Martin, Inc, Schenectady, New York 12301-1072 USA

Thermophotovoltaic (TPV) devices have been fabricated for applications requiring a 0.55 eV band gap using epitaxial structures on GaSb substrates. GaInSb active layers have been successfully grown by Organometallic Vapor Phase Epitaxy (OMVPE) using step grading layers to manage the epilayer-substrate lattice mismatch and GaInAsSb layers lattice matched to the GaSb substrate have been grown by OMVPE and Liquid Phase Epitaxy (LPE). Alternative structures have been explored including those with n and p emitter dopings; both thin and thick emitter structures, devices with and without surface passivation; and devices with and without mesa etching. Primary measurements have been dark I-V, illuminated I-V, and quantum efficiency. To date, lattice matched quaternary devices with thick p-type emitters and lattice-matched surface passivation layers have resulted in the best devices; with approximately 90% internal quantum efficiency, dark current Js of 15mA/cm2, n factor of approximately unity, and open circuit voltage of 0.32V with a corresponding short-circuit current density of 2.4A/cm2 and a fill factor of 0.66. Comparable characteristics have been achieved with similar devices without surface passivation and non-lattice matched GaInSb ternary devices with appropriate step grading; namely a 60% internal quantum efficiency, dark current Js of 240mA/cm2, n factor of approximately unity, and open circuit voltage of 0.23V with a corresponding short-circuit current density of 1A/cm2 and a fill factor of 0.70. Key device processing procedures include nonalloyed Au p-type ohmic contacts, alloyed Au-Ti-Sn or Au-Sn n-type ohmic contacts, and thick-Ag top-surface contact grids using a lift-off process. For the numerous device structures explored, the minority carrier diffusion length in n-type active layers is restricted to 1-2 microns, while in p-type material the electron diffusion length is approximately 5-10 microns.

10:10 AM
In Situ Measurement of Monolayer Interfaces by Surface Photo Absorption: NIGEL JOHN MASON[1]; Peter John Walker[1]; [1]University of Oxford, Clarendon Laboratory, Oxford, Oxfordshire OX1 3PU UK

In MOVPE grown InAs/GaSb superlattices, the interface between the two binaries can be biased towards a monolayer of InSb or of GaAs depending on the switching sequence of the alkyls at the interface. We have previously shown the importance of such interfaces on the optical, structural and electrical properties of such superlattices. The growing surface of the superlattice has been monitored by surface photoabsorption (SPA), p-polarised 633 nm laser beam which impinges on the crystal surface at Brewster's angle [about 70ϒ] and as such, is influenced strongly by the first few surface monolayers. This optical arrangement is ideal because the laser beam enters and leaves the inner liner through small holes in the quartz. As these holes are located in the top corners of the inner square liner they perturb the main flow only slightly because at this point in the liner the flow is nearly stagnant. For the first time we have been able to detect, using SPA, the growth of the [ideal] one monolayer and [non-ideal] two or more monolayers of GaAs or InSb at the interface. These interface conditions have been investigated ex-situ, by Raman scattering and electrical and structural techniques. By using a novel polarised Raman arrangement we are able to probe separately the interface produced when InAs is grown on GaSb and also that when GaSb is grown on InAs. The Raman shows that under ideal conditions the interface vibration related to the GaAs interface is a sharp peak at about 249 cm^{-1} and that rela ted to the GaSb vibration is at 239 cm^{-1}. Under non-ideal conditions these shift to higher energies, corresponding to increased strain within the structure. Electrical and structural results will also be presented to show the influence of the interfaces on these properties.

10:30 AM Break

11:00 AM
LP-MOVPE and Characterization of Strained InAs(P)/InAsSb Superlattices for IR Emitters: ALEXANDER BEHRES[1]; Dirk Püttjer[1]; Klaus Heime[1]; [1]RWTH Aachen, Institut für Halbleitertechnik, Templergraben 55, Aachen, D-52056 Germany

Strained InAsSb-containing superlattices are promising as active structures in mid-IR emitters due to their low band gap and due to strain-induced suppression of non-radiant Auger recombination. In a first step, we used InAs as barrier material. The structural and optical properties of these superlattices were characterized using X-ray and photoluminescence (PL) measurements. For samples of ten periods of 10 nm InAsSb wells and 50 nm InAs barriers a maximum Sb content of 5.7% is possible without causing strain-induced degradation of the layer stack. Varying the Sb content the PL peak at 10 K can be shifted from 3000 nm to 3600 nm. Temperature-resolved PL measurements show that the peak rapidly decreases with increasing temperature. Above 80 K, no signal is visible at all. In the second step, we compensated for the compressive strain of the InAsSb wells by adding phosphorous into the barriers. These superlattices show very good structural and optical properties up to an Sb content of 18%.

11:20 AM
Growth of Tellurium Doped Indium Antimonide for Magnetoresistors: DALE L. PARTIN[1]; Michael W. Pelczynski[2]; [1]General Motors Corporation, Research and Development Center, Physics and Physical Chemistry Department, 30500 Mound Road 106, Box 9055, Warren, MI 48090-9055 USA; [2]Emcore Corporation, 394 Elizabeth Avenue, Somerset, NJ 08873 USA

Indium antimonide magnetoresistors are of interest for magnetic position sensors in very demanding environments. The use of tellurium as an n-type dopant was studied using Hall effect measurements up to 200 ϒ C, Hall depth profiling, and Secondary Mass Spectroscopy. The films were grown by MOCVD using trimethylindium, trisdimethylaminoantimony, and diethyltelluride. It was found that the incorporation of tellurium strongly depends upon the 5/3 ratio during growth, implying that it is influenced by the availability of antimony vacancies. Thus, our results show that the reproducibility of tellurium doping is not limited by memory effects in a well-designed reactor, but by the control of stoichiometry. It is now possible to grow films with optimum doping profile and with good uniformity and reproducibility over hundreds of runs. These films can be used to make magntoresistors which have good sensitivity to a magnetic field and good stability over a wide temperature range.

11:40 AM
The Growth of AlInSb by Metal-Organic Chemical Vapor Deposition: KEVIN CHARLES BAUCOM[1]; Robert M. Biefeld[2]; Andrew A. Allerman[3]; [1]Sandia National Laboratories, 1126, PO Box 5800, Albuquerque, NM 87185-0601 USA; [2]Sandia National Laboratories, 1113, PO Box 5800, Albuquerque, NM 87185-0601 US; [3]Sandia National Laboratories, 1313, PO Box 5800, Albuquerque, NM 87185-0603 USA

AlxIn1-xSb is of interest for its potential application in a variety of optoelectronic and electronic devices such as infrared detectors, resonant tunneling diodes , and laser diodes as well as a variety of other semiconductor heterostructures. We will report for the first time, the synthesis of this material by metal-organic chemical vapor deposition (MOCVD). We have grown AlxIn1-xSb epitaxial layers by MOCVD using tritertiarybutylaluminum (TTBAl), trimethylindium (TMIn), and triethylantimony (TESb) as sources in a high speed rotating disk reactor. Growth temperatures of 435 to 505 oC at 200 torr were investigated. The V/III ratio was varied from 1.6 to 7.2 and TTBAl/(TTBAl+TMIn) ratios of 0.26 to 0.82 were investigated. AlxIn1-xSb compositions from x = 0.002 to 0.52 were grown. Under these conditions no Al was incorporated for TTBAl/(TTBAl+TMIn) ratios less than 0.62. Hall measurements of AlxIn1-xSb showed hole concentrations between 5x1016 cm-3 to 2x1017cm-3 and mobilities of 24 to 91 cm2/Vs for not intentionally doped AlxIn1-xSb.

12:00 PM
Tellurium Doping of GaSb and Ga(0.8)In(0.2)Sb Layers Grown by MOVPE: ISHWARA B BHAT[1]; HASSAN EHSANI[1]; Collin Hitchcock[1]; Ronald Gutmann[1]; Greg Charache; Mathew Freeman[2]; [1]Rensselaer Polytechnic Institute, ECSE Department & Center for Integrated Electronics and Electronics Manufacturing, 110, 8th Street, Troy, NY 12180-3590 USA; Lockheed Martin, Inc., Schenectady, New York 12301-1072 USA

GaInSb material system is attractive for application in thermophotovoltaic (TPV) cells since its band gap can be tuned to match the radiation from the emitter. In this paper, we will present n-type doping studies carried out in GaSb and Ga0.8In0.2Sb to fabricate TPV cells. GaSb and Ga0.8In0.2Sb epitaxial layers were grown on GaAs and GaSb substrates by metalorganic vapor phase epitaxy (MOVPE) using diethyltelluride (DETe) as the n-type precursor. As-grown Ga0.8In0.2Sb layers were p-type with carrier concentrations in the mid-1016 cm-3 range. N-type layers with carrier concentrations between 5 x 1017 cm-3 and 2 x 1018 cm-3 were obtained by varying the DETe mole fraction. Calibrated secondary ion mass spectrometry (SIMS) measurements show that the percentage of active Te decreases from 75% to 35% as the Te concentration increases from 5 x 1017 cm-3 to 2 x 1018 cm-3. Variable temperature Hall and photoluminescence measurements were carried out on layers grown on semi-insulating GaSb and on layers grown on semi-insulating GaAs substrates. Both SIMS and Hall measurements show that the doping efficiency is higher by a factor of 2-4 when layers were grown on GaSb substrates. Even though Te doping studies have been reported in GaSb before, to our knowledge, this is the first detailed study on Ga0.8In0.2Sb.

Tuesday PM - June 2, 1998

Late News Session - 7:30 PM to 8:00 PM

Tuesday PM June 2, 1998
Room: Grand Ballroom D & E
Location: Sheraton Grande Torrey Pines

Poster Session - 8:00 PM to 10:00 PM

Tuesday PM June 2, 1998
Room: Scripps Ballroom
Location: Sheraton Grande Torrey Pines

Session Chairs: M. Tischler, Epitronics Corp., Phoenix, AZ 85027 USA; A. Clawson, University of California - San Diego, La Jolla, CA 92093 USA

Process Models

(1) 3D Analysis of MOCVD in the In-Ga-As-P System in Horizontal Reactors by Numerical Modeling: LEV KADINSKI[1]; Martin Dauelsberg[1]; Peter Kaufmann[1]; Clemens Lindner[1]; Yuri N. Makarov[1]; Gert Strauch[2]; Holger Jurgensen[2]; [1]University of Erlangen-Nuremberg, Institute of Fluid Mechanics, LSTM, Cauerstr. 4, Erlangen, 91058 Germany; [2]AIXTRON AG, Kackertstr. 15-17,Aachen, 52072 Germany

The goal of the presented work is to show the effect of three—dimensional convective flow, wafer rotation and formation of deposits on side and top walls on thickness and compositional uniformity in a horizontal tube reactor used for the MOVPE growth of binary and ternary layers in the material system In-Ga-As-P. A detailed three-dimensional model is used for the analysis of the effect of different transport mechanisms on uniformity of the deposition. The mathematical description consists of the solution of coupled flow,heat and mass transfer including heat conduction in solid parts,radiative heat transfer and multicomponent species transport. A kinetic model considering the wall deposition rates for the system In-Ga-As-P is used to predict the formation of deposits. The computational results are compared with experimental data obtained in the AIX-200 and the AIX-200/4 horizontal tube reactors.It is shown thatcontrol of deposit formation during MOVPE in the horizontal reactorsis crucial for growth of ternary layers with uniform composition. Optimization of the reactor design and the process are discussed in detail. Growth of the epitaxial layers with highly uniform thickness and composition is demonstrated.

(2) Modeling and Experimental Verification of Transport and Deposition Behavior During MOVPE of $Ga_{1-x}In_xP$ in the Planetary Reactor: MARTIN DAUELSBERG[1]; Lev Kadinski[1]; Yuri N. Makarov[1]; Thomas Bergunde[2]; Gert Strauch[3]; Holger Jurgensen[3]; [1]University of Erlangen-Nuremberg, Institute of Fluid Mechanics, LSTM, Cauerstr. 4, Erlangen, 91058 Germany; [2]Ferdinand-Braun-Institute, Rudower Chaussee 5, Berlin,12489 Germany; [3]AIXTRON AG, Kackertstr. 15-17, Aachen, 52072 Germany

The computational prediction and experimental verification of the MOVPE growth process of $Ga_{1-x}In_xP$ using trimethylgallium, trimethylindium and tertiarybutylphosphine or phosphine in the production scale multiwafer Planetary Reactors AIX 2000, AIX 2400 and AIX 2400G3 are presented. The modeling approach consists of computing flow, heat and multicomponent mass transfer for chemically reacting gas flows with large temperature and density gradients. Particular emphasis is laid on the accurate prediction of radiative heat transfer. Mass transport limited growth on the substrates and kinetically limited wall deposition are taken into account. Reaction rate constants for the strongly temperature dependent formation of wall deposits are determined by deliberate deposition studies at non-optimalthermal conditions. Calculated and measured growth rate and compositional distributions are compared and conclusions are drawn with respect to the mechanisms that determine the solid composition of $Ga_{1-x}In_xP$ at the various growth conditions, i. e. growth temperatures, pressures and flow rates. The reactor types are compared with each other. The modeling studies resulted in reproducible growth rate and compositional uniformities.

(3) Three-Dimensional Modeling Analysis Of Deposition Uniformity In Industrial Multiwafer Planetary Reactors: YURI EGOROV[1]; Alexander O. Galyukov[2]; Lev Kadinski[1]; YURI N. MAKAROV[1]; Alexander Zhmakin[3]; Gert Strauch[4]; Michael Heuken[4]; Holger Jurgensen[4]; [1]University of Erlangen-Nuremberg, Institute of Fluid Mechanics, LSTM, Cauerstr. 4, Erlangen, 91058 Germany; [2]Advanced Technology Center, Advanced Technology Center, St. Petersburg, Russia; [3]A. F. Ioffe Physical Technical Institute, St. Petersburg, Russia; [4]AIXTRON AG, Kackertstr. 15-17, Aachen, 52072 Germany

Multiwafer Planetary Reactors were widely used for the production of various semiconductor devices. In the present paper for the first time a systematic three-dimensional modelinganalysis of factors influencing the uniformity of the deposition in the Planetary Reactors is performed for the MOVPE of GaAs and GaN. Three-dimensional flow pattern and species transport in the reactor chamber are considered in detail in the paper. Rotation of satellites with the wafers results in an effective averaging of the deposition rate distribution and this is the key mechanism providing growth of epitaxial layers with highly uniform properties. Due to the additional averaging by the second rotation, it is shown that any three-dimensional variation in the gas exhaust flow pattern could have only minor effects on the deposition uniformity. 3D flow variations at the gas inlet are considered with respect to total flow of carrier gas, type of carrier gas and design of inlet. With this 3D simulation software it is understood how to use an optimum combination of these parameters and how stable processes and uniformity are controlled.

(4) Simulation of Flow and Growth Phenomena in a Close-Spaced Reactor: THEODOROS G. MIHOPOULOS[1]; Steven G. Hummel[2]; Klavs F. Jensen[3]; [1]MIT, Rm 66-513, 25 Ames St., Cambridge, MA 02139 USA; [2]Hewlett-Packard Laboratories, 3500 Deer Creek Road, Palo Alto, CA 94303 USA; [3]MIT, Rm 66-566, 25 Ames St., Cambridge, MA 02139 USA

Reactor design is one of the key factors determining the degree of uniformity and interface abruptness of films deposited by Metalorganic Vapor Phase Epitaxy (MOVPE). A novel design finding increasing use is the 'close-spaced-injector' where a water-cooled injection showerhead is placed very close (1-2 cm) to the substrate in a vertical cold-wall reactor. We present a combined experimental and modeling analysis of such a reactor. Since the showerhead is comprised of individual jets, there are issues of whether the jets penetrate in the reactor and locally influence chemistry and uniformity. Three dimensional simulations of fluid flow, heat chemical species transfer show that under typical MOVPE operating conditions, complete mixing of precursors from adjacent jets occurs and the deposition is axisymmetric. Two dimensional calculations are then used to investigate effects of total flowrate, spin rate, and reactor pressure on film uniformity, absolute growth rate and flow stability. The modeling conclusions are validated by comparison with experimental studies on close-spaced reactor used for the deposition of AlGaAs materials. The role of showerhead temperature on uniformity and chamber deposits will also be discussed.

Production

(5) Growth of High-Efficiency InGaN MQW Blue and Green LEDs Using Large-Scale Production MOCVD Reactor and Their Characterization: C. A. TRAN[1]; R. F. Karlicek[1]; M Schurman[1]; I Ferguson[1]; R. Stall[1]; A. Onsinski[1]; J. Ramer[1]; [1]Emcore Corp., 394 Elizabeth Avenue, Somerset, NJ 08873 USA

We report the epitaxial growth of blue and green LEDs with wavelengths longer than 450 nm and 500 nm, resp., in a large scale production MOCVD reactor. The growth of candela-class blue and green LEDs is carried out in a large-scale production MOCVD reactor equipped with in-situ reflectance spectroscopy. The reactor is capable of yielding 6 x 2" wafers for each run. Properties of n-type, p-type GaN, AlGaN as well as the phase separation of indium in InGaN MQW will be described and discussed. High electron carrier mobility (650 cm2/vs \@ 300K) in undoped GaN, high hole concentration (1e18 cm-3) in p-GaN and photoluminescence emission longer than 500 nm in InGaN/GaN MQW were achieved. The LEDs have active layer composed of a stack of InGaN/GaN wells clad by AlGaN on p-contact side. The forward voltage is as low as 3V and the power output at 20 mA is better than 2 mW for the blue LEDs (460nm). The impact of this work is that high brightness Blue and Green LEDs based on InGaN/GaN material can be produced in large scale using production MOCVD reactors.

(6) High Quality III-Nitride Material Grown in Mass Production MOCVD Systems: OLIVER SCHOEN[1]; Bernd Schineller[2]; Dietmar Schmitz[1]; Michael Heuken[1]; HOLGER JUERGENSEN[1]; [1]AIXTRON AG, Kackertstr. 15-17, Aachen 52072 Germany; [2]RWTH Aachen, Institut für Halbleitertechnik, Templergraben 55, Aachen, 52072 Germany

Since GaN and its related alloys, InGaN and AlGaN, further increase in importance, demand for reliable and efficient mass production systems is steadily rising. To meet this demand our MOCVD systems and production processes are continuously improved. Here we present some of the latest results obtained from AIX 2000HT Planetary Reactors® in a configuration of 7 x 2" which provides unique uniformity capabilities due to the two fold rotation of the substrates and the hot flow inlet. Typical V/III ratios used for high quality GaN are as low as 1000, the group III efficiency obtained is 23% and higher. Thickness homogeneities have been shown to be better than 1% on full 2" wafers. Composition uniformity of ternary material determined by 300K PL-mappings show peak wavelength variations typically less than 1 nm for AlGaN and GaInN. Low temperature photoluminescence and reflectance spectra of GaN layers reveal free exciton transitions. Typical background electron concentrations be-low 5·1016 cm-3 are obtained. Intentional doping over 1018 cm-3 p type and 1020 cm-3 n type with state of the art uniformity are demonstrated.

(7) Highly Uniform AlAs/GaAs, InGa(Al)P/GaAs and InGaAs(P)/InP Structures Grown in a Three 2" Wafer Close-Spaced Vertical Rotating Disk Reactor: KOEN VANHOLLEBEKE[1]; LAURENCE CONSIDINE[2]; Ingrid Moerman[1]; Piet Demeester[1]; Edward J. Trush[2]; John A. Crawley[2]; [1]University of Gent, Information Technology, Sint-Pietersnieuwstraat 41, Gent 9000 Belgium; [2]Thomas Swan & Co , Unit 1C, Button End, Harston, Cambridge, CB2 5NX United Kingdom

Previously we have reported the MOVPE growth of uniform AlGaAs/GaAs and InGaAs(P)/InP structures grown in a three 2" wafer close-spaced vertical rotating disk reactor at reduced pressure. Extending this work we now report photoluminescence (PL) and x-ray diffraction (DXRD) results for growth at atmospheric pressure including the InGa(Al)P materials system. For AlAs/GaAs layers we have achieved a total thickness variation within +/- 2% for the three wafers over a radial distance of 48 mm in both the x and y directions and a standard deviation (stdev) of 0.69% measured by DXRD. In the InGaAs system we have achieved PL wavelength stdev of 0.869nm over all 3 wafers excluding the outer 2mm. The best composition uniformity we have obtained in the InGaAsP system yields a PL wavelength stdev of 1.8

nm over a 48 mm radial distance. For InGaP we have obtained an indium composition variation within the wafer of 0.203%.

(8) MOVPE Growth of High Power 0.5 Watt 35 Ghz MMICs : IAN FERGUSON[1]; C. Beckman[1]; Zhe Chuan FENG[1]; R. A. Stall[1]; Hong Hou[2]; Leye Aina[3]; [1]EMCORE Corporation, Research Development, 394 Elizabeth Avenue, Somerset, NJ 08873 USA; [2]Sandia National Lab., MS0603, 1515 Eubank S.E., Albuquerque, NM 87185 USA; [3]Epitaxial Technologies, 1450 South Rolling Road, Baltimore, MD 21227 USA

Pseudomorphic high electron mobility transistor (p-HEMT) structures have been grown by low-pressure metalorganic vapor phase epitaxy (MOVPE) in a high speed rotating reactor for microwave millimeter integrated circuits (MMIC) device applications. Device structures grown on 3" diameter GaAs wafers are shown to be high quality from the whole wafer, non-destructive, characterization techniques such as photoluminescence, sheet resistivity and high resolution X-ray diffraction, comparable to similar MBE-grown wafers. Subsequently fabricated 38 GHz LNA MMICs inserted into the production line exhibited low noise, high frequency, high power performance with 20 mB gain, 4 dB noise figure and RF and DC yields as high as 72%. Similarly produced, MOVPE grown power p-HEMT wafers resulted in 38 GHz power amplifier MMICs with 23 dBm (~0.2W) output power at the 1 dB compression point and a gain of 20 dB. The yield for the power p-HEMT wafers was as high as 48% and is better than the average MBE-grown power p-HEMT wafer. Based on this experience a 35 GHz, ˚-watt power amplifier MMIC was designed specifically for MOVPE grown material that can be used in kA-band wireless applications. Fabricated device wafers from this mask set yielded 5.55 x 3.2 mm MMIC chips with saturated output power of over ˚-Watt at 34 GHz and 0.46 Watt at 35 Ghz.

(9) Spectroscopic Process-Sensors in MOVPE-Device-Production: KOLJA HABERLAND[1]; Paul Kurpas[2]; Markus Pristovsek[1]; Jörg-Thomas Zettler[1]; Markus Weyers[2]; Wolfgang Richter[1]; [1]Technische Universität Berlin, Institut für Festkörperphysik, Sekr. PN 6-1, Hardenbergstr. 36, Berlin D-10623 Germany; [2]Ferdinand-Braun-Institut für Höchstfrequenztechnik, Rudower Chaussee 5, Berlin, D-12489 Germany

In recent years ellipsometry and Reflectance-Anisotropy-Spectroscopy (RAS/RDS) have proved to be ideal techniques for optical in-situ measurements in research [1]. However, in production environments more robust and compact optical sensors, maintaining the bulk- and surface-sensitivity of the research systems, are needed. Simplified RAS- and reflectance-systems could serve as realtime growth-monitor and process-control-sensors. Very few requirements on the epitaxial system (e. g. only one window for normal incidence) are combined with a maximum of available information about bulk and surface. This paper presents results gained with optimized setups for combined RAS- and reflectance-measurements. Measurements have been performed in standard epitaxial systems on rotating samples. Complete process-fingerprints of HBT- and DBR-semiconductor-device-growth are presented, yielding information such as surface conditions (clean, smooth, oxidized), doping level, adsorbat covering, layer relaxation and temperature changes. [1] J.-T. Zettler, Prog. Chrystal Growth and Charact., vol. 35, 27-98 (1997).

(10) In Situ Characterization of GaAs Growth in Nitrogen Atmosphere During MOVPE: A Comparison to Hydrogen Atmosphere: HILDE HELEN HARDTDEGEN[1]; Markus Pristovsek[2]; H. Menhal[2]; J.-T. Zettler[2]; W. Richter[2]; D. Schmitz[3]; [1]Research Center Juelich, Inst. of Thin Film and Ion Technology D-52425 Juelich Germany; [2]Technische Universität Berlin, Institut fuer Festkoerperphysik, PN 6-1, Hardenbergstr. 36, Berlin, - D-10623 Germany; [3]AIXTRON AG, Kackertstr. 15 - 17, Aachen, - D-52072 Germany

The influence of the carrier gas atmosphere in MOVPE is investigated in situ in the temperature range between 400 and 720°C by means of reflectance anisotropy spectroscopy. We will report on two types of experiments: the first dealt with the determination of the transition temperature from the layer by layer growth to the step flow growth mode on a slightly misoriented GaAs substrate <(001) substrates oriented 0.3° towards [110]>. Information about diffusion lengths of the growth species is obtained. The results of the study will be presented in detail and show, that the transition temperatures and therefore the diffusion lengths are independent on growth ambient, as already suggested by the phase diagrams. The second set of experiments dealt with the reflectance anisotropy as a function of surface temperature under non-growth conditions with and without AsH_3 stabilization. Studies at a constant AsH_3 partial pressure reveal, that the carrier gas has an influence on arsenic coverage. The arsenic desorption in both ambients was investigated as a function of temperature. Up to 650°C the same processes, reconstructions and comparable activation energies are observed. Consequences for the growth process are discussed.

(11) Contributions to Understanding the Optical Properties of Partially Ordered $(Al_{0.3}Ga_{0.7})_{0.52}In_{0.48}P$ Deposited by MOVPE Using N_2 Or H_2 as the Carrier Gases: R. SCHMIDT[1]; T. Hauck[1]; M. v.d. Ahe[1]; Ch. Dieker[1]; D. Meertens[2]; M. Luysberg[2]; Hilde Helen Hardtdegen[1]; D. Schmitz[3]; [1]Research Center Juelich, Inst. of Thin Film and Ion Technology D-52425 Juelich Germany; [2]Research Center Juelich, Department for Solid State Physics, D-52425 Juelich Germany; [3]AIXTRON AG, Kackertstr. 15 - 17, D-52072 Aachen Germany

AlGaInP was deposited lattice matched to GaAs at growth temperatures between 720 and 780°C (a parameter range used for LED structures) by MOVPE using the carrier gases nitrogen and hydrogen and (001) substrates with different misorientations. We will report on a comparative study of the optical and structural properties of these layers using photoluminescence spectroscopy (PL) at 300 and 2 K and transmission electron microscopy (TEM). In principle, a higher amount of order and an up to 35 meV lower PL-emission energy was observed for the nitrogen samples compared to the H_2 samples. Ordering also affects the room temperature spectra: broadening is observed. The optical quality of the layers for LED application is therefore difficult to assess by PL. Spectra of AlGaInP recorded at 2 K showed a systematic resemblance to GaInP spectra, in which three more or less well resolved PL-transitions are observed. A model was developed and will be introduced, which explains the connection between two of the three transitions. The influence of domain size on PL peak energy shifts and peak intensity will be presented and discussed.

(12) Mass Production of Very Uniform III-V Semiconductor Materials for Optoelectronic and Electronic Device Applications in Advanced Planetary Reactors®: DIETMAR SCHMITZ[1]; Gert Strauch[1]; HARRY PROTZMANN[1]; Holger Juergensen[1]; [1]AIXTRON AG, Kackertstr. 15-17, Aachen 52072 Germany

Electronic consumer products (cellular phones, data storage units, LED and LASER- printers and LED full-colored displays) require state of the art compound semiconductor devices. Large quantities are needed and the fabrication process has to provide high wafer throughput and yield. To meet the targets of this market, a well proven production tool, the Planetary Reactor®, has been improved to meet the production focus and flexibility required. The wafer capacity of the advanced reactors is between 15 x 2" and 35 x 2" or 9 x 4". The material uniformity of AlGaInP on 9 x 4" is an excellent 1 nm in emission wavelength and better than 0.5 % in film thickness. These numbers are obtained on full wafer mappings. The efficiency for precursors is 45% for TMGa and over 50% for TMAl. Sheet resistance topograms for Si and Carbon doping levels usually required in devices show uniformity better than 1%. The benefits of this design together with a fully automated cassette to cassette loading system and the impact on reduction of cost of ownership will be discussed in detail.

Precursors

(13) Gas Chromatography-Mass Spectroscopy in CVD Precursor Analyses: An Essential Tool for Improving Quality Control in Precursor Syntheses: MICHAEL E. BARTRAM[1]; [1]Sandia National Laboratories, Chemical Processing Sciences, MS 0601, Albuquerque, NM 87185-0601 USA

The development of the precursors used currently in CVD processes has been facilitated over the years by combining novel synthetic methods with sophisticated analytical tools such as FT-NMR, spark-source MS, ICP-AA, and ICP-MS. These techniques provide essential information about metal contaminants at the ppm level. However, our GCMS analyses reveal significant levels of organic impurities in numerous CVD precursors, suggesting that analytical methods have yet to be exploited fully for the optimization of precursor synthesis and purification. Decomposition on the GCMS chromatographic column often precludes the development of effective GCMS analytical methods for highly reactive precursors. However, judicious column selection combined with low column temperatures and line shape analyses has allowed precursors critical to CVD processes to be evaluated in terms of impurities, in-situ purification, and decomposition reactions within storage vessels. Among these are tert-butyl arsine (TBA), tris-dimethylamino antimony (TDMAA), trimethylamino alane (TMAA), tetraethylorthosilicate (TEOS), and bis-cyclopentadienyl magnesium (MgCp2). In each bubbler (except for TEOS), at least three compounds and in one case, in excess of 11 components were observed in addition to the desired precursor. Oxygen containing hydrocarbons were detected in three MgCp2 bubblers among a sampling of six bubblers from three manufacturers. In some instances, the precursors could be purified in-situ with a simple procedure. TMAA had six sim ilar compounds of dimeric alkylalanes present, as well as three other compounds in what may be a series of amine-alane oligomers. Overall, these results suggest that GCMS could be a key tool for dispelling the mystery surrounding the contents of precursor bubblers if it is utilized for the improvement of synthetic processes and for the assurance of quality control in the production of CVD precursors. (Sandia is operated by Sandia Corporation, a Lockheed Martin Company, for the USDOE under DE-AC04-94AL85000.)

(14) MOVPE of AlAsSb Using Tritertiarybutylaluminum: CHRISTOPH GIESEN[1]; Xiangang Xu[2]; Martin Manfred Beerbom[1]; Klaus Heime[1]; [1]RWTH Aachen, Institut für Halbleitertechnik, Templergraben 55, Aachen, D-52056 Germany; [2]Simon Fraser University, Department of Physics, Burnaby BC, V5A 1S6 Canada

We investigated the growth of AlAsSb on InAs substrates as cladding material for Sb-based IR-lasers. Also we used S.I. GaAs substrates for electrical characterizations. To reduce the high p-type background doping due to C and O incorporation we chose tritertiarybutylaluminum (TTBAl) as Al-precursor, which has weaker C-Al-bounds compared to TEAl or TMAl. The use of a standard set-up to control the TBAs partial pressure in the gas phase was difficult and resulted in lateral and vertical inhomogenities of the As content in the solid. By using a dilution set-up, normally used for dopant precursors, we were able to produce layers with good structural qualities and smooth surface morphology. We achieved AlAsSb with low hole concentrations between $5 \cdot 10^{16}$ cm^{-3} and $3 \cdot 10^{17}$ cm^{-3} and very high mobilities up to 500 cm^2/Vs at 77 K and 300 cm^2/Vs at room temperature. Using DEZn and DETe we achieved p- and n-type doping of $2 \cdot 10^{19}$ cm^{-3} and $5 \cdot 10^{16}$ cm^{-3}, respectively.

(15) PMN Thin Film Growth Using Solid-Source MOCVD: SANG-YUN LEE[1]; Han-Jin Lim[1]; Robert S. Feigelson[1]; [1]Stanford University, Center for Materials Research, 435 Santa Teresa, Stanford University, Stanford, CA 94305-4045 USA

Pure $Pb(Mg_{1/3},Ni_{2/3})O_3$(PMN) and $Pb(Mg_{1/3},Ni_{2/3})O_3$-$PbTiO_3$ (PMN-PT) thin films were successfully grown on the $SrRuO_3$ electrodes at (100) $SrTiO_3$ substrates by the solid-source MOCVD method. It is known that this method has the capability of producing high quality films on larger area with excellent step coverage and controlling the stoichiometry precisely, especially for multi-cation systems. The degrees of crystallinity and surface morphology variations according to different PT contents were studied by XRD and AFM. Stoichiometry and thickness of PMN films were analyzed by RBS. From XRD, (100) preferred oriented PMN films were detected. As the amount of PT increases, higher intensity of (100) PMN films were observed. At optimal conditions, rocking-curve FWHM values were 0.3ϒ. From AFM analysis, more dense and uniform PMN films were grown as PT content increased. The relationship between dielectric properties and PT contents will be studied.

(16) Pyrazolato Complexes as Alternative Source Compounds for Epitaxial Film Growth: CHARLES H. WINTER[1]; Dirk Pfeiffer[1]; Jeffrey G. Cederberg[2]; Thomas D. Culp[2]; B. Bieg[2]; Kevin L. Bray[2]; Thomas F. Kuech[2]; [1]Wayne State University, Department of Chemistry, 5101 Cass Avenue, Detroit, MI 48202 USA; [2]University of Wisconsin, Department of Chemical Engineering, 1415 Engineering Drive, Madison, Wisconsin 53706 USA

Source compounds containing cyclopentadienyl and 1,3-diketonate ligands are widely used as source compounds in chemical vapor deposition procedures, since these ligands tend to produce compounds that are volatile and exhibit good thermal stability. However, the presence of direct metal-carbon or metal-oxygen bonds in the source compounds can lead to undesired element contamination in the film material along with concomitant reductions in materials properties. Furthermore, many metal complexes containing 1,3-diketonate ligands are oligomeric, and have unacceptably low vapor pressures. We will describe the synthesis, characterization, and properties of group 2 metal (Mg, Ca, Sr, Ba) and lanthanide (Y, Er, Lu) compounds that contain pyrazolato ligands as the anionic donors. Pyrazolato ligands are anionic, five-membered heterocycles with two adjacent nitrogen atoms. In the group 2 metal and the lanthanides, both nitrogen atoms are bonded to the metal. Therefore, the pyrazolato ligand is isoelectronic with 1,3-diketonate ligands and represents an alternative avenue for CVD precursor design. The use of several of the pyrazolato complexes as sources in MOVPE processes will be described.

(17) Towards the Establishment of Specifications for OMVPE Chemical Sources: RICHARD H. PEARCE[1]; Nam Tran[1]; [1]Akzo Nobel Chemicals Inc., Deer Park, Texas USA

New methods of analysis of metalorganics for OMVPE are described which provide very sensitive and reproducible results for oxygen and metallic impurities in such common sources as trimethyl -aluminum, -gallium and -indium. Data for alternative vendors is presented which show wide variations in the quality of sources currently available. The appropriateness of the presented methodology as industry-standard practice is advanced.

Doping/Defects

(18) Si-Doping of MOVPE Grown InP and GaAs by Using the Liquid Si Source Diteriarybutyl Silane: S. LEU[1]; H. Protzmann[1]; F. Höhnsdorf[1]; W. STOLZ[1]; [1]Philipps-University, Material Science Center and Department of Physics, Hans-Meerwein-Str., Marburg, 35032 Germany

With the aim of an all liquid source MOVPE process, the liquid Si-compound ditertiarybutyl silane ((t-C4H9)2-Si-H2, DTBSi) has been investigated as a doping source for InP and GaAs using TBP and TBAs as less hazardous group V-sources. Because of the common alkyl group of the used Si- and group-V-precursors a simplified reaction chemistry is expected. The Si-incorporation behaviour as a function of growth temperature and V/III-ratio is studied by temperature-dependent Hall and calibrated SIMS measurements. Uncompensated n-type InP and GaAs layers are achieved up to the 1018 cm-3 doping range. The carrier concentration is directly proportional to the DTBSi/group-III-partial pressure ratio with a slope of unity. The Si-concentration determined by SIMS is identical to the measured carrier concentration. The doping behaviour as a function of temperature and V/III ratio will be presented and discussed. Under optimized conditions, variations of the sheet resistance of n-GaAs:Si down to s = 1% across a 2" wafer are obtained, thus, rendering DTBSi an interesting doping source for device applications.

(19) Low-Temperature MOVPE Growth And Doping Of Gallium Arsenide With Carbon Tetrachloride: B. K. HAN[1]; M. J. Begarney[1]; D. C. Law[1]; Q. Fu[1]; L. Li[1]; H. Yoon[1]; M. S. Goorsky[1]; R. F. Hicks[1]; [1]University of California, Chemical Engineering and Materials Science Departments, 405 Hilgard Ave., Los Angeles, CA 90095-1592, USA

The chemistry of doping gallium arsenide with carbon during metalorganic vapor-phase epitaxy has been studied by monitoring the reactor effluent gases with on-line infrared and mass spectroscopies. In addition, the surface structure of the films was characterized by scanning tunneling microscopy. As the CCl_4 partial pressure increased from $1x10^{-4}$ to above $1x10^{-3}$ atm, the GaAs growth rate decreased and fell to zero. The reduction in growth rate was primarily due to a reaction between adsorbed gallium and chlorine to produce volatile GaCl. Gallium arsenide etching by adsorbed chlorine to produce $GaCl_3$ was insignificant below a threshold CCl_4 partial pressure of ~$1x10^{-3}$ atm at 450-550°C. At the onset of film etching, the surface structure changes from being smooth and ordered to rough and disordered. The relationship between the CCl_4 decomposition kinetics and the carbon doping levels in the films will also be discussed.

(20) Incorporation of C and O In (AlGa)As Grown by Using TBAs: S. LEU[1]; F. Höhnsdorf[1]; W. STOLZ[1]; A. Salzmann[2]; R. Becker[2]; A. Greiling[2]; [1]Philipps-University Marburg, Material Science Center and Department of Physics, Hans-MeerweinStr., Marburg 35032 Germany; [2]sgs MOCHEM products GmbH, Marburg, 35037 Germany

The understanding of the unintentional incorporation of C and O is of key importance, in particular for high Al-content epitaxial layers and device structures. In this study, a variety of both TMGa and TMAl as well as TBAs batches has been used to grow (AlGa)As (xAl=0.85) by MOVPE in the temperature range of 625°C to 725°C using different V/III-ratios and reactor pressures. The C and O levels have been determined by calibrated SIMS. The primary source of C is the methyl group of the group-III-compounds. The C-level shows a quadratic reduction as a function of the V/III-ratio for low ratios and a smaller decline for higher V/III-ratios. O-contamination originates both from some batches of TMAl as well as TBAs. Two sources of O are identified in some TBAs batches due to their characteristic incorporation behaviour, which significantly deviates from that reported for AsH3-growth. Using specific purification steps of the TBAs these impurities were drastically reduced, leading to state-of-the-art low O-content (AlGa)As.

(21) DLTS Studies of Deep Levels in Er Doped GaAs and $Al_xGa_{1-x}As$ Grown by MOVPE: J. G. CEDERBERG[1]; T. D. Culp[1]; B. Bieg[1]; D. Pfeiffer[2]; C. H. Winter[2]; K. L. Bray[1]; T. F. Kuech[1]; [1]University of Wisconsin, Department of Chemical Engineering, 1415 Engineering Dr., Madision, WI 53706 USA; [2]Wayne State University, Department of Chemistry, Detroit, MI 48202 USA

Semiconductors doped with rare earth elements represent a possible route to the integration of optical components onto Integrated Circuits (IC). Compared to Er-doped Si, the larger band gap of GaAs reduces lifetime and intensity quenching of the characteristic $4I_{13/2}$-to-$4I_{15/2}$ Er luminescence at higher temperatures. We have investigated erbium-doped GaAs grown by Metal-organic Vapor Phase Epitaxy (MOVPE), utilizing the new Er precursor compound, tris(3,5-di-t-butylpyrazolato)bis(4-t-butylpyridine)Er. Photoluminescence (PL) studies of Er-doped GaAs reveal strong and sharp optical emission at 1.54 mm, with the optical emission being quenching in n-type but not p-type GaAs. This dependence on doping type can be explained by the enhanced Auger recombination in n-type GaAs over p-type materials. Deep Level Transient Spectroscopy (DLTS) of both Si and Se- doped GaAs, co-doped with erbium and oxygen, reveals several defects in the upper half of the conduction band between 0.41 and 0.77 eV. The defects introduced exhibit a variety of characteristics, including Frenkel-Poole barrier lowering. Results on the dependence of the Er emission on carrier type and concentration will be presented, and will be extended to Er-doped $Al_xGa_{1-x}As$ alloys. The effect of the larger alloy band gap on the defect structure, introduced by Er, will also be presented. The impact of the deep level defects on the applicability of rare earth-doped optical devices manufactured from compound semiconductor materials is discussed.

(22) Silicon as the p-Type Dopant in GaSb and Ga0.8In0.2Sb Grown by MOVPE: ISHWARA B BHAT[1]; Hassan Ehsani[1]; Collin Hitchcock[1]; Ronald Gutmann[1]; Greg Charache[2]; Matthew Freeman[2]; [1]Rensselaer Polytechnic Institute, ECSE Department & Center for Integrated Electronics and Electronics Manufacturing, 110 8th Street, Troy, NY 12180-3590 USA; [2]Lockheed-Martin, Inc, Schenectady, New York 12301-1072 USA

Zinc is the most commonly used p-type dopant in GaSb and $Ga_{0.8}In_{0.2}Sb$ grown by metalorganic vapor phase epitaxy (MOVPE). Control of its incorporation at the low doping regime is difficult, since zinc organometallics generally have high vapor pressure. Moreover, they are very sensitive to oxygen and moisture that may be present in the reactor. Recently, we have shown that Si is a well-behaved p-type dopant in GaSb and $Ga_{0.8}In_{0.2}Sb$ materials grown by MOVPE. P-type doping was achieved using silane gas as the dopant precursor and excellent control in the low doping regime was obtained using this source. In this paper, we will present additional results on the electrical and optical properties of Si doped GaSb and $Ga_{0.8}In_{0.2}Sb$ layers grown on GaSb and GaAs substrates. Secondary ion mass spectrometry (SIMS), variable temperature Hall measurements and photoluminescence measurements were used to characterize the layers. Using semi-insulating GaSb substrates, electrical properties of p-type layers grown on lattice-matched and lattice mis-matched substrates were compared for the first time. SIMS measurements were used to determine the degree of activation in the layers grown on these two types of substrates. Thermophotovoltaic devices with excellent electrical characteristics were fabricated using these p-type active layers.

(23) SEM and CL Study of the Epitaxial-Lateral-Overgrowth (ELO) Process for GaN: Zhonghai Yu[1]; M.A.L. Johnson[1]; T. McNulty[1]; J.D. Brown[1]; J.W. Cook, Jr.[1]; J. F. SCHETZINA[1]; [1]North Carolina State University, Box 8202, Raleigh, NC 27695 USA

Growth of GaN by MOVPE on mismatched substrates such as sapphire and SiC produces a columnar material consisting of many hexagonal mm in diameter. However, the epitaxial-lantern (ELO) process for GaN creates a new material - crystal GaN. We have studied this process using reactor featuring vertical gas flows and fast rotation. First, GaN/sapphire layers ~1 mm thick grown using the standard low-temperature-buffer by high temperature-GaN film growth technique. wafers were then removed from the reactor and ~100 nm of SiO2. Next, a mask set was employed to define a series of parallel SiO2 stripes along [1-100] separated by VIAs (windows) using standard photolithographic techniques. Reactive ion etching was then used to remove the SiO2 from the window areas and expose the underlying parallel GaN stripes. The wafers were then returned to the MOVPE reactor where ELO growth of GaN was initiated. A series of samples was synthesized which show ELO of GaN from its initial stages where the ELO process begins at the edges of the SiO2 strips to its final stage where complete coalescence of adjacent ELO layers occurs near the centers of the SiO2 stripes. SEM images show that the (0001) GaN surface remains very flat as the ELO process proceeds with the lateral growth front consisting of {1-101} planes. Cathodoluminescence images at 590 nm clearly show the spotty deep-level emission from the columnar GaN as it emerges from the window areas. In addition, very bright deep-level CL emission is associated with the strain field that accompanies the conversion of columnar GaN in single-crystal GaN via the ELO process. As the growth of GaN continues to spread laterally onto the SiO2 stripes, the deep-level luminescence completely disappears and is replaced with pure band-edge CL at ~365 nm. This emission occurs in the lateral overgrowth region beyond the strain field and is maintained throughout the remainder of the ELO process until coalescence of adjacent ELO layers occurs near the centers of the SiO2 stripes. Thus the CL dominated by pure band-edge emission is the optical signature of this new single-crystal GaN material.

Nitrides

(24) Crystallochemical Evaluation of Substrate Materials for Epitaxial Growth of Al- and Ga-Nitrides: NIKOLAI I. LEONYUK[1]; [1]Moscow State University, Moscow 119899 Russia

The device characteristics of thin films based on the AlN-GaN system have a large dependence on the substrate materials, because heteroepitaxial film becomes dominated by extended defects arising, first of all, from the substrate/film lattice mismatch. This paper results an attempt to develop structural criteria to guide the search for more effective substrates for the deposition of AlN, CaN and (Al,Ca)N films following the authors experience concerned with crystallochemical aspects in crystal growth of oxide materials. Over fifty various inorganic crystals as well as many of their solid solutions have been examined in search for a replacement substrate. Among them, the main attention was paid to candidates from the viewpoint of phase stability, easy of growth and other physico-chemical properties. The epitaxial relations were found between some of crystallographic orientations of the Al,Ga-nitrides and substrates like $A1_2 0_3$, MgD, ZrO_2, HfO_2, $MgAl_2O_4$, $TiZn_2O_4$, $YAlO_3$, $LaAlO_3$, $LaGaO_3$, $LaCaO_3$, $NdCaO_3$, $KTaO_3$, $SrTiO_3$, Si, SiC. In this connection, the Hartman-Perdok concept was used to estimate the atomic surface topology of the film/substrate interface. In conclusion, some recent experimental results will be discussed as well.

(25) Growth and Characterization of GaN on LiGaO2: SHUKUN DUAN[1]; Xuegong Teng[1]; Peide Han[2]; Da-Cheng Lu[2]; [1]Chinese Academy of Sciences, National Integrated Optoelectronics Laboratory, Institute of Semi Conductors, Beijing, 100083 China

GaN epilayers are grown on (001) $LiGaO_2$ substrates with two different polarity domains by LP-MOVPE. The A domain has higher etching rate than that of 5 domain. To avoid the peeling-off of GaN film, the growths carry out in extremelylow hydrogen partial pressures at 850°C. The growth rate on B domainis faster than that on A domain. X-ray rocking curves show that the film grown on A domain has better quality (FWHM0002 =248 arcsec) than that on B domain FWHM0002 =433 arcsec) . TEM image shows that the threading dislocation density on A domain is obvious lower than that on sapphire. Room temperature PL measurements show that the main peak is 358 nm with FWHM 23.6 nm on the B domain and broad yellow emission (532 nm) on the A domain. In conclusion LiGaO2 with a single domain is promising substrate for the growth of high quality GaN films.

(26) Nucleation and Growth of GaN by MOCVD on a Surface Template of Oxidized AlAs: NOBUHIKO P. KOBAYASHI[1]; Junko T. Kobayashi[1]; Won-Jin Choi[1]; P. Daniel Dapkus[2]; [1]Compound Semiconductor Laboratory, Department of Materials Science and Engineering, University of Southern California, 3651 Watt Way, VHE 313, MC 0241, Los Angeles, CA 90089-0241 USA; [2]Compound Semiconductor Laboratory, Department of Electrical Engineering and Materials Science, University of Southern California, 504 Powell Hall, Los Angeles, CA 90089-0271 USA

Oxidized epitaxial AlAs grown by MOCVD on (111) Si has been used as a surface for growth of single crystal GaN by MOCVD. We focus on the GaN nucleation mechanism that leads to single crystal GaN on this oxide (AlOx), the bulk of which appears to be an amorphous/fine-grain phase. AFM, RHEED and TEM are used to examine the AlOx surface and the interface between AlOx and GaN. Microscopic morphology on the AlOx surface is found to consist of densely packed domain-like features. In addition, a crystallographic surface symmetry appears to exist on the AlOx surface. Comparison among several AlOx surfaces prepared by different procedures suggests that the AlOx surface created at the interface between a GaAs cap layer and the AlAs layer acts as a template to nucleate single crystal GaN. GaN nucleation mechanisms as well as the conditions of growth for both the AlAs will be discussed.

(27) Photocurrent of 1eV GaInNAs Lattice-Matched to GaAs: JOHN F. GEISZ[1]; Danial F. Friedman[1]; Jerry M. Olson[1]; Sarah R. Kurtz[1]; [1]NREL, 1617 Cole Blvd., Golden, CO 80401 USA

The spectral photocurrent response, or quantum efficiency, of GaInNAs lattice-matched to GaAs with a bandgap of 1 eV has been measured in an electrochemical cell in order to optimize material quality for use in a three or four junction solar cell lattice-matched to GaAs or Ge. GaInNAs with 3% nitrogen grown by MOVPE using dimethylhydrazine as a nitrogen source was found to be p-type with hole concentrations of $1x10^{17}$ cm^{-3} due to unintentional carbon doping as observed by SIMS. This unintentionally doped material typically had 20% relative quantum efficiencies 200 meV above the bandedge. By doping the material with Si, Se, or Zn, we find that the quantum efficiency is strongly correlated with the carrier concentration. Relative quantum efficiencies range from 40% at a carrier concentration of $1x10^{16}$ cm^{-3} down to <1% at carrier concentrations above $1x10^{18}$ cm^{-3}. Attempts to improve material quality and understand these trends are discussed.

(28) Stimulated Emission from Optically Pumped Cubic GaN/AlGaN Double Heterostructures: JUN WU[1]; Hiroyuki Yaguchi[1]; Georg Mohs[1]; Takao Aoki[1]; Makoto Kuwata Gonokami[1]; Kentaro Onabe[1]; Hiroyasu Shiraki[2]; [1]The University of Tokyo, Department of Applied Physics, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033 Japan; [2]The University of Tokyo, RCAST, Komaba 4-6-1, Meguro-ku, Tokyo 153-0041 Japan

We report on the observation of stimulated emission from the cleaved edge of optically pumped cubic GaN/AlGaN double heterostructures at 10 K. The GaN/AlGaN heterostructures were grown on GaAs (100) substrates by MOVPE using 1,1-dimethylhydrazine as the N source. A heterostructure consists of a 150-nm-thick cubic $Al_{0.1}Ga_{0.9}N$ layer, a 200-nm-thick cubic GaN active layer, and a 10-nm-thick cubic $Al_{0.25}Ga_{0.75}N$ clad layer. The cavity length is 0.6 mm. A third harmonic generation (355 nm) of Q-switched Nd: YAG laser, with 30 Hz, 7 ns pulse was used for optical pumping. The emission spectra showed that above the threshold power density (2.5 MW/cm^2), strong stimulated emission can be clearly observed at 384 nm on the longer-wavelength side of the spontaneous emission. With increasing excitation power density, further red-shift of stimulated emission was also observed.

Low Dimensional Structures

(29) Self-Organized GaInAs Islands Grown from Tertiarybutylarsine at Atmospheric: TARJA KORKALA[1]; [1]Helsinki University of Technology, Optoelectronics Laboratory, Otakaari 7A, Espoo FIN-02150 Finland

GaInAs islands with x(In)=0.5 are grown on (100) GaAs substrate by atmospheric-pressure metal-organic vapor phase epitaxy using tertiarybutylarsine as an arsenic source. The critical thickness for the island formation is about 4 ML at 470-550°C. It is observed that the growth rate and V/III ratio have an substantial effect on the uniformity and density of the islands. At the growth temperature range studied the island density decreases with increasing V/III ratio varied in the range of 8-60. At 510°C low growth rates produce the most dense and homogeneous distribution of islands. However, at 550°C the uniformity and the density are practically equal at the growth rate range of 0.5-4.0 ML/s. Photoluminescence from the overgrown sample indicate that the highest optical properties are obtained with the growth rate of 2.5 ML/s. The narrowest ground and clearly resolvable excited state peaks have the width of less than 40 meV.

(30) UV Laser Selective Growth of InAs Quantum Dots: ANDREAS WANKERL[1]; Alfred Todd Schremer[1]; James Richard Shealy[1]; [1]Cornell University, OMVPE Facility, School of Electrical Engineering, 20 Thornwood Drive, Ithaca, NY 14850 USA

We report on the selective area growth of InAs quantum dots on GaAs by UV laser stimulated organometallic vapor phase epitaxy. Operating in the kinetically limited regime, exposure to a 248.2 nm CW laser beam enhances the growth rate locally via adlayer photolysis, which causes the transition from 2D to 3D growth mode to occur in the laser stimulated region only. Size and density of the locally grown InAs islands are assessed by atomic force microscopy. Photoluminescence spectra from the UV laser stimulated growth region show both wetting layer and quantum dot luminescence, whereas only the wetting layer peak is present in the spectra from the dark grown regions. Photoluminescence maps show good spatial agreement between the region exhibiting quantum dot luminescence and the UV stimulated spot size.

(31) Optical Transitions in Strain-Induced Quantum Dots with Modified Self-Organized InP Stressors: MARKKU SOPANEN[1]; [1]Helsinki University of Technology, Optoelectronics Laboratory, Otakaari 7A, Espoo FIN-02150 Espoo Finland

InP islands are grown on GaAs substrate at the growth temperatures of 600-680°C using atmospheric-pressure metal-organic vapor phase epitaxy and tertiarybutyl sources for arsenic and phosphorous. Deposition of 3 ML of InP with a growth rate of 1.5 ML/s results in the formation of very uniform InP islands with an areal density in the range of 109 cm-2. The average height of the uniform islands can be controlled in the range of 10-30 nm by changing the growth temperature. The photoluminescence spectra of the uncapped samples are dominated by two 0-dimensional features, a type-II transition between the electrons confined into the InP islands and the holes in GaAs and transitions related to the confinement potential in GaAs created by the strain field of the InP islands. Time-resolved luminescence studies show a decay time of about 10 ns and 1 ns for the type-II and the strain-induced dot transition, respectively.

(32) Multiatomic Step Formation During GaAs/AlGaAs Multiple Quantum Well Growth on Patterned Vicinal Substrates and Its Application to Quantum Wire Structures: YASUHIRO ODA[1]; Takashi Fukui[1]; [1]Hokkaido University, Research Center for Interface Quantum Electronics, North 13 West 8, Sapporo, Hokkaido 060-8628 Japan

We report on the formation process and characterization of multiatomic steps grown by MOVPE on patterned vicinal (001) GaAs substrates which have 0.6-4.0um period mesa stripes. Formation process of multiatomic step on patterned vicinal substrates is investigated by cross-sectional SEM and AFM observations. Multiatomic steps with the same period to the pattern are formed during GaAs/AlGaAs growth. The uniformity of multiatomic step period and the straightness of step edges are much improved compared to the multiatomic step formed on vicinal substrates. The step formation depends strongly on pattern period and growth thickness and less on misorientation direction and growth temperature. For example, the angles between the multiatomic step edge and (001) terraces change 24 degree for 4.0um period to 11 degree for 0.6um. Details of formation processes will be discussed. We also fabricate GaAs quantum wire (QWR) structures utilized these structures, and confirm the emission from QWR structures by CL spectra and CL images at 4.2 K.

(33) Effect of the Growth Parameters on the Luminescence Properties of High Quality GaAs/AlGaAs Multiquantum Wells on (111)A Substrates by MOVPE: ALFREDO SANZ-HERVÁS[1]; Soohaeng Cho[1]; Jongseok Kim[1]; ARNOLDO MAJERFELD[1]; Constantino Villar[2]; B.W. Kim[3]; [1]University of Colorado, Department of Electrical and Computer Engineering, CB425, Boulder, CO 80309 USA; [2]ETSIT-UPM, Dpto. de Tecnología Electrónica, Ciudad Universitaria, 28040 Madrid, Spain; [3]Electronics and Telecommunications Research Institute, PO Box 106, Yusong, Taejon 305-600 Korea

We report a study of the growth parameters and their effect on the structural and optical properties of GaAs/AlGaAs Multi-Quantum Well (MQW) structures grown on novel (111)A-oriented GaAs substrates by atmospheric-pressure Metalorganic Vapor Phase Epitaxy (MOVPE). The MQW structures had typically 25 periods with a well width of 40 Å and an Al fraction in the barriers of 25 % and were grown at 600 °C using V/III ratios ranging from 20 to 150, various growth rates, and exact (111)A and misoriented substrates. The crystal quality was assessed by high-resolution X-ray diffractometry. The optical quality was evaluated by low temperature photoluminescence (PL) and photoreflectance spectroscopies. We determined the growth conditions to obtain high structural quality and optimum PL emission intensity. A PL linewidth of 10.5 meV was achieved, which is the lowest value reported to date for GaAs/AlGaAs MQWs on (111)A or (111)B GaAs by any growth technique.

(34) Selective Area MOVPE Growth of Prism-Shaped GaAs Resonators for Folded Cavity Surface Emitting Lasers: WLODEK STRUPINSKI[1]; Andrzej - Malag[2]; [1]Institute of Electronic Materials Technology, III-V Epitaxy, Wolczynska 133, Warsaw 01-919 Poland; [2]Institute of Electron Technology, Optoelectronics, al.Lotnikow 32/46, Warsaw, 02-668 Poland

Selective Area (SA) MOVPE proves to be an effective method of manufacturing non-planar structures with precisely controlled sizes and orientations of their facets. Excellent flatness of the facets makes SA MOVPE especially useful for optoelectronic applications such as microcavities. In the work we used this technique to grow of prism-shaped GaAs cavities for novel prismatic (folded) cavity surface emitting laser diodes. A concept of this devices has been recently proposed. Critical points in growing the cavities are: i)to ensure 90deg angle at top corner, ii)to obtain flat walls of the GaAs prism (of the size of 4 micr. at the base) with the sharp top (without a platen), iii)to avoide excessive number of polycrystalline precipitates on a surface of a dielec tric mask (100nm thick) despite very dissadvantageous ratio of openings to masked area. Growth-rate calculations have been performed using total area of mask openings as an active substrate surface. For realisation of proper prisms growth the pulsing epitaxy technique using Aixtron MOVPE LP system was applied, where interruption growth periods enabled efficient surface molecules migration into openings. Optimisation of the growth/interruption time versus partial pressure of gallium was the key to get suitable for laser application shape of prisms. The best results for 2 micr. high prisms have been obtained for 200 pulses of 2s growth/3s interruption, when total pressure and temperature were 100mbar and 700degC, respectively. To improve laser characteristics, embedding of quantum films inside the prism cavity is under investigation.

Device Structures

(35) Growth Monitoring of GaInP/GaAs Heterojunction-Bipolar-Transistors by Reflectance-Anisotropy-Spectroscopy: PAUL KURPAS[1]; Michael Arens[2]; Detlef Gutsche[1]; Eberhard Richter[1]; Frank Brunner[1]; Markus Weyers[1]; [1]Ferdinand-Braun-Institut (FBH), Rudower Chaussee 5, Berlin D-12489 Germany; [2]Sentech Instruments GmbH, Rudower Chaussee 6, Berlin, 12484 Germany

Reflectance-Anisotropy-Spectroscopy (RAS) was applied as in-situ probe during the growth of GaInP/GaAs Heterojunction-Bipolar-Transistors (HBT). Production conditions, i.e. wafer rotation, were used in an AIX200 MOVPE system. The amplitude of the oscillating signal (RAS transients taken at a fixed photon energy) gives the same information on surface anisotropy as obtained on static wafers. In transients at 2.8 eV each layer of the HBT structure is represented by a specific signal amplitude. Even n-GaAs layers with different doping levels (1017 - 1018 cm-3) are clearly distinguished. GaInP etch-stop and emitter layers cause pronounced interference structures that allow for the assessment of the emitter thickness on nm scale. Due to its self-normalizing signal RAS measurements are reproducible and largely undisturbed by wafer wobble making this technique compatible with production requirements. Its sensitivity to doping types and levels yields information not provided by other optical techniques and makes it a suitable finger-printing tool.

(36) Surface Characterization of Ordered (GaIn)P Using HRTEM: TORSTEN SASS[1]; Ines Pietzonka[1]; Volker Gottschalch[1]; Gerald Wagner[1]; [1]Universitaet Leipzig, Fakultaet f. Chemie u. Mineralogie, Linnestr.3-5, Leipzig, D-04103 Germany

A detailed knowledge of the nature of the sample surface contributes to the understanding of the growth mechanism of MOVPE grown layers and enables the control of the growth process for device structures. AFM investigations revealed differences of the surface morphology between GaAs and (GaIn)P. To resolve the monolayer steps High Resolution-TEM experiments have been carried out on [110]-cross-sectional specimen of GaAs and CuPt-type ordered (GaIn)P. The samples under investigation were grown by low pressure MOVPE on nominally (001) GaAs substrates using phosphine, tertiarybutylphosphine and ditertiarybutylphosphine as group-V precursors. The influence of the growth temperature, the angle of substrate misorientation towards the [1-10] direction and the different group-V precursors on the distribution of monolayer steps has been determined. A correlation was found between the surface morphology and ordered domains in (GaIn)P. The additional characterization of the sample surfaces using AFM revealed island-like structures on all (GaIn)P-layers. Our results indicate distinct differences in the growth mechanisms of (GaIn)P and GaAs.

(37) MOCVD Ga0.75In0.25As0.2Sb0.8PiN Structure Materials for 2.4 um Photodectors: RUIWU PENG[1]; Cheng Peng[1]; Zanguo Wang[1]; [1]Chinese Academy of Science, Shanghai Institute of Metallurgy, Shanghai 20050 China

GaInAsSb alloys lattice matched to GaSb substrates seems to be ideally suitable for the optoelectronic devices of wavelength range from l.7 to 4.2. Several works on the preparation MOCVD GaInAsSb have been published but few papers described the doping process and electrical properties. This paper described the preparation of n- and p— GaInAssb epilayers together with their electrical properties and PIN device performances. Under optimum conditions the undoped Ga1-xIn-xAs1-ySby (x=0~0.3 and y = l ~ 0.8) grown on GaSb substrates have been obtained with good morphology. For preparation of PIN structure materials the n- and p~ doping processes for GaSb and GaInAsSb epilayers were studied. A saturation doping level at n = 5 x 1017 cm-3 was appeared for n- doped epilayers. Unlike the Te- doping, the Zn-doping levels increases from 1 x 1017 to I x 1018 cm-3 with DEZe partial pressure increasing from 5 x 10-7 to 1 x l0-5 atm. The variation of mobilities vs. carrier concentrations of unintentional and intentional n- and p- doped GaSb and GaInAsSb epilayers were shown with comparison of the published data. For device application we also determined the conduction types of GaSb and GaInAsSb epilayers grown on GaSb substrates by thermoelectric probe using the thermoelectric force or Seebeck voltage generated by a temperature gradient. By increasing the In component XIn,so as to decrease the band gap of GaInAsSb, we found the voltage difference between the two probes changes from positive to negative when XIn 0.25. It seem to be impossible to fabricate an GalnAsSb PIN junction that has a detecting wavelength longer then 3 u m unless the operation temperature was reduced lower then the room temperature. In present paper the PIN structure materials consisting unintentional doped p-GaInAsSb homojunction in a slightly n- doped Ga1-xInxAs1-ySby (x =0.25 and y = 0.8) epilayer on Te doped GaSb substrate was used to fabricate the 2.4 u m photodetectors. The spectral response and detectivity measurements of several photodetectors showed that D* = 2.3 x 1010 (for 2.2 u m) and 1.6 x 1010 (for 2.4 u m) cm. Hz12 .w-1 at room temperature were achieved. These data are greater than that published for LPE and MOCVD devices.

(38) In-Situ Monitoring of GaAs and InP Oxide Desorption in MOVPE: KERSTIN KNORR[1]; Daniel Fischer[2]; Jörg-Thomas Zettler[1]; Elisabeth Steimetz[1]; Wolfgang Richter[1]; [1]Technical University of Berlin, Solid State Physics, PN 6-1, Hardenbergstr. 36, Berlin D-10623 Germany; [2]Hahn-Meitner-Institut GmbH, Glienicker Str. 100, Berlin, Berlin D-14109 Germany

Most epitaxial processes in MOVPE of III-V semiconductors start with thermal desorption of the oxide layer at the substrate surface. In MBE the oxide desorption temperatures are known and monitoring the oxide desorption with RHEED is a standard procedure. In MOVPE oxide desorption turns out to be significantly modified by the actual gas phase. Therefore reflectance anisotropy spectroscopy (RAS) and spectroscopic ellipsometry (SE) are used here in-situ to study the oxide desorption of GaAs and InP. The influence of different ambient gases (H2, N2, H2/hydrides, N2/hydrides, H2/alternative V-precursors) and differently prepared oxides on the desorption temperature and the resulting surface roughness and surface reconstruction is studied. Before growth oxide thickness was measured with SE and it is found that different oxide thicknesses also cause different desorption temperature ranges and different roughnesses. The surface morphology of substrate surfaces is additionally studied ex-situ by atomic force microscopy (AFM). The results are summarized in an oxide desorption model.

(39) AlInGaAs QW Laser Characteristics as a Function of Oxygen Associated with Trimethylindium: JOHN STUART ROBERTS[1]; J.P. R. David[1]; P. L. Tihanyi[2]; L. Smith[3]; [1]University of Sheffield, Dept of Electronic Engineering, Mappin Street, Sheffield S1 3JD UK; [2]PLT Technology Inc., 7D Herman Drive, Simsbury, CT 07006 USA; [3]Epichem Ltd., Power Road, Bromborough, Wirral, Merseyside L62 3QF UK

The inclusion of indium into a quantum well (QW) laser gain region has been shown to improve operating lifetime by pinning defect propagation. [1]. In this presentation the characteristics of GRINSCH laser diodes will be presented where the QW is constructed from AlInGaAs. Two wavelengths form the core of the investigation, principally 808 nm and 740 nm where the indium fraction is approximately 6% and the Al fraction has been varied to control the operating wavelength. These two wavelengths are of commercial importance for high power applications. Although the time-zero threshold and slope efficiency are acceptable for both wavelengths, lifetimes were dependent upon the source of trimethylindium. SIMS assessment of an InAlAs test structure clearly identified a significantly greater oxygen concentration from one particular TMI source. When this TMI was used for the MOVPE growth of 808 nm GRINSCH lasers, all devices showed rapid degradation, typically a 14% threshold current increase over 140 hours for a constant 200mW output. [1] "Growth of InAlGaAs strained quantum well structures for reliable 0.8 micron lasers J.A.Baumann, R.J.Daley, R.G.Waters, S.L.Yellen, C.Harding and A.Shepard. J.Electronic Materials Vol.23 No2 (1994) 207-216

(40) Selective Growth and Regrowth Of High Al Content AlGaAs for Use in BH Lasers: WON-JIN CHOI[1]; P. Daniel Dapkus[1]; [1]University of Southern California, Department of Electrical Engineering, University Park, Los Angeles, CA 90089-0271 USA

We demonstrate an enabling technology approach for fabricating selectively grown BH lasers by MOCVD based on selective growth and regrowth of AlAs and AlGaAs. Carrier and light confining layers as well as current blocking layers in ultralow threshold current VCSELs and WDM VCSEL arrays are enabled by our results. Techniques for regrowth of active layers of lasers as well as selective growth of AlAs current blocking layers will be presented. The techniques are employed for the growth of a 3 step AlGaAs/GaAs/InGaAs laser with comparable performance to devices grown in a single step and to demonstrate the use of selectively grown AlAs native oxide layers as current blocking layers (CBL) in BH lasers. 3 step BH InGaAs quantum well edge emitting lasers with AlAs native oxide CBL have been fabricated using this technology with threshold currents as low as 11 milliamps for 8 μm wide stripes. The leakage current at -15Volts was as low as several nanoamperes.

(41) InGaP/GaAs Shadow-Mask for Optoelectronic Integration and MBE Regrowth: PETER VELLING[1]; Bernhard Knuepfer[2]; Walter Fix[2]; Werner Prost[1]; G H Doehler[2]; F J Tegude[1]; [1]Gerhard-Mercator-Unversity-Duisburg, Solid-State Department, Kommandantenstrasse 60, Duisburg 47057 Germany; [2]Friedrich-Alexander-University Erlangen-Nuernberg, Institute of Technical Physics, Erwin-Rommelstrasse 1, Erwin-Rommelstrasse 1, Erlangen, 91058 Germany

Selective growth and monolithic integration of optoelectronic components can be substantially improved by epitaxial shadow mask technology. Well known is the substrate rotation dependent MBE modulation doping for advanced n-i-p-i modulators. However, the formerly used AlGaAs/GaAs shadow masks grown by MBE results in substantial technological problems such as complicated regrowth on Al-containing layers, low growth rate for up to 6 μm thick layers, low and only one-directional etch selectivity which results in poor mask undercut. In this work we will present the development of a novel InGaP/GaAs mask incorporating 700 nm lattice matched InGaP and embedded layer sequences for pin-diode, pinFET, and HBT grown by LP-MOVPE. This technology provides excellent masks for easy MBE regrowth, which solves all of the above problems mainly due to the extremely high and bi-directional etch selectivity. In addition, the embedded devices exhibit state-of-the-art performance e.g. the leakage current of the pin-diode is less than 10 pA (5 V) and the highly sensitive pinFET-switch shows a channel conductance modulation of 105. Based on these achievements a novel highly sensitive receiver could be realized based on a (preliminary hybrid) integration of pinFET and HBT. An output current switching of 120 μA at an optical input power as low as 0.2 nW is demonstrated and also a transimpedance gain of 3500 V/W at 140 μA optical input power. Our results suggest that the sophisticated shadow mask technology becomes feasible on an industrial level by MOVPE/ MBE hybrid growth.

(42) Growth of InGaAsP in a Stagnation Flow Vertical Reactor Using TBP and TBA: IN KIM[1]; Dae-Gye Chang[1]; P. Daniel Dapkus[1]; [1]University of Southern California, Dep. Electrical Engineering-Electrophysics and Materials Science, University Park, SSC 502, MC 0483, Los Angeles, CA 90098-0483 USA

Growth of InP and InGaAsP using tertiarybutylphosphine (TBP) and tertiarybutylarsine (TBA) with a showerhead stagnation flow vertical reactor is reported for the first time. Thermal decomposition at the inlet and coating of the showerhead can affect reproducibility for inlet-susceptor spacings of 1-2 cm. This work demonstrates that the reactor can be used with TBP and TBA by keeping the boundary layer for their thermal cracking thinner than the inlet susceptor spacing. It is also found that reduced boundary layer thickness is necessary in achieving high quality material at low V/III ratio. The incorporation of group III element is controlled by the momentum boundary layer in most cases, while the decomposition rate is the key factor in group V incorporation. Taking a full advantage of the uniformity of this vertical reactor design, the stagnation flow design is found to add more controllability to the growth condition.

(43) MOVPE Growth of Tunable DBR Laser Diode Emitting at 1060 nm: FRANK BUGGE[1]; Arne Knauer[1]; Ute Zeimer[1]; Juergen Sebastian[1]; V. B. Smirnitski[1]; A. Klehr[1]; Marcus Weyers[1]; Guenther Traenkle[1]; [1]Ferdinand-Braun-Institut, Materials Technology, Rudower Chaussee 5, Berlin D-12555 Germany

Tunable DBR laser diodes (LD) emitting at 1060 nm were fabricated by MOVPE. For such a long emission wavelength a high indium content in the InGaAs quantum well is necessary. In-segregation, a reduced In-incorporation due to the high strain and the danger of strain relaxation require a careful optimization of the In-profile and the growth conditions. The DBR LD was grown in a 2-step epitaxy where the gratings were produced in a GaAs waveguide layer and overgrown by a AlGaAs cladding layer. Regrown laser diodes with 50 µm stripe width and without DBR section show threshold current densities similar to laser diodes grown by one step epitaxy (slope efficiency = 0.96 mW/mA; j(th) = 104 A/cm-2). A very low threshold of 12 mA and an output power up to 55 mW in cw were achieved for a DBR LD with 5 µm ridge width and 30% output facet reflectivity. The linewidth at 30 mW is lower than 0.85 MHz and the continuous tuning range without mode hopping is higher than 300 GHz.

(44) Doping Optimizations for InGaAs/InP Composite Channel HEMTs: JEAN DECOBERT[1]; Gaelle Rondeau[1]; Carine Ladner[1]; Hassan Maher[1]; Aline Falcou[1]; Sylviane Biblemont[1]; Georg Post[1]; [1]France Telecom — CNET, CCO/TMO, 196 av Henri RAVERA, BP107, Bagneux, Cedex 92225 France

InGaAs/InP composite channel HEMTs are good candidates for 40 Gbit/s modulator driver applications where both high speed and high breakdown voltage are required. To achieve simultaneously these criteria, different arsenide layers in the double channel have been grown by LP-MOVPE : lattice matched InGaAs, pseudomorphic InGaAs and double InGaAs lattice matched channel with an InAlGaAs δ-doped separator. For each structure, δ-doping level must be precisely adjusted as well as the n type donor concentration in the InP sub-channel. In this study, Hall mobilities and sheet carrier densities at 300K have been measured on three different patterns : 1) with undoped InGaAs cap layer kept on, 2) with cap layer recessed, 3) with cap layer recessed and TiAu gate metalization deposited. Hall data compared to static and dynamic characteristics measured on transistors near the Hall patterns will be presented for the different heterostructures. This optimisation has led to a transistor with f_T/f_{max} = 80/160GHz for 0.4 µm gate length.

II-VI

(45) MOCVD of Vertically Stacked CdSe/ZnSSe Quantum Islands: UDO W. POHL[1]; Rolf Engelhardt[1]; Volker Türck[1]; Dieter Bimberg[1]; [1]Technical University of Berlin, Institute of Solid State Physics, Secr. PN5-1, Hardenbergstr. 36, Berlin, D-10623 Germany

The use of vertically stacked quantum dots in the active region of a laser diode has proved to increase the material gain and to induce excitonic waveguiding. We studied stacks of nominally 1 monolayer thick CdSe layers inserted between ZnSSe barriers of different composition and spacer thicknesses, cladded by ZnMgSSe. Formation of CdSe quantum islands with three-dimensionally confined excitons was proven by low-temperature cathodoluminescence. Strong vertical coupling of the islands starts below 50 Å and results in a luminescence red-shifted with respect to the emission of uncoupled islands. The luminescence half width sensitively depends on the interface quality. Best results were obtained with barriers using a Se to Zn ratio near unity. Diffusion of Cd at an increased ratio and interface roughening at a reduced ratio are revealed by X-ray studies on ZnCdS/ZnSSe structures. Control of composition, the effect of strain and optical properties of the quantum islands will be presented.

(46) Synthesis of CdSe Quantum Dot - ZnS Matrix Thin Films Via Electrospray: JASON R. HEINE[1]; Javier Rodriguez-Viejo[2]; Moungi G. Bawendi[3]; Klavs F. Jensen[4]; [1]Massachusetts Institute of Technology, Materials Science and Engineering, 66-501, 77 Massachusetts Avenue, Cambridge, MA 02139 USA; [2]Universidad Autonoma de Barcelona, Grupo de Fisica de Materiales I, Dpto Fisica, 08193, Bellaterra, Spain; [3]Massachusetts Institute of Technology, Chemistry, 6-223, 77 Massachusetts Avenu, Cambridge, Massachusetts 02139 USA; [4]Massachusetts Institute of Technology, Materials Science and Technology, 66-566, 77 Massachusetts Avenue, Cambridge, Massachusetts 02139 USA

A modified organometallic chemical vapor deposition (OMCVD) technique is used to incorporate luminescing II-VI nanocrystals (NCs) into ZnS thin films. The NCs are synthesized in organic solution and consist of a CdSe core and ZnS shell. The ZnS matrix is deposited by OMCVD from diethyl zinc and hydrogen sulfide while the NCs are delivered to the film surface via electrospray. Varying the size of the CdSe NC core enables tunable emission from the blue to the red. The ZnS shell provides electronic and chemical passivation of the CdSe core improving its luminescence and thermal stability. The thin films exhibit room temperature photoluminescence (PL) and cathodoluminescence (CL) dominated by emission from the NCs. PL quantum efficiencies greater than ten percent have been achieved. The dependence of thin film luminescence and microstructure on deposition temperature is studied using optical spectrometry and x-ray diffraction. Particular emphasis is placed on the relationship between the host ZnS structure and the optical properties of the NC-ZnS composite thin film.

(47) Thin Films of CdTe/CdS Grown by MOCVD for Photovoltaics: Rebecca A Berrigan[1]; STUART J.C. IRVINE[1]; Brian Klaveness[1]; David J Cole-Hamilton[2]; David Ellis[2]; [1]North East Wales Institute, OMRL, Plas Coch, Mold Road, Wrexham, Wales LL11 2AW United Kingdom; [2]University of St. Andrews, Chemistry Dept, Purdie Building, North Haugh, St. Andrews, Fife KY16 9ST United Kingdom

The CdTe/CdS/(SnO2 or ITO)/glass structure is a promising photovoltaic structure, but reported efficiencies fall well short of the theoretically derived potential of approximately 30%. The potential exists to utilise MOCVD in the deposition, controlled doping and contacting of material suitable for thin, lightweight, highly efficient solar cells suitable for space applications. Previously, growth of CdTe/CdS photovoltaic devices by MOCVD has concentrated on the absorbing layer but not the whole structure. MOCVD growth of CdS and CdTe onto ITO coated glass, via the controlled pyrolysis of dimethylcadmium, ditertiarybutylsulphide and diisopropyltellurium are reported. Optimised nucleation of CdS onto ITO exhibit an average grain size of approximately 10 micron with preferred orientation of (100). Absorption and transmission spectra of these CdS films will be presented, indicating that lower temperatures (< 300° C) are preferred for MOCVD growth in maximising transmission. Growth of CdTe with preferred orientation (111) is shown to produce films also containing grains of 10 micron average size indicating good nucleation of CdTe onto CdS. Cadmuim telluride films doped using trisdimethylaminoarsenic were then grown on Cl doped CdS films and first results have been obtained to confirm the formation of a working photovoltaic structure. Electrical characterisation results of these devices will be presented.

(48) A New Mechanism for Nitrogen Incorporation In ZnSe: B. HAHN[1]; E. Griebl[1]; M. Kuttler[2]; W. GEBHARDT[1]; D. Bimberg[2]; [1]Universität Regensburg, Institut für Festkörperphysik, Universitätsstr. 31, 93040 Regensburg Germany; [2]TU-Berlin, Institut für Festkörperphysik, Hardenbergstr. 36, 10623 Berlin, Germany

P-type conductivity of ZnSe:N grown by MOVPE is still hard to obtain. Especially the incorporation mechanism of the doping species is not yet well understood. Therefore we investigated systematically the interaction of various Zn-precursors (dimethyl-zinc, diethylzinc, dimethylzinc-triethylamine) with commonly used Nitrogen sources (substituted amines and phenylhydrazine) in combination with di-tert. butylselenide as selenium source. The experiments were conducted in photoassisted and conventional growth mode. In both cases we observed a pronounced influence of the zinc source on the doping efficiency of the nitrogen precursors. The later is mainly determined by positive charge located at the H-atom of the NH-group. The influence of the dissociation energy of the N-alkyl bond is however negligible. Based on the experimental observations and MO-calculations we propose a reaction mechanism for the incorporation of nitrogen at the growing surface, which occurs via a reaction of the undecomposed nitrogen precursor with alkyl-zinc complexes on the crystal surface.

Surface Characteristics

(49) An Atomic-Resolution Study of MOCVD-Prepared As/Vicinal Ge(100): WILLIAM E. MCMAHON[1]; John F. Geisz[1]; Jerry M. Olson[1]; [1]National Renewable Energy Lab, 1617 Cole Blvd., Mail Stop 3212, Golden, CO 80401 USA

Atomic-resolution scanning tunneling microscope (STM) images have been obtained of vicinal (100) Ge and As/Ge surfaces prepared in a low-pressure metal-organic vapor deposition (MOCVD) chamber. Combined with in-situ reflectance-difference spectra, these images have allowed us to identify the surface phases in an MOCVD environment. The three main phases are clean Ge(2x1), As/Ge(1x2) and As/Ge(2x1). As/Ge(1x2) is formed in the presence of background As_4 with no other source of As, while As/Ge(2x1) is formed when the surface is exposed to AsH_3. All of these phase changes are reversible. In addition, a transition to a rough surface at high temperatures is observed. Detailed images of the step structures on these surfaces reveal a step structure which is consistent with existing theories for step-driven nucleation of single-domain GaAs on Ge(100) miscut towards (111). Relevance to GaAs/Ge nucleation and growth will be discussed.

(50) MOCVD Growth of Single Monolayers of InAs in GaAs Studied by Time-Resolved Reflectance Difference Spectroscopy: JAMES ANIL GUPTA[1]; Simon P. Watkins[1]; Richard A. Arès[2]; Georg Soerensen[1]; [1]Simon Fraser University, Department of Physics, Simon Fraser University, Burnaby, BC V5A 1S6 Canada; [2]Nortel Ltd., Nortel Ltd., Ottawa, Ontario Canada

Using reflectance difference spectroscopy (RDS), we have obtained real-time spectroscopic data of the evolution of the GaAs(100) surface during the deposition of a single InAs monolayer (ML), and subsequent growth of a GaAs capping layer. This reflectance-difference information was obtained by recording multitransient spectra, at fixed energies from 1.5 to 4.9 eV during the growth of 35 periods of an InAs(1 ML) /GaAs(100 Å) superlattice. From an initial d(4X4)-like GaAs surface under tertiarybutylarsine the RDS spectrum changes rapidly to a (2X4)-like InAs spectrum following the deposition of 1 ML of InAs. In contrast, during the growth of the GaAs cap, the evolution to the characteristic spectrum of the GaAs growing surface occurs over several monolayers . Growth temperature effects were studied in a series of such samples produced at temperatures from 450 to 600 °C. Samples were characterized using atomic force microscopy and high-resolution X-ray diffraction.

(51) An X-ray Standing Wave Study of Ultrathin InAs Films in GaAs(100) Grown by Atomic Layer Epitaxy: JAMES ANIL GUPTA[1]; Joseph C. Woicik[2]; Simon P. Watkins[1]; K. E. Miyano[3]; J. G. Pellegrino[2]; E. Daryl Crozier[1]; [1]Simon Fraser University, Department of Physics, Simon Fraser University, Burnaby, BC V5A 1S6 Canada; [2]National Institute of Standards and Technology, National Institute of Standards and Technology, Gaithersburg, Maryland 20899 USA; [3]Brooklyn College, Department of Physics, Brooklyn College, Brooklyn, New York 11210 USA

Synchrotron X-ray Standing Wave measurements have been used to study 1 monolayer and 1/2 monolayer InAs films buried in GaAs(100). The films were grown by atomic layer epitaxy using trimethylgallium, tertiarybutylarsine and trimethylindium. For the full monolayer we find the indium atoms reside 1.565±0.010 Å above the GaAs(004) substrate planes. The coherent fraction of 0.69±0.06 indicates a reasonably smooth interface, as confirmed by the photoluminescence full-width at half maximum of 5.7 meV. The half monolayer is slightly less strained, with the indium atoms at 1.53±0.01 Å above the substrate planes. These results compare favourably with results from similar samples produced by molecular beam epitaxy.

(52) Investigation of Surfaces and Interfaces of Epitaxial Structures by Reciprocal Mapping of Bragg-Surface Diffraction: SÉRGIO LUIZ MORELHÃO[1]; Antonio Carlos Franco da Silveira[1]; Eduardo Abramof[2]; Alain André Quivy[3]; [1]Universidade de São Paulo, Departamento de Física Aplicada, CP 66318, São Paulo, SP 05315-970 Brazil; [2]Instituto Nacional de Pesquisas Espaciais, Lab. Associado de Sensores e Materiais, CP 515, São José dos Campos, SP 12201-970 Brazil; [3]Universidade de São Paulo, Lab. de Novos Materiais Semicondutores, CP 66318, São Paulo, SP 05315-970 Brazil

Bragg-Surface diffraction (BSD) is a special case of three-beam diffraction, where the secondary beam is scattered in the surface parallel direction. Under BSD condition, the surface-detour reflection (secondary plus coupling reflections) transfers some of the secondary beam intensity into the monitored primary beam. The regime, primary or secondary extinction, in which such transfer takes place, depends on the crystalline perfection of the surface. Therefore, by mapping the BSD condition, in a omega:phi scan technique, information regarding the lattice coherence length (dislocation density) and in-plane mosaicity has been obtained [1,2]. In most commercial diffractometers for semiconductor analysis, instrumental modifications (mainly regarding the incident beam optics) would be necessary in order to map a BSD properly. It is a strong limitation for a wide use of the technique as an analytic tool for studding surfaces and interfaces. In this work, we are proposing a new procedure to investigate the BSD. In a triple axis diffractometer, reciprocal space mapping of Bragg symmetric reflection (primary reflection) is performed in and out of the BSD condition. When a forbidden or weak primary reflection is chosen, the intensity distribution around the primary reciprocal lattice point, i.e. the rod of the primary reflection, is defined by the surface-detour reflection. The procedure has been applied to study effects of epitaxial growth on the surface of GaAs [001] substrates. The quality of surface before and after the growth of GaAs buffer layers, and the propagation of defects into GaAlAs layers and superlattices. Although the structures were growth by molecular beam epitaxy, the procedure reported here is general to any epitaxial growth technique. [1] Appl. Phys. Lett. 71(18), 2614 (1997)[2] J. Appl. Cryst. 29, 446-456 (1996)

(53) Real-Time Spectroscopic Ellipsometry and FTIR Spectroscopy Monitoring of Ti1-xNbxO2 Growth by Plasma-Enhanced MOCVD: YUFEI GAO[1]; [1]Pacific Northwest National Lab, Environmental Molecular Sci. Lab, P.O. Box 999, MS K8-93, Richland, WA 99352 USA

Ti1-xNbxO2 films with Nb content up to 20 at.% were grown on Si(100) at temperatures from 400 °C to 800 °C using Ti isopropoxide and Nb ethoxide. Real-time spectroscopic ellipsometry and FTIR have been used simultaneously to monitor growth of the Ti1-xNbxO2 thin films. Time-dependent ellipsometric data obtained during the MOCVD growth were fitted using the Cauchy function for Ti1-xNbxO2 to determine optical constants, growth rates, and layer thickness. The refractive index of the films increases as increasing the growth temperatures, while the refractive index changes slightly as a function of Nb contents at a given temperature. The increase of the refractive index is primarily due to a phase transition from pure anatase at 400 °C to pure rutile at 750 °C. Moreover, the data fitting using a surface roughness layer revealed that the film growth can be divided into three stages: nucleation and coalescence, homogenous growth, and surface roughness evolution. Real-time FTIR spectra taken just above the substrate surface suggested that there was no gas phase decomposition of the precursor vapor at substrate temperature up to 800 °C. However, the composition was observed when the oxygen plasma power was increased to 800 W.

(54) Early Stages of Heteroepitaxy of Gallium Phosphide on Silicon: KLAUS J. BACHMANN[1]; Nkadi Sukidi[2]; Vijay Narayanan[3]; Subhash Mahajan[3]; [1]North Carolina State University, Department of Materials Science and Engineering and Department of Chemical Engineering, Box 7919, Raleigh, NC 27695 USA; [2]North Carolina State University, Department of Materials Science and Engineering, Box 7919, Raleigh, NC 27695 USA; [3]Arizona State University, Department of Chemical, Bio and Materials Engineering, PO Box 876006, Tempe, AZ 85287-6006 USA

The nucleation, coalescence of islands and heteroepitaxial film growth of GaP on low index faces of GaP is characterized by real-time monitoring using p-polarized reflectance (PR), laser light scattering (LLS), in conjunction with atomic probe and transmission electron microscopy studies of surface topography, facetting and evolution of the microstructure in later stages of island growth. The initial nucleation results in perfect GaP nuclei. The size of these nuclei increases with increasing temperature and is limited under conditions of chemical beam epitaxy to ≤ 15nm. Nucleation is preceded by an incubation period of duration τ_i, which is a sensitive function of surface orientation [$\tau_i(100) < \tau_i(111) < \tau_i(311)$] and of substrate temperature. The observed decrease of τ_i with increasing temperature is related to the surface kinetics. Also, characteristic features in the PR and LLS intensity are discussed in the context of process control that must include the early stages of incubation and nucleation to control the quality of heteroepitaxial film growth.

Wednesday AM - June 3, 1998

Plenary Session

Wednesday AM Room: Grand Ballroom D & E
June 3, 1998 Location: Sheraton Grande Torrey Pines

Session Chairs: R. D. Dupuis, The University of Texas at Austin, Microelectronics Research Center, Austin, TX 78712-1100 USA; J. Olson, National Renewable Energy Laboratory, Golden, CO 80401 USA

8:20 AM INVITED PAPER
Exploitation of Surface Selective Growth in Metalorganic Growth Technologies for Device Applications: E. VEUHOFF, Siemens Corporate Technology, Dept. ZT KM 4, D-81730 Munich, Germany

Surface selective growth (SGG) is gaining importance for the realization of complex device concepts. An understanding of SGG mechanisms in growth and doping is required for the optimization of device structures, and moreover it is the basis for the development of novel advanced devices. The paper addresses basic SGG mechanisms both in metalorganic vapor phase epitaxy (MOVPE) and in metalorganic molecular beam epitaxy (MOMBE/CBE). It is described how these mechanisms can be exploited for the fabrication of complex devices focusing on the InP based material system. Additionally it is shown that with novel precursors new effects can be observed in SGG. Results of discrete and integrated devices are presented. The potential of SGG in MOVPE and MOMBE for an industrial use is discussed in a critical comparison.

8:50 AM INVITED PAPER
Progress in the Crystal Growth and Future Prospects of Nitrides by Metalorganic Vapor Phase Epitaxy: I. AKASAKI[1]; [1]Meijo University, Nagoya, Japan

Progress in the crystal growth and basic understanding of the growth mechanism for the heteroepitaxial growth of GaN on highly mismatched substrates by MOVPE have enabled us to grow high quality thin GaN, AlGaN, GaInN and even AlInN films and their heterostructures with specular surfaces free of cracks. Conductivity control of both n-type and p-type nitrides has also been achieved. These achievements have led to the realization of high performance light emitters, field effect transistors and UV detectors. Quite recently, reduction of dislocation density has also been achieved by either lateral overgrowth or multi buffer layer technique, which will surely lead to the realization of much higher performance devices based on nitrides. Future prospects of the nitride based novel devices will also be discussed.

9:20 AM Break into Parallel Sessions

Quantum Wells, Wires, and Dots

Wednesday AM Room: Grand Ballroom A & B
June 3, 1998 Location: Sheraton Grande Torrey Pines

Session Chairs: R. d. Dupuis, The University of Texas, Austin, TX 78712-1100 USA; L. Samuelson, Lund University, S-221 00 Lund, Sweden

9:30 AM
GaNAs/GaInAs Short-Period Super-Lattice Quantum Well Structures Grown by MOCVD Using TBAs and DMHy: TOMOYUKI MIYAMOTO[1]; Shunichi Sato[2]; Zhong Pan[1]; Dietmar Schlenker[1]; Fumio Koyama[1]; Kenichi Iga[1]; [1]Tokyo Inst. of Tech., P & I Lab., 4259 Nagatsuta, Midori-ku, Yokohama, Kanagawa 226-8503 Japan; [2]Ricoh Co., Ltd., General Electronics R & D Center, 5-10 Yokatakami, Kumanodo, Takadate, Natori, Miyagi 981-12 Japan

The MOCVD growth of GaInNAs/GaAs quantum wells (QWs) using TBAs and DMHy was studied for realizing 1.3mm lasers on GaAs substrates. It is one of the problems on MOCVD growth of GaInNAs that the nitrogen (N) composition of GaInNAs is limited to much smaller than that of GaNAs grown at the same nitrogen supply. In this study, we grew GaInNAs QWs as a short-period super-lattice using GaNAs and GaInAs to realize a high N incorporation. Both layers had 3 monolayer thickness and the total thickness of the well was 6nm. The In composition of GaInAs layer was 0.6. By comparing the peak wavelength of a room temperature photoluminescence with a sample without the DMHy flow, we observed 20nm red shift of emission wavelength from GaNAs/GaInAs QW. The estimated N composition in the GaNAs layer was 0.003 and it was found that the required DMHy flow could be as low as about 1/10 compared with that of a conventional GaInNAs for the same N composition.

9:50 AM
GaInAsN/GaAs Quantum Wells Grown by Low Pressure OMCVD: RAJARAM BHAT[1]; Lourdes - Salamanca-Riba[2]; [1]Corning Inc., NVC 3Z-203, 331 Newman Springs Rd., Red Bank, NJ 07701 USA; [2]University of Maryland, Department of Materials & Nuclear Engineering, Building 090, College Park, Maryland 20742-2115 USA

We will report on the growth and characterization of both thick GaInAsN layers and GaInAsN/GaAs quantum wells using dimethylhydrazine as the nitrogen source. The layers were characterized using DCXRD, room temperature photoluminescence, surface photovoltage spectroscopy, optical microscopy, TEM, and SIMS. Well defined Pendellosung oscillations observed in x-ray rocking rocking curves of GaInAsN layers indicated that the crystalline quality was excellent. While photoluminescence emission was observed in GaAsN, emission from GaInAsN was observed either when the In content was low or when the In content was high and the N content low. We speculate that this behaviour is due to deep levels, possibly oxygen related, being introduced from the dimethylhydrazine source. Despite these limitations, GaInAsN/GaAs quantum wells with emission wavelengths as long as 1.32 microns have been achieved, although the emission intensity from these wells was seen to drop off significantly beyond ~1.2 microns. The effect of annealing on the quantum well emission intensity and wavelength will also be reported.

10:10 AM
MOVPE Growth of Strained InGaAsN/GaAs Quantum Wells: HISAO SAITO[1]; Toshiki Makimoto[1]; NAOKI KOBAYASHI[1]; [1]NTT Basic Research Laboratories, Material Science Research Laboratory, 3-1, Morinosato Wakamiya, Atsugi-shi, Kanagawa Pref. 243-0198 Japan

Strained $In_{0.3}Ga_{0.7}As_{1-X}N_X$ (x=0~0.01)/GaAs quantum wells (QWs) of 10-nm thickness were grown by MOVPE at 500ϒC using dimethyl hydrazine (DMHy) as a nitrogen source. Nitrogen is incorporated non-linearly into the solid with an increase in the ratio of DMHy partial pressure in the vapor phase. The peak energy of photoluminescence (PL) is red-shifted up to the composition of x=0.002 with showing a large band-gap bowing of - 82 eV. The as-grown $In_{0.3}Ga_{0.7}As_{0.99}N_{0.01}$ QW has a weak PL intensity, which is more than two orders of magnitude lower than that of $In_{0.3}Ga_{0.7}As$ QW, but by annealing in N_2 atmosphere at 650ϒC, the PL intensity is recovered and shows a peak at 1.26-micron at 10 K. By the SIMS analysis, a hydrogen incorporation of as high as 6x1019cm-3 is observed in as-grown $In_{0.3}Ga_{0.7}As_{0.99}N_{0.01}$ QW and the hydrogen concentration is reduced to 2.5x1019 cm-3 after 1 hour annealing. It is considered that the hydrogen incorporation is due to the incomplete decomposition of $NH_{2\ in}$ DMHy and that the depassivation of hydrogen by annealing results in the recovery of PL intensity.

10:30 AM Break

11:00 AM

Photoluminescence Excitation Spectroscopy of GaPAsN/GaP Lattice-Matched Multiple Quantum Well Structures: Goshi Biwa[1]; Hiroyuki Yaguchi[1]; KENTARO ONABE[1]; Yasuhiro Shiraki[2]; [1]The University of Tokyo, Department of Applied Physics, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033 Japan; [2]The University of Tokyo, Research Center for Advanced Science and Technology, 4-6-1 Komaba, Meguro-ku, Tokyo 153-0041 Japan

We first report on the MOVPE growth of $GaP_{0.85}As_{0.13}N_{0.024}$/GaP lattice-matched multiple quantum well (MQW) structures. In the low temperature photoluminescence (PL) and PL excitation (PLE) spectra of the MQW structures with larger well width (>36A), no remarkable change can be seen compared with GaPAsN bulk. On the other hand, MQWs with very thin well layers(16A and 24A) exhibit the large blue shift of the absorption edge in PLE spectra, and the additional PL peak appears at this absorption edge. These behaviors are considered to be due to the exciton localization in GaPAsN layers; the quantum confinement effects does not occur until the well width is decreased to the extent of the wave functions of localized excitons. In addition, PL intensities of all MQW samples at room temperature are 10^3 or 10^4 times larger than that of GaPAsN bulk because of effective carrier confinement and few misfit dislocations.

11:20 AM

1-eV Solar Cells with GaInNAs Active Layer: DANIEL J. FRIEDMAN[1]; John F. Geisz[1]; Sarah R. Kurtz[1]; Jerry M. Olson[1]; [1]National Renewable Energy Laboratory, 1617 Cole Blvd., Golden, CO 80401 USA

The GaInP/GaAs tandem solar cell has achieved record-setting efficiencies of 26% under the AM0 (space) spectrum, and 30% at 500 suns terrestrial. It has been calculated that if a 1-eV GaAs-lattice-matched cell could be fabricated, it could be used as the basis for extending the tandem structure to four-junction structures with efficiencies of 46% (500 suns) and 36% (AM0). Here, we demonstrate 1-eV solar cells based on GaInNAs active layers on GaAs. The cells were grown by MOVPE, using dimethylhydrazine as the nitrogen source. The resulting quantum efficiencies have well-defined absorption edges of 1 to 1.1 eV, but magnitudes of only about 0.2. Open-circuit voltages range from 0.39 to 0.49 eV, short-circuit-currents from 5.3 to 7.3 mA/cm^2, and fill factors from 45% to 68%. The dependence of these device parameters on the GaInNAs materials properties will be discussed.

11:40 AM

Formation and Characterization of 70nm-Period Lateral Surface Superlattices Grown on GaAs Multiatomic Steps by MOVPE: MASASHI AKABORI[1]; Junichi Motohisa[1]; Takashi Fukui[1]; [1]Hokkaido University, Research Center for Interface Quantum Electronics, North 13 West 8, Sapporo, Hokkaido 060-8628 Japan

We report on the formation and characterization of novel lateral surface superlattices (LSSLs) utilizing multiatomic steps which are known to be formed naturally on vicinal surfaces during MOVPE. The potential modulation of present LSSL is brought forth by the periodic thickness modulation of a GaAs layer in an AlAs/GaAs/n-AlGaAs selectively doped double heterostructure grown on GaAs multiatomic steps. The period of LSSL is about 70nm, and its amplitude is estimated to be 17meV. The transport properties in periodic potential is characterized at low temperatures. The anisotropy of mobility is found for the current parallel and perpendicular to the steps. In addition, the magnetoresistance shows the "Weiss oscillations". Furthermore, when the Fermi energy is set sufficiently below the barrier height of periodic potential, clear conductance oscillations are observed in the drain current - gate voltage characteristics of a narrow channel device, which are thought to originate from the Coulomb blockade effect with multiple tunnel junctions.

12:00 PM

Effect of Interface Roughness on Performance of AlGaAs/InGaAs/GaAs Resonant Tunneling Diodes: JIANG LI[1]; T. F. Kuech[1]; A. Mirabedini[2]; L. J. Mawst[2]; D. Botez[2]; D. E. Savage[3]; R. J. Matyi[3]; [1]University of Wisconsin-Madison, Chemical Engineering Department, 1415 Engineer Dr., Madison, WI 53706 USA; [2]University of Wisconsin, Electrical Engineering Department, 1415 Engineering Dr., Madison, WI 53706 USA; [3]University of Wisconsin-Madison, Materials Science and Engineering, 1500 Engineering Drive, Madison, WI 53706 USA

The interface roughness of AlGaAs/InGaAs/GaAs double barrier quantum well structures were controllably altered by changing substrate surface misorientation and growth interruption time at the MOVPE growth interfaces. AFM and X-ray reflectance measurements were used to quantify the interface roughness. The InGaAs quantum wells grown on singular substrates show an island growth mode, while step-bunched growth is observed on the misoriented substrates. Short growth interruption timeof typically ~15 sec decreases the InGaAs/AlGaAs interface roughness. The low temperature I-V characterization of the resonant tunneling diodes based on this quantum well structure is sensitive to the quantum well interface roughness. A simulation was used to quantitatively correlate the interface roughness to the I-Vcharacteristics and subsequent device performance.

Selective Area Growth

Wednesday AM Room: Grand Ballroom D & E
June 3, 1998 Location: Sheraton Grande Torrey Pines

Session Chairs: J. Olson, National Renewable Energy Laboratory, Golden, CO 80401 USA; E. Veuhoff, Siemens Corporate Technology, D-81730 Munich, Germany

9:30 AM

Material Localisation at GaInAsP Rigde-Structures Selectively Grown by MOMBE: MARTIN HURICH[1]; Rainer Butendeich[1]; Harald Heinecke[1]; [1]University of Ulm, Dept. Semiconductor Physics, Albert-Einstein-Allee 45, 89081 Ulm, Germany

GaInAsP ridges with vertical side walls can be achieved by metalorganic molecular beam epitaxy (MOMBE) when using substrates with misorientated surfaces. The anisotropic surface diffusion of group III growth species leads to localisation in material composition at these vertical side walls and at the transition (111) facets. Spatially resolved photoluminescence measurements show a second recombination signal at lower recombination energies. The behaviour of the intensity and the energy offset compared to the recombination originated from the ridge centre has been investigated for different GaInAsP material composition. For that purpose, selectively grown InP ridge structures have been overgrown with quaternary GaInAsP (lambda = 950 to 1550 nm) and ternary GaInAs layers. Both energy confinement and recombination intensity of the side facet recombination signal show a maximum (DeltaEg,max = 111 meV) at nominal material composition with wavelength between 1050 and 1250 nm. The effect of group III alcyle prereactions on this localisation will be discussed for the application in low dimensional structures.

9:50 AM

Step-Free Surface and Interface by Finite Area MOVPE: TOSHIO NISHIDA[1]; Tetsuya Akasaka[1]; Yoshiharu Yamauchi[1]; Naoki Kobayashi[1]; [1]NTT Basic Research Laboratories, Material Science Research Laboratory, 3-1, Morinosato Wakamiya, Atsugi-shi, Kanagawa Pref. 243-0198 Japan

Atomically step-free surfaces and interfaces are characterized by AFM and spatial resolved photoluminescence. Step-free surface of GaAs, InAs and $Al_{0.3}Ga_{0.7}As$ are obtained on GaAs (111)B substrates by finite area epitaxy such as by growth on patterned substrate or by selective area growth. Stoichiometry control by in-situ surface photo absorption measurement is indispensable in atomic flatness control. We discuss flattening mechanism both on migration and on desorption. Utilizing desorption balance condition, step-free surface is possible however large its size is, as long as its size is finite. A 100-micron-wide step-free GaAs surface was obtained utilizing desorption balance. An 8-micron-wide step-free monolayer InAs/GaAs quantum well and 2-3 micron wide step-free area in $GaAs/Al_{0.3}Ga_{0.7}As$ quantum well were also obtained. We also show the versatility of this method in the MOVPE of InP and GaN.

10:10 AM

Narrow-Stripe Selective Growth of High Quality MQW by Atmospheric Pressure MOVPE: KAZUO MORI[1]; Hiroshi Hatakeyama[1]; Kiichi Hamamoto[1]; Keiro Komatsu[1]; Tatsuya Sasaki[1]; Takashi Matsumoto[1]; [1]NEC Corporation, Optoelectronics and High Frequency Device Research Laboratories, 34, Miyukigaoka, Tsukuba, Ibaraki 305-8501 Japan

Narrow-stripe selective MOVPE is very attractive method for fabricating opto-electronic devices, because active and passive waveguides can be directly formed on a narrow (<2 micrometers)-stripe region without any chemical etching process and exhibit low propagation loss due to flat (111)B side facets. In this paper, we report on atmospheric pressure narrow-stripe selective MOVPE, for the first time. An extremely large bandgap wavelength shift of 370nm was obtained for selectively grown InGaAsP/InGaAsP MQW with small mask width variation (0~30 micrometers), retaining good selectivity. This value was four times lager than that by 75 Torr growth. High quality MQWs with flat interfaces and narrow RT PL FWHM of 35meV (4 microwatts/1 micrometer-ϕ) were obtained by controlling surface migration of metalorganic species. Based on these results, 1.55 MQW FP-LDs were fabricated and the RT CW threshold current was as low as 5mA.

10:30 AM Break

11:00 AM

Control of Selective Area Growth and Regrowth of InP on Mesas by MOCVD Using TBP: IN KIM[1]; Denis Tishinin[1]; P. Daniel Dapkus[1]; [1]University of Southern California, Dep. of Electrical Engineering-Electrophysics, University Park, SSC-502, MC-0483, Los Angeles, CA 90089-0483 USA

The selective area growth (SAG) and regrowth of InP using tertiarybutylphosphine (TBP) around mesa structures for application to buried hetrerostructure (BH) fabrication is presented. Reduced leakage currents through current blocking layers are achieved by regrowth on vertical sidewall of dry etched structures compared to sloped chemically etched structures owing to the different growth morphologies of the two structures. Dependence of the growth behavior on V/III ratio, growth temperature, and reactor pressure shows that a well defined high index plane is formed over a limited range from the mesa when enough TBP is decomposed to limit the In species migration length. Unfortunately, this condition is fulfilled by using a low temperature, high V/III ratio, and high reactor pressure which conflict with the optimized SAG conditions. We will discuss the compromises that need be made to optimize this regrowth and to achieve planarized regrowth on the mesa structure after dielectric removal.

11:20 AM

Planar Selective Regrowth of High Resistivity Semi-Insulating InP by LP-MOVPE for Buried Lasers Using TBP: HERVÉ SIK[1]; Yann Le Bellego[1]; Pascal Win[1]; Sophie Bouchoule[1]; Gilles Patriarche[1]; Pierre Boulet[1]; Gilles Le Mestreallan[1]; Abdallah Ougazzaden[1]; [1]France Telecom - CNET, DTD/OOG, 196, Avenue Henri Ravera, BP107, Bagneux, Cedex 92225 France

LP-MOVPE selective regrowth of Fe-doped InP layers on non planar heterostructures has been studied to achieve current confinement in buried heterostructure lasers. Further technological processing after regrowth require a planar surface without overgrowth on both sides of the ridge mask. Approaches previously reported are either difficult to reproduce or deteriorate the material quality. Here, we have studied the growth behaviour of Fe-doped InP in different conditions. We have noted that the initial growth step is an important phase to define the features of the final grown pattern. Appropriate growth conditions with TBP have been found to planarize the surface without edge effect. In these conditions a resistivity higher than 10^8 Ω.cm is obtained. A perfect selectivity is obtained even with a mask as large as 500 µm. Material quality has been characterized by SEM and TEM. Further materials characterizations and device results will be presented.

11:40 AM

Overgrowth of Trenches with (AlGa)As Using MOVPE: LARS HOFMANN[1]; Arne Knauer[1]; Ingrid Rechenberg[1]; Ute Zeimer[1]; Siegfried Gramlich[1]; Jürgen Sebastian[1]; Markus Weyers[1]; [1]Ferdinand-Braun-Institut für Höchstfrequenztechnik, Rudower Chaussee 5, Berlin D-12489 Germany

Real index self-aligned structure (RISAS) laser structures were produced by MOVPE by filling trenches in (InGa)P with (AlGa)As waveguide layers. A homogeneous, well defined refractive index profile is important for laser function. Inhomogeneous Al-distribution in the trenches, influencing the refractive index, were revealed by cathodoluminescence. Using high-resolution scanning electron microscopy, the influence of growth parameters and orientation of the trenches on the development of the growth front during overgrowth and on the surface morphology is shown. To minimize the region with different refractive index on the sidewalls high temperature and low reactor pressure are used. A change in growth rate causes no effect on the structure. While for [1-10]-oriented trenches, a higher V/III-ratio results in a stronger inhomogenity of the Al content, no influence of the V/III-ratio for [110]-trenches is observed. The results of the growth studies were successfully used for growing laser structures.

12:00 PM

Multiple-Wavelength Vertical-Cavity Surface-Emitting Laser Arrays Fabricated by Selective Area Epitaxy: HONG Q HOU[1]; M E Coltrin[1]; B E Hammons[1]; K D Choquette[1]; N. Y. Li[2]; [1]Sandia National Laboratories, Compound Semiconductor Materials, MS 0603, Albuquerque, NM 87185 USA; [2]University of New Mexico, Center for High-Technology Materials, Albuquerque, NM 87106 USA

A 2-dimensional (2D) vertical-cavity surface-emitting lasers (VCSELs) array with each element emitting at different wavelength is very desirable for wavelength-division multiplexing (WDM) fiber-optic communication systems and free-space reconfigurable interconnects. We report fabrication of such an array using selective area growth (SAG) technique by MOVPE. We have used a two-dimensional steady-state finite-difference calculation to model the flux of materials on the masked and exposed areas of an annular-ring array pattern. The thickness and composition enhancements of perfectly-selectively grown InGaAs/GaAs/AlGaAs heterostructures measured from thickness profiler and cathodoluminescence measurements are in an excellent agreement with the modeled results. With this design the quantum-well emission wavelength from each array element changes to longer wavelength with the enhanced thickness of the optical cavity due primarily to the composition enhancement in the InGaAs layer. This "tracking" of the emission wavelength with the cavity mode wavelength is extremely attractive for achieving uniform laser characteristics from each array element. We have grown VCSELs emitting at ~940 nm wavelength with InGaAs/AlGaAs quantum wells embedded in AlGaAs/GaAs DBR mirrors. A 4x4 selectively-oxidized VCSEL array with chirped wavelengths as designed are achieved with a single SAG for the cavity region. The research was performed at Sandia National Laboratories, a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under contract No. DE-AC04-94AL85000.

High Power, High Temperature Semiconductor Materials and Devices

Wednesday PM June 3, 1998
Room: Grand Ballroom A & B
Location: Sheraton Grande Torrey Pines

Session Chairs: G. B. Stringfellow, University of Utah, Department of Materials Science, Salt Lake City, UT 84112 USA; K. Furuya, Tokyo Institute of Technology, Tokyo 152 Japan

2:00 PM

Development of a Borosilicate-Glass-Bonded Compliant Substrate: DARREN M. HANSEN[1]; Peter D Moran[1]; Kathy A. Dunn[2]; Susan E. Babcock[2]; Richard J Matyi[2]; Thomas F. Kuech[1]; [1]University of Wisconsin, Chemical Engineering, 1415 Engineering Drive, Madison, WI 53706-1691 USA; [2]University of Wisconsin, Materials Science, 1500 Engineering Drive, Madison, WI 53706-1691 USA

The critical thickness limitation for lattice mismatched heteroepitaxial growth could potentially be removed by the use of a compliant substrate. A compliant substrate allows for the growth of a lattice-mismatched material on an extremely thin "substrate", typically <10 nm, which is supported by a low viscosity compliant layer. This work presents initial results for the development of a borosilicate-glass-bonded compliant substrate. This compliant substrate consists of a 10 nm GaAs layer bonded to a borosilicate glass engineered to have a low viscosity at the growth temperature of the lattice mismatched layer. Strain relief during lattice mismatch growth is provided by viscous flow of the compliant layer driven by the shear stress generated during growth. This compliant substrate was used to grow 2 um of In0.45Ga0.55As (3.1% lattice mismatch to GaAs). Initial results from x-ray diffraction and Orientational Imaging Microscopy experiments demonstrated that epitaxy was achieved between the growth and template layer. These results demonstrate the ability to form thin films (<10 nm) on a glass substrate. Optical microscopy, atomic force microscopy, and scanning electron microscopy were also used to characterize both the initial borosilicate-glass-bonded compliant substrate as well as the grown structures.

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Control of Dopant Distribution Profiles in GaInP Laser Diodes with Mg- and Se-Doped AlInP Cladding Layers: ROLF WINTERHOFF[1]; [1]Universität Stuttgart, 4. Physikalisches Institut, Pfaffenwaldring 57, Stuttgart, Baden-Württemberg 70550 Germany

High doping levels on either side of a double heterostructure laser are required for optimal performance and temperature stability, especially in the AlGaInP material system. However in most cases these are accompanied by strong diffusion during growth, shifting the p-n-junction and damaging the active zone. We investigated the possibility of suppresssing the diffusion towards the active zone by introducing thin intermediate layers of different materials and doping levels as well as short period superlattices. Using SIMS measurements we found that non Indium containing layers as GaP and GaAs are suited to at least slow down diffusion of the magnesium on th p-side and produce a rather steep dopant front. On the other hand the presence of the additional interfaces going along with that seems to have a negative influence on the electrical properties of the device, resulting in increasing threshold currents and reduced quantum efficiencies. To determine the decisive factors for this behavior, further optical measurements were carried out on the samples. In another approach the ability of highly n-doped AlInP intermediate layers was investigated.

2:40 PM

Optimization of p-Dopant Profiles for GaInAsP MQW Laser Structures in MOMBE: Philipp Kroener[1]; Horst Baumeister[1]; EBERHARD VEUHOFF[1]; Michael Popp[2]; Harald Heinecke[2]; [1]Siemens AG, Dept. ZT KM 4, Otto-Hahn-Ring 6, Munich, Germany D-81730; [2]University of Ulm, Dept. of Semiconductor Physics, Albert-Einstein-Allee 45, Ulm, D-89069 Germany

For industrial device fabrication in metalorganic molecular beam epitaxy (MOMBE/CBE) gaseous dopant sources are preferred as in MOVPE. In both technologies, diethylzinc is used. However, dopant diffusion effects can be detrimental to device performance. The critical parts in InP based ridge waveguide laser structures are the active region with GaInAsP confinement layers, MQW layers and the p-type region with InP spacer layer, GaInAsP etch stop layer and InP cladding layer. Growing Zn doped InP in between GaInAsP layers always leads to a significant Zn diffusion into the adjacent GaInAsP layers. This effect is much more pronounced in MOMBE than in MOVPE. It is demonstrated how this effect is reduced by insertion of undoped intermediate layers, and by compensating Si codoping in the spacer and adjacent layers taking advantage of the Fermi level effect. Applying these techniques, reduced threshold current densities and improved high temperature performance can be obtained. The results are discussed by models of dopant diffusion in MOMBE in comparison to MOVPE.

3:00 PM

Design, Growth and Performance of Different QW Structures for Improved 1300 nm InGaAsP Lasers: CHRISTOFER SILFVENIUS[1]; Hjalmar S. Granberg[1]; Gunnar Landgren[1]; [1]Royal Institute of Technology (KTH), Department of Electronics, Laboratory of Semiconductor Materials, Electrum-229, Kista, S-164 40 Sweden

We have investigated three alternative InGaAsP 1300 nm compressively strained MQW-lasers by simulation and LP-MOVPE fabrication. The designs have radically different MQW-compositions but similar calculated properties concerning gain, carrier distribution, thresholds and optical output. The structures considered have constant-As, constant-Ga or InAsP/quaternary (λ_g=1100 nm) materials in wells and barriers. Growth conditions were optimised for each design. Evaluation of the constant-As MQW resulted in poor XRD-peaks and PL-response. The InAsP MQW's exhibited clearly defined XRD-satellites but as the As-content was increased to reach 1300 nm, PL properties degraded severely. In contrast, the constant-Ga MQW indicated superior material quality with excellent PL and XRD properties. Measurements of broad area lasers made from these constant-Ga structures with up to 12 QW's resulted in excellent numbers, $\alpha_{internal}$=10/cm, $\eta_{internal}$=80%, and J_{th}=120A/cm^2/well. Apparently the constant-Ga structure allows some strain compensation and simultaneously avoids the problem with growth undulation/interdiffusion typically encountered for the InAsP and constant-As cases.

3:20 PM Break

3:40 PM

Growth and Characterizaton of Impatt Diodes for RF Applications: D. K. GASKILL

Abstract not available.

4:00 PM

Influence of Structural In0.48Ga0.52P/GaAs Heterojunction Properties on Hole Confiment and Transport in DB-RTD and HBT: PETER VELLING[1]; Guido Janssen[1]; Michael Agethen[1]; Werner Prost[1]; Franz Josef Tegude[1]; [1]Gerhard-Mercator-University-Duisburg, Solid-State Electronics Department, Kommandantenstrasse 60, Duisburg 47057 Germany

In0.52Ga0.48P/GaAs-heterostructures were grown by LP-MOVPE in order to determine the influence of the interface characteristics on structural and electronic device properties. Superlattices and p-type RTD structures were used for a detailed interface characterization due to evaluation of the quasi-forbidden (200)-reflex in GaAs by HR-XRD, dynamical theory and analytical equations based on kinematical theory. The formation of a strained In0.52Ga0.48As-interlayer of at least 1 ML at the InGaP-to-GaAs transition is determined by simulation as well as by analytical equations correlated to specific layer. The impact of strained interlayer on hole confinement in HBT and vertical transport is studied. P-type RTDs exhibiting excellent data of peak-current density SPeak>1.104 A/cm2, Peak-to-valley-ratio PVR>2 and negative differential resistance up to T=200K are realized still showing non-symmetric current-voltage characteristics which are attributed to the interlayer. In HBTs the emitter-base junction is most essential. In emitter-up devices the critical GaAs-to-InGaP BE-junction may explain the measured moving emission in photoluminescence. However, the less abrupt inverse interface cause several problems in collector-up HBT and may inhibit the future development of this device.

4:20 PM

Comparison of Single- and Double-Barrier Pseudomorphic GaInP/GaInAs HFETs: SHELDON MCLAUGHLIN[1]; XIANGANG XU[2]; Simon P. Watkins[2]; Colombo R. Bolognesi[1]; [1]Simon Fraser University, School of Engineering Science, 8888 University Drive, Burnaby, British Columbia V5A 1S6 Canada; [2]Simon Fraser University, Department of Physics, 8888 University Drive, Burnaby, British Columbia V5A 1S6 Canada

To date, most published reports of GaInP/GaInAs HFETs (or HEMTs) have focused on single-barrier GaInP/GaInAs quantum well structures with the GaInAs QW grown directly on a GaAs buffer. In the present work, we compare the performance of single-barrier GaInP/GaInAs/GaAs and double-barrier GaInP/GaInAs/GaInP/GaAs doped-channel HFETs grown on GaAs S.I. substrates. Our epitaxial layers were grown on S.I. GaAs substrates in a Thomas Swan MOCVD reactor equipped with TBA and TBP precursors. The HFET structures use a very thin 200 Å GaAs buffer layer, and the channel layers consist of a 150 Å $Ga_{0.85}In_{0.15}As$ channel doped with Si to 3 x 10^{12} cm^{-2}. Double barrier HFETs show higher transconductances and output resistances, and thus provide a higher voltage gain gm/gd: A comparison of 1um gate devices with IDmax = 350-400 mA/mm reveals a 60 % increase in the voltage gain for the double barrier devices. These results are attributed to the improved channel confinement in double barrier quantum wells. A comparison of DC, RF and isolation properties will be presented.

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Ordering in (Ga,In)(As,P) Grown on GaAs by Metalorganic Vapour Phase Epitaxy: ARNE KNAUER[1]; G. Oelgart[2]; A. Oster[1]; F. Bugge[1]; F. Bugge[1]; S. Gramlich[1]; P. Ernst[3]; M. Weyers[1]; [1]FBH, Rudower Chaussee 5, Berlin, D-12489 Germany; [2] Universität Leipzig, Fakultät für Physik und Geowissenschaften, Linnéstr. 5, Leipzig, Sachsen D-04103 Germany; [3]Universität Stuttgart, Physikalisches Institut, Pfaffenwaldring 57, Stuttgart, D-70550 Germany

Ordering in (Ga,In)(As,P) grown on GaAs by metalorganic vapour phase epitaxy was investigated by photoluminescence and diffraction methods. The data show that the occurrence of different ordering variants is not only sensitive to the growth conditions and the layer composition but also to small off-orientations from (100). At low arsenic content (about 15 %) the ordering is similar to (In,Ga)P. In (100) just oriented and slightly {111}A off-oriented layers (< 5°) two CuPt-type ordering variants in the {111}B planes were detected. The different intensities of the X-ray diffraction reflexes of the ordered superlattices in the <511>B directions correlate well with the measured small off-orientation (< 8 min) of the sample. At high arsenic content (about 70 %) photoluminescence excitation spectroscopy reveals that ordering leads to a valence band splitting value of 7.9 meV.

5:00 PM

The Miscibility Gap and Its Relevance toMOVPE of III/V Semiconductors: ALEXANDER BEHRES[1]; Dirk Püttjer[1]; Klaus Heime[1]; [1]RWTH Aachen, Institut für Halbleitertechnik, Templergraben 55, Aachen, D-52056 Germany

Although in nearly all ternary and quaternary systems a miscibility gap is predicted, experimental observation of phase separation in MOVPE is rare. The reasons are the stabilizing effect of the substrate and the fact that MOVPE is far from thermodynamic equilibrium. Phase separation became a more dominant problem when nitrides and antimonides were introduced in MOVPE because alloys of atoms with very different covalent binding radii have extremely large miscibility gaps, as for example InPSb. We numerically calculated the binodal and spinodal curves for ternary and quaternary alloys using the DLP model. Then, we experimentally measured the "real" miscibility gap in the GaInAsP and in the InPSb material systems. X-ray measurements show that the theoretical p redictions are very exact in the case of InPSb. In InGaAsP, strain-balanced superlattices had to be used to experimentally detect the shape of the miscibility gap. Finally, strategies were derived to intentionally provoke or inhibit phase separation.

Nitrides: Growth, Defects, Characterization and Devices - Session II

Wednesday PM — Room: Grand Ballroom D & E
June 3, 1998 — Location: Sheraton Grande Torrey Pines

Session Chairs: S. DenBaars, University of California, Santa Barbara, CA 93106 USA; I. Akasaki, Meijo University, Nagoya, Japan

2:00 PM

Influence of Ammonia Surface Reactions in GaN CVD: MICHAEL E. BARTRAM[1]; [1]Sandia National Laboratories, Chemical Processing Sciences Department, MS 0601, Albuquerque, NM 87185-0601 USA

Engineering GaN films to have specific sets of properties requires a process model that can be applied over a wide range of deposition conditions. Within this type of robust process model, the chemistry model must utilize accurate rate constants for the GaN precursor reactions. To this end, the goal of this work is to identify the reaction pathways on the surface and measure the kinetics associated with those reactions on GaN. In this study, ultra-high vacuum thermal desorption mass spectroscopy measurements of $N^{15}H_3$ chemisorbed on GaN(0001) demonstrated that ammonia can undergo both reversible and irreversible decomposition on the surface. Overall, $N^{15}H_n$ fragments and surface hydrogen from ammonia dissociation either (I) recombined to liberate $N^{15}H_3$ or (II) decomposed further to enrich the surface with nitrogen. This was accompanied by the desorption of N^{15}_2, $N^{15}N^{14}$, N^{14}_2,and H_2 at a temperature below that required for congruent GaN sublimation. Under no condition was $N^{14}H_3$ observed. These reactions are the "crossroads" for the other important reaction avenues on the surface. Con sidering case I, production of surface hydrogen from ammonia decomposition suggests that this rate may be sensitive to hydrogen coverage and hence be influenced by the H_2 carrier gas used commonly in GaN CVD. Case II suggests that in addition to supplying the nitrogen for GaN growth, ammonia decomposition can also lead to the extraction of nitrogen from the surface when the nitrogen coverages are sufficiently high. This catalytic removal of surface nitrogen in the form of $N^{15}N^{14}$ and not $N^{14}H_3$ indicates further that N-H bond formation as an initial step in potential hydrogen etching reactions can not compete with the tremendous driving force of the NN bond energy (226 kcal/mol). Therefore, while the nitrogen feed to the surface in the form of ammonia is necessary to compensate for congruent GaN sublimation and also contribute to GaN growth, it can also provide a low energy reaction pathway for the removal of nitrogen from a nitrogen enriched surface. This suggests that the overall nitrogen incorporation rate must be well-matched to the Ga deposition rate to maintain the proper stoichiometry and a reproducible overall growth rate. We have also observed that ammonia lowers the temperature for the desorption of TMG from defects on the surface. This decrease in the TMG-surface bond energy which can also lower the TMG residence time on the surface, suggests ammonia surface reactions have the potential to inhibit TMG reactions during GaN CVD. (Sandia is operated by Sandia Corporation, a Lockheed Martin Company, for the USDOE under DE-AC04-94AL85000.)

2:20 PM

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

Growth of high Al-fraction (>15%) AlGaN is necessary to realize the full potential of III-nitrides in the UV optoelectronics. Gas phase reaction between ammonia (NH3) and Trimethylaluminum (TMA) is known to cause adduct formation leading to the depletion of reactants in the gas phase. We will report the results of the in-situ monitoring of the growth rate variations by optical reflectance over a wide range of gas compositions. The formation of the (TMA:NH3) adduct not only depletes TMA from gas stream but also indirectly inhibits the incorporation of Trimethylgallium (TMG). It is observed that the incorporation of TMG could be reduced by more than 60%, probably due to either the scavenging effect of TMG by the TMA:NH3 adduct in the gas phase, or an adduct-related site blocking on the surface. The material (electrical and optical) quality of AlGaN grown under different degrees of gas-phase reaction will also be presented. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under Contract DE-AC04-94AL85000.

2:40 PM

A Reaction-Transport Model for AlGaN MOVPE Growth: THEODOROS G. MIHOPOULOS[1]; Vijay Gupta[1]; Klavs F. Jensen[1]; [1]Massachusetts Institute of Technology, Department of Chemical Engineering, Cambridge, MA 02139 USA

Metalorganic Vapor Phase Epitaxy (MOVPE) of AlGaN involves complex chemistry and transport phenomena which determines the quality of the deposited layers. The process has been studied experimentally, but a detailed understanding is missing for the mechanism underlying growth rate reduction at high temperatures and pressures, in particular the variation in severity of this effect with different reactor configurations. We present a systematic study, including quantum chemistry calculations and finite element reactor modeling, of the key processes leading to the observed growth behavior. The energetics and kinetics of formation of Lewis acid-base adducts of the organometallic precursors [TMGa:NH3 and TMAl:NH3] and subsequent elimination of methane were investigated using hybrid density functional theory (B3LYP) and transition state theory. The adduct pathway leads to the formation of stable dimer and trimer ring species containing Ga, Al, and N which strongly influence growth behavior in the reactor. Thermodynamic and kinetic results from these studies, combined with reported data for gas-phase decomposition of TMGa and TMAl, are used in macroscopic reactor modeling studies to develop a reaction-transport model for AlGaN MOVPE growth. The model predicts growth rates in excellent agreement with experimental data for growth of GaAlN in different reactor configurations, including horizontal and 'close-spaced-injector' reactors. Formation of dimers and trimers is identified as the major pathway for decreased growth efficiency with increasing pressure. A pathway involving nucleation and growth of oligomers from dimers and trimers and ultimately particle formation is consistent with decreased growth efficiency with increasing temperature. The very good agreement of simulations with experimental data across reactor configurations adds further support to the proposed mechanisms for AlGaN.

3:00 PM

Reactor Inlet Designs for Growth of GaN: C. THEODOROPOULOS[1]; H. K. Moffat[2]; T. J. Mountziaris[1]; [1]State University of New York at Buffalo, Dept. of Chemical Engineering, 303 Furnas Hall, Buffalo, NY 14260 USA; [2]Sandia National Laboratories, P.O. Box 5800-0601, Albuquerque, NM 87185 USA

This work focuses on the study of optimal gas inlet designs of vertical stagnation flow and rotating disk MOVPE reactors used for growth of GaN films from trimethyl-gallium and ammonia. During MOVPE of GaN, the two precursors can react with each other to form adducts, even at low temperature. Parasitic pre-reactions may reduce the film growth rate (or prevent growth altogether) and can adversely affect film quality. The objective of this work is to use reaction-transport simulations of GaN growth to optimize gas inlets and gas flow rates in order to obtain uniform film growth and minimize parasitic pre-reactions. Two- and three- dimensional simulations of the transport phenomena and kinetics for such systems are performed using home made finite element codes and Sandia's MPSalsa code. Kinetic models reported in the literature (and their extensions) that contain precursor condensation reactions are used and validated against reported experimental data. A range of actual and conceptual gas inlets are studied and compared, varying from axisymmetric split inlets, consisting of concentric rings, to the elaborate designs of commercial reactors.

3:20 PM Break

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AlN and AlGaN Growth Using Low-Pressure Metalorganic Chemical Vapor Deposition: FUMIHIKO NAKAMURA[1]; Shigeki Hashimoto[1]; Masaki Hara[1]; Toshiharu Imanaga[1]; Hiroji Kawai[1]; Masao Ikeda[1]; [1]Sony Corporation, Research Center, 174, Fujitsuka-cho,, Hodogaya-ku, Yokohama 240 Japan

AlN and AlGaN are useful to make a heterostructure on GaN base materials for applications to FET, LED, and LD. It is difficult, however, to make high quality AlGaN films with high Al content. We used low-pressure MOCVD at 250-700 Torr and C-face sapphire wafers as the substrate. TMG and TMA and NH3 were used as sources. In AlGaN growth the reactor-pressure dependence and TMA-flow-rate dependence were investigated. Both experiments show that the amount of loss of carried TMA is proportional to the partial pressure of TMA. As an application of AlN thin film to devices we fabricated an insulated gate heterostructure field transistor (IG-HFET). The AFM image of 4nm-thick AlN on GaN shows a rough surface composed of approximately 500nm-size grains. Nevertheless the device could operate with the highest transconductance gm of 235mS/mm for Lg=1.4micron so "far reported".

4:00 PM

Influence of Buffer Layers on the In-Content of GaInN-Layers: JUERGEN OFF[1]; Arno Kniest[1]; Ferdinand Scholz[1]; Oliver Ambacher[2]; [1]4. Phys. Inst., Universitaet Stuttgart, Pfaffenwaldring 57, Stuttgart, Baden-Wuerttemberg Germany; [2]Walter Schottky Institut, TU Muenchen, Am Coulombwall, Garching, Bayern Germany

We have studied the influence of different buffers or nucleation layers on the composition of GaInN-layers grown by LP-MOVPE. The indium-content was measured by XRD, with the symmetrical (002) and the asymmetrical (105) reflex. On the one hand, we have grown GaInN at 750°C of about 100nm thickness on GaN-buffers. The GaN-buffer was deposited on an AlN-nucleation layer at 1000°C. The thickness of the buffer is between 30 nm and 1µm. The XRD-measurments show a decrease of the In-content in the GaInN-layer with an increase of the thickness of the GaN-buffer. Additionally the reciprocal space map shows a decrease of the degree of relaxation of the GaInN. 100nm GaInN on 1µm GaN-buffer is almost fully strained. On the other hand, we deposited GaInN-layers on different low temperature nucleation layers. This layers are relaxed. However, the In-content obviously depends on the type of nucleation layer and is up to 30% higher compared to the growth on GaN buffer layers.

4:20 PM

Self-compensation in Mg Doped p-Type GaN Grown by MOCVD: HARALD OBLOH[1]; Karl-Heinz Bachem[1]; Ulrich Kaufmann[1]; Michael Kunzer[1]; Arun Ramakrishnan[1]; Peter Schlotter[1]; [1]Fraunhofer Institut IAF, Epitaxy EP, Tullastrasse 72, Freiburg, Baden-Wuerttemberg 79108 Germany

Magnesium is the only useful p-type dopant for group III-nitrides. For most MOCVD GaN:Mg samples the hole density after thermal annealing remains limited to values below 5E17 1/cm^3 even for highest Mg-concentrations. One reason for the low hole density is that for high Mg-concentrations compensation of acceptors becomes a major problem. We have investigated the hole concentration and the Mg related photoluminescence bands as a function of Mg-concentration. The hole concentration was found to reach a maximum for [Mg] near 3E19 1/cm^3. When increasing the Mg-concentration beyond this value the hole density drops rapidly. The analysis of the PL spectra reveals, that near the maximum of the hole concentration the radiative recombination mechanism changes from a free-to-bound to a donor-acceptor-pair transition. These results strongly indicate that selfcompensation effects limit the hole density in GaN:Mg samples. Based on experience with II-VI compounds we will present a model describing the selfcompensation mechanism.

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Growth and Characterization of Strongly P-Type Mg-Doped GaN: PETER KOZODOY[1]; Steven P. DenBaars[2]; Umesh K. Mishra[1]; [1]University of California at Santa Barbara, Department of Electrical and Computer Engineering, Engineering I, Santa Barbara, CA 93106 USA; [2]University of California at Santa Barbara, Materials Department, Engineering II, Santa Barbara, CA 93106 USA

Mg-doping of GaN for p-type conduction is an essential technology for high quality nitride-based optoelectronic devices. The doping efficiency is observed to be a very sensitive function of growth conditions, requiring a detailed investigation of the growth parameter space. In this work, Mg-doped p-type GaN samples have been grown by MOVPE under a variety of conditions and have been analyzed by Hall effect measurements, photoluminescence and SIMS. The nominal doping level, determined by the Mg to Ga flow ratio, was kept constant. Hole concentrations above $1x10^{18}$ cm^{-3} have been achieved under optimized growth conditions. Growth parameters such as reactor pressure, growth rate and V/III ratio were observed to dramatically impact the electrical properties of these films, changing conductivity values by an order of magnitude. The SIMS data, however, show little evidence for a change in the chemical concentration of Mg atoms. A model involving compensation by native donors is proposed to explain the changing electrical properties.

5:00 PM
The Influence of Mg-Concentration, Annealing Condition and Carrier Gas on the Electrical and Optical Properties of GaN:Mg Grown by MOVPE: BERND SCHINELLER[1]; Axel Guttzeit[1]; Markus Schwambera[1]; Klaus Heime[1]; Oliver Schön[2]; Michael Heuken[2]; [1]RWTH-Aachen, Institut für Halbleitertechnik, Templergraben 55, Aachen, D-52056 Germany; [2]AIXTRON AG, Kackertstr. 15-17, Aachen, D-52072 Germany

Annealing was found to effuse hydrogen from the lattice, hence, activating the passivated Mg-acceptors to yield p-type conductivity. We investigated the optical and electrical properties of GaN doped over a wide range of Mg-concentrations. The layers were grown at 1100°C in an AIX 200 RF MOVPE-system using the standard precursors and were annealed in a separate furnace for 15 minutes at temperatures between 600°C and 800°C. In low temperature photoluminescence we observed acceptor bound excitons and two different donor-acceptor pair recombinations (DAP) whose relative intensities depend on the doping level. At high doping levels we observe a broad blue luminescence band that we associate with a DAP involving two deep donors introduced by the high concentration of Mg. These optical data will be set into perspective to electrical, x-ray and secondary ion mass spectroscopy measurements. The influences of the carrier gas and the growth and annealing conditions will also be addressed.

Thursday AM - June 4, 1998

Plenary Session

Thursday AM	Room: Grand Ballroom D & E
June 4, 1998	Location: Sheraton Grande Torrey Pines

Session Chairs: R. M. Biefeld, Sandia National Laboratory, Albuquerque, NM 87185-0601 USA; I. B. Bhat, Rensselaer Polytechnic Institute, Troy, NY 12180-3560 USA

8:20 AM INVITED PAPER
Surface Photoabsorption Monitoring of III-V and GaN MOVPE Surfaces: NAOKI KOBAYASHI[1]; [1]NTT Basic Research Laboratories, Material Science Research Laboratory, 3-1, Morinosato Wakamiya, Atsugi-shi, Kanagawa 243-0198 Japan

Surface photoabsorption (SPA) method is a measurement using p-polarized light reflectance near Brewster angle. Since the electric field of incident p- polarized light has vertical and horizontal components, the horizontal component can respond to the anisotropic surface bonding, and the vertical one responds to the isotropic surface dielectric constant. As a result, SPA can monitor not only twofold symmetry surfaces such as GaAs (001) but also threefold symmetry surfaces such as GaAs (111)B and wurzite GaN (0001). For twofold symmetry surfaces, by subtracting spectra measured for two orthogonal principal azimuths of [110] and [1-10], the obtained spectrum corresponds to the optical transition of anisotropic surface bonding such as group V-dimer. For threefold symmetry surfaces, the surface stoichiometry can be monitored precisely. As-rich trimer surface, ¸19x¸19 surface and Ga-rich surface can be distinguished for the GaAs (111)B. For wurzite GaN (0001), Ga-rich and N-rich stoichiometry can be monitored. It was found that, in the optimal growth condition of GaN MOVPE using the partial pressure ratio of ammonia to trim ethylgallium more than 1000 and hydrogen carrier gas, the surface during growth was Ga-rich stoichiometry. This work was done in collabolation with Y. Kobayashi and T. Nishida, NTT Basic Research Labs, Japan.

8:50 AM INVITED PAPER
Ferroelectric Oxide Epitaxial Thin Films: Synthesis and Non-Linear Optical Properties: BRUCE W. WESSELS[1]; [1]Northwestern University, Materials Science and Engineering and Electrical and Computer Engineering, 2225 N. Campus Dr., Evanston, IL 60208 USA

There is a resurgence of interest in the synthesis of oxide thin films for applications including electro-optic devices, second harmonic generation, and as optical amplifiers. For integration in opto-electronic integrated circuits (OEICs), a viable technology for the deposition of optical quality epitaxial thin films is required. We have been developing metalorganic chemical vapor deposition for the synthesis of ferroelectric oxide thin films. Initial emphasis has been on $BaTiO_3$ because of its excellent electro-optic and non-linear optical properties. Epitaxial thin films have been prepared with excellent ferroelectric and non-linear optical properties. Second order non-linear optical susceptibilities of the thin films approaching the bulk va lue have been measured. The doping of the thin films with the rare earth Er has been achieved. Strong characteristic 4f shell guided wave fluorescence has been observed at 1.54 microns under optical excitation. This suggests that $BaTiO_3$ thin films may be suitable as a gain medium for integrated optical amplifiers. Thin film waveguide electro-optic modulators have also been fabricated. In addition to $BaTiO_3$, ferroelectric niobate epitaxial thin films have been deposited and their electro-optic properties measured. Prospects and challenges for utilization of these ferroelectric oxide epitaxial thin films in OEICs will be discussed.

9:20 AM Break into Parallel Sessions

Nitrides: Growth, Defects, Characterization and Devices - Session III

Thursday AM June 4, 1998 | Room: Grand Ballroom A & B | Location: Sheraton Grande Torrey Pines

Session Chairs: R. Biefeld, Sandia National Laboratory, Albuquerque, NM 87185-0601 USA; P. Demeester, IMEC-University of Gent, B-9000, Gent, Belgium

9:30 AM

MOCVD Growth of Group III Nitrides with Novel Nitrogen Precursors: KERSTIN KNORR[1]; Carsten Möller[1]; Jochen Gottfriedsen[2]; UDO W. POHL[1]; Wolfgang Richter[1]; Herbert Schumann[2]; [1]Technical University of Berlin, Institute of Solid State Physics, Secr. PN6-1, Hardenbergstr. 36, Berlin, D-10623 Germany; [2]Technical University of Berlin, Institute of Anorganic and Analytic Chemistry, Secr. C2, Str. des 17. Juni 137, Berlin, D-10623 Germany

MOCVD of group III nitrides with novel nitrogen precursors is a key issue for low temperature growth below the decomposition temperature of ammonia. We present first results with triazoles, ethylenimine and tertiarybutylhydrazine (TBHy) as N-precursors. While deposition with ethylenimine induced GaN whisker growth, the use of tertiarybutylhydrazine resulted in mosaic epitaxial layers at growth temperatures as low as 650°C and V/III-ratios <100. Cubic and hexagonal GaN material was grown on GaAs(001) and sapphire, respectively. The concentration of impurities is found to be strongly influenced by the TBHy quality. Nitridation of the substrate was a crucial step for the structural quality of the layers as proved by X-ray diffraction (XRD). We thus studied nitridation of GaAs surfaces in-situ by reflectance anisotropy spectroscopy (RAS) and ex-situ by Auger electron spectroscopy (AES) and atomic force microscopy (AFM). Spectral RAS measurements were recorded to determine the surface reconstruction prior to deposition, and RAS transients were used to monitor the temperature and time dependant changes of the surface during nitridation.

9:50 AM

GaN Growth on Ozonized Sapphire (0001) Substrates by MOVPE: TOHRU HONDA[1]; Akira Inoue[2]; Miyuki Mori[2]; Tomoe Shirasawa[2]; Nobuaki Mochida[2]; Kouji Saotome[2]; Takahiro Sakaguchi[2]; Akira Ohtomo[3]; Masashi Kawasaki[3]; Hideomi Koinuma[3]; Fumio Koyama[2]; Kenichi Iga[2]; [1]Kohgakuin University, Dept. of Electronic Engineering, 2665-1, Nakano-machi, Hachiohji-shi, Tokyo 192-0015 Japan; [2]Tokyo Institute of Technology, Precision and Intelligence Laboratory, 4259 Nagatsuta, Midori-ku, Yokohama 226-0026 Japan; [3]Tokyo Institute of Technology, Materials and Structures Laboratory, 4259 Nagatsuta, Midori-ku, Yokohama 226-0026 Japan

The ozonization of sapphire (0001) substrates has been performed prior to metalorganic vapor phase epitaxy (MOVPE) to remove carbon-pollution of sapphire substrates. The ozonization was carried out using an oxygen gas and a low-pressure mercury lamp irradiation. The result of X-ray diffraction indicates that the distribution of a c-axis tilting in the GaN layer was reduced by ozonization treatment. The photoluminescence intensity was higher than that without ozonization. The surface morphology of GaN layers also became smooth. The ozonization process is found to be effective to grow a high-quality GaN on sapphire. It is reported that oxide compounds tend to be polluted by carbon particles. Generally, a thermal heat treatment over 1000 ϒC is effective to remove a surface pollution. The carbon-related pollution was remained after the thermal heating at 1000 ϒC. It indicates that the carbon pollution cannot be removed using the thermal heating. On the other hand, using an ozone treatment, the carbon contamination on the sapphire substrate was almost removed.

10:10 AM

Thermal Nitridation of GaAs: JINGXI SUN[1]; Ling Zhang[1]; T. F. Kuech[1]; [1]University of Wisconsin-Madison, Department of Chemical Engineering, 1415 Engineering Drive, Madison, WI 53706 USA

A thin nitride layer can be formed through the ammonia-based nitridation of GaAs surfaces. This thin nitride layer is of great interest for III-V semiconductor technology since it can both passivate GaAs surfaces, by reducing the surface state density, and provide "template" for subsequent GaN deposition. The nitridation of GaAs surfaces has been performed by thermal annealing GaAs using MOVPE system under ammonia environment. The motion of GaAs surface Fermi level has been studied, and hence the surface charge density, due to thermal nitridation using photoreflectance (PR) spectroscopy. Samples consisting of an undoped GaAs on buried highly doped n-GaAs (UN+) and p-GaAs (UP+) structures allow for the determination of the surface electric field. These structures were grown by MOVPE and nitrided within the MOVPE growth system with and without exposure to air. Arsine and Trimethyl gallium (TMG) pretreatments employed in MOVPE system have prepared the initial GaAs surfaces for the subsequent nitridation. Our results show that the surface Fermi level can be shifted 0.2 eV toward conduction band edge for UN+ structures and 0.1 eV toward valence band edge for UP+ structures from the normally midgap 'pinned' position. The evolution of surface morphology of the nitrided surface was followed by atomic force microscopy (AFM). The detailed dependence of surface Fermi level and morphology on temperature, nitridation time, flow rates, and substrate crystallographic orientation is presented.

10:30 AM Break

11:00 AM

Micro Raman and Micro Photoluminescence Study of Cubic GaN Grown on 3C-SiC (001) Substrates by Metalorganic Vapor Phase Epitaxy: HIROYUKI YAGUCHI[1]; Jun Wu[1]; Baoping Zhang[2]; Yusaburo Segawa[2]; Hiroyuki Nagasawa[3]; Kentaro Onabe[1]; Yasuhiro Shiraki[4]; [1]The University of Tokyo, Department of Applied Physics, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113 Japan; [2]The Institute of Physical and Chemical Research (RIKEN), Photodynamics Research Center, 19-1399 Koeji, Nagamachi, Aoba-ku, Sendai, Miyagi 980 Japan; [3]Hoya Corporation, R&D center, 3-3-1, Musahino, Akishima-shi, Tokyo 196 Japan; [4]The University of Tokyo, Research Center for Advanced Science and Technology, 4-6-1 Komaba, Megruo-ku, Tokyo 153 Japan

We have investigated MOVPE-grown cubic GaN on 3C-SiC (001) substrates using micro Raman and micro photoluminescence spectroscopy. Under some growth conditions, GaN grains of several 10 micron size were grown on 3C-SiC substrates. Polarized micro Raman spectra unambiguously showed that rectangular flat facets and inclined facets of the GaN grains correspond to cubic phase regions and hexagonal phase regions, respectively. To examine the photoluminescence properties of "pure" cubic GaN, micro photoluminescence was performed by focusing a laser beam on the rectangular flat facet. A sharp photoluminescence line with the full width at half maximum of 5 meV was observed, which is the smallest value to date and shows that the crystal quality of the cubic phase region is excellent. We could clearly identify free exciton, donor bound exciton and acceptor bound exciton emissions in cubic GaN for the first time.

11:20 AM

Relationship between Physical Properties and Gas Purification In GaN Grown By Metalorganic Vapor Phase Epitaxy: MARIE ANTOINETTE DI FORTE-POISSON[1]; David Lancefield[2]; Estela Pereira[3]; Bela Pecz[4]; Jean Di Persio[5]; [1]Thomson CSF, LCR, Dom. de Corbeville, Orsay, Essonne 91404 France; [2]University of Surrey, Physics Dept, University of Surrey, Guilford, Surrey GU2 5XH UK; [3]University of Aveiro, Physics Dept, Campus de Santiago, Aveiro, 3818 Portugal; [4]RITP Of Budapest, Physics Dept, Foti ut 56, Budapest, H-1325 Hungaria; [5]University of Lille, Physics Dept, Villeneuve D'Ascq, Lille, North 59000 France

In this paper, we report on the structural, optical and electrical properties of LP-MOCVD GaN grown on miscut and exactly oriented sapphire substrates, as a function of gas purification. A two step procedure growth is performed in H2 and N2 main flows, at low pressure

(600mb), using TEG and NH3 as Ga and N sources. First a GaN nucleation layer is deposited at low temperature (500C°). In the second step, the GaN epilayer is grown at high temperature (1000° C). Several growth parameters have been varied to optimize GaN films : growth temperature and thickness of the nucleation layer, growth temperature of the sapphire nitridization, growth temperature of the epilayer, and NH3 or N2 different origin purifiers. Characterisation performed on the epilayers inclu des photoluminescence, SIMS, TEM, high resolution X-Ray, Hall and CV measurements. SIMS and CV experiments, achieved on GaN layers indicate that high purity NH3 is a significant source of oxygen contamination. GaN epilayer background doping increases linearly with the increase oxygene, as a function of NH3 purifier origin or the saturation degree of NH3 purifier. Some GaN properties are not degraded by oxygen contamination :FWHM of X-Rays Peaks around 26 arcsec - 80 arcsec, no broad band yellow emission, μ(300K)~ 80 cm2V-1s-1 (n~ 2*1E19 cm-3), were achieved for GaN samples with oxygen concentration ~ 3*1E19 cm-3 checked by SIMS. Three different origin NH3 purifiers were tested, the corresponding GaN characteristics are the following: purifier ANd-Na~4.5*1E17 cm-3, μ(300K)= 300cm2V-1s-1FWHM(XRay) = 200 arcsecFWHM(PL at 10K) = 10 meV, important broad band yellow emission[O]~1.3*1E18 cm-3 purifier BNd-Na~2*1E19 cm-3, μ(300K) = 80cm2V-1s-1FWHM(XRay) = 26 arcsec - 80 arcsecFWHM (PL at 10K) = 80 meV, no broad band yellow emission[O] ~ 3*1E19cm-3 purifier CNd-Na~2*1E17cm-3, μ(300K) ~250 cm2V-1s-1FWHM (XRay) = 34 arcsec - 60 arcsecFWHM (PL at 10K) < 10meV, very important broad band yellow emission. [O]<1*E18cm-3 (to be confirmed)Further details related to the role and incorporation mechanism of oxygen in GaN, will be presented.

11:40 AM

Nonlinear Dependence of N Incorporation on In Composition in GaInNAs: DANIEL J. FRIEDMAN[1]; John F. Geisz[1]; Sarah R. Kurtz[1]; Jerry M. Olson[1]; Robert Reedy[1]; [1]National Renewable Energy Laboratory, 1617 Cole Blvd, Golden, CO 80401 USA

$Ga_{1-3\delta}In_{3\delta}N_{\delta}As_{1-\delta}$ with a few % In and N has recently been demonstrated as a 1-eV material lattice-matched to GaAs. Similarly, it is expected that for $Ga_{0.5-3\delta}In_{0.5+3\delta}N_{\delta}As_{1-\delta}$, which is lattice-matched to InP, band gaps from ~0.7-0.3 eV should be achievable if a few % N could be incorporated. Here, we compare the growth of GaInNAs/InP with GaInNAs/GaAs. Epilayers of both alloy compositions were grown under comparable conditions by MOVPE with dimethylhydrazine. Nitrogen concentrations were determined from lattice constants (by XRD), and selectively cross-checked by SIMS. For GaInNAs/GaAs, nitrogen concentrations as high as 3% were measured, with corresponding bandgaps down to 0.96 eV. In contrast, for GaInNAs/InP, neither XRD nor bandgap shows significant N incorporation. SIMS measurements of typical epilayers support this observation, showing a N concentration at least 100x smaller in GaInNAs/InP than in GaInNAs/GaAs. Thus, N incorporation in GaInNAs falls off superlinearly with In concentration.

In-Situ Probes, Real Time Monitoring and Process Control

Thursday AM — Room: Grand Ballroom D & E
June 4, 1998 — Location: Sheraton Grande Torrey Pines

Session Chairs: I. B. Bhat, Rensselaer Polytechnic Institute, ECSE Department, Troy, NY 12180-3590 USA; N. P. Kobayashi, University of Southern California, Department of Materials Science and Engineering, Los Angeles, CA 90089-0241 USA

9:30 AM

Characterisation of III-V Desorption by Surface Photoabsorption: Daniel Anthony Allwood[1]; NIGEL JOHN MASON[1]; Peter John Walker[1]; [1]University of Oxford, Clarendon Laboratory, Oxford, Oxfordshire OX1 3PU UK

The thermal desorption of the oxides of several III-V substrate materials has been investigated by surface photoabsorption (SPA). In this preliminary study GaAs, GaP, GaSb, InAs, InP and InSb substrates were slowly heated under molecular hydrogen, with and without various group V precursors (e.g. arsine, which may be a source of atomic hydrogen), to desorb surface oxides prior tol (MOVPE) growth. SPA was performed by probing these surfaces with p-polarised 633 nm laser radiation throughout desorption and the reflected beam intensity constantly monitored. Such an arrangement allows the oxide desorption to be observed clearly, non-destructively and continuously. MOVPE requires semiconductor nucleation of very high structural integrity. It is of primary importance, therefore, that surface oxides are removed efficiently while bulk stoichiometry is retained at the surface and minimal damage introduced. At present, oxide desorption mechanisms relevant to MOVPE are somewhat unclear and a better understanding of the processes can only improve the quality of growth. Substrates were either used 'epiready' or after further preparative procedure in order to change the surface conditions, e.g. oxide type/thickness. Furthermore, comparisons have been made between substrates from different manufacturers. This has allowed oxide thicknesses and desorption activation energies to be estimated and some chemical assignments of oxides to be tentatively made. The role of atomic hydrogen in deoxidation at atmospheric pressure is also discussed. This wide ranging survey of different III-V substrates and different surface treatments therefore provides data that will, it is hoped, lead to an improved understanding of surface oxides and their desorption for the purposes of semiconductor growth.

9:50 AM

Surface Photoabsorption Studies of The Growth of III-V Semiconductors on Glass: REBECCA FRANCIS YATES[1]; Heather Margaret Yates[1]; Martyn Ernest Pemble[1]; [1]University of Salford, Chemistry, The Crescent, Salford, Greater Manchester M5 4WT UK

As part of our programme aimed at the production of quantum dot structures of III-V materials on glass-based substrates for potential optical/display applications we present surface photoabsorption (SPA) data for the deposition of InP and GaP on bare and SnO2-coated glass substrates by metalorganic chemical vapour deposition. For both systems the SPA technique is shown to be highly sensitive to the onset of growth and reveals that under the conditions employed induction periods are observed resulting in a significant delay between the introduction of the reagents (trimethylindium or trimethylgallium and phosphine)and the onset of growth. Furthermore these induction periods are dependent upon the initial state of the substrate surface and the sequence of reagent introduction. In addition, the SPA data at longer times reveals oscillation which are attributed to interferometric growth rate oscillations. These data for varying grwoth rates and varying induction periods are discussed in terms of possible surface mechanisms and the likely influence of surface morphology on these mechanisms.

10:10 AM

In-Situ Monitoring of GaSb, GaInAsSb, and AlGaAsSb: CHRISTOPHER J. VINEIS[1]; Christine A. Wang[1]; Klavs F. Jensen[2]; William G. Breiland[3]; [1]MIT Lincoln Laboratory, Electro-optical Materials and Devices, 244 Wood Street, Group 83, Lexington, MA 02173 USA; [2]Massachussetts Institute of Technology, Dept. of Chemical Engineering, 77 Mass. Ave., Cambridge, MA 02139-4307 USA; [3]Sandia National Laboratories, Dept. 1126, MS 0601, Albuquerque, NM 87185 USA

Spectral reflectance has been demonstrated as a useful tool for in-situ monitoring of organometallic vapor phase epitaxy of III-V arsenides, phosphides, and nitrides. For growth of III-V antimonide-based alloys with smaller energy gaps, however, high absorption can limit the wavelength range over which useful information can be extracted. In this paper, we show that silicon photodiode detector arrays are suitable for monitoring the growth of GaSb, AlGaAsSb, and GaInAsSb with cutoff wavelengths of 1.7, 1.2, and 2.2 um, respectively. These alloys were grown lattice matched to GaSb in a vertical rotating-disk reactor, which was modified to accommodate near normal reflectance without affecting epilayer uniformity. Using a virtual interface model, the growth rate and complex refractive index at the growth temperature have been extracted for these alloys over various spectral ranges. Excellent agreement is obtained between the extracted rate and that determined by ex-situ measurement. Optical constants are compared to theoretical predictions based on an existing dielectric function model for these materials. Furthermore, quantitative analysis of the entire reflectance spectrum yields valuable additional information on the approximate thickness of overlayers on the pre-growth substrate and the existence of strained layers.

10:30 AM Break

11:00 AM

In-Situ Monitoring of GaN MOVPE by Shallow-Angle Reflectance Using Ultraviolet Light: YASUYUKI KOBAYASHI[1]; TETSUYA AKASAKA[1]; NAOKI KOBAYASHI[1]; [1]NTT Basic Research Laboratories, Material Science Research Laboratory, 3-1, Morinosato Wakamiya, Atsugi-shi, Kanagawa Prefecture 243-01 Japan

Shallow-angle reflectance using ultraviolet light is applied to the in-situ monitoring of GaN MOVPE on c-plane sapphire substrates. This technique makes it possible to monitor in-situ not only the surface stoichiometry but also growth rates and surface flatness. The 325-nm line of a He-Cd laser is used. The incident angle is 75ϒ. This shorter wavelength light is scattered more intensely and the oblique incidence is more sensitive to surface roughness compared with normal incidence. After nitridation at 1050ϒC, TEG is supplied to the GaN surface at 600ϒC. The reflectivity oscillates three times and then becomes almost constant. The oscillation period corresponds to a thickness of 70 nm and the fact that there is almost no decrease in the reflectivity means the GaN is flat. During GaN growth at 1000ϒC, when the growth parameters are not optimized, damping of the oscillation is observed due to the high density of hexagons. This method enables us to efficiently optimize the growth parameters which are interrelated.

11:20 AM

Growth and In-Situ Monitoring of GaN Using IR Interference Effect: LAURENCE CONSIDINE[1]; Edward J. Thrush[1]; John A. Crawley[1]; Koen Jacobs[2]; Wim Van der Stricht[2]; Ingrid Moerman[2]; Piet Demeester[2]; [1]Thomas Swan & Co, Ltd., Unit 1C, Button End, Harston, Cambridge CB2 5NX United Kingdom; [2]University of Gent, Information Technology, Sint-Pietersnieuwstraat 41, Gent, - 9000 Belgium

Previously we have reported the MOVPE growth of GaN and related materials on (0001) sapphire in a close-spaced vertical rotating disk reactor. In this paper we report on the continued development of GaN growth using this reactor configuration which is now widely employed in device fabrication programmes. Specifically we report in-situ monitoring of the growth process by infrared (IR) radiation interferometry based on low cost optical pyrometry. During growth the amplitude of the substrate IR radiation exhibits oscillations which can be used for real-time monitoring of the growth. These oscillations provide a useful tool to study the effects of a number of growth parameters and can considerably shorten the optimisation procedure. In this case infrared radiation interferometry has been used to study the effects on material quality and growth rate of parameters such as reactor pressure, nucleation layer growth and overlayer growth temperature.

11:40 AM

In Situ Selective Etching of GaAs by AsCl3 for Regrowth on AlGaAs in Metalorganic Vapor Phase Epitaxy: HONG Q. HOU[1]; B. E. Hammons[1]; W. G. Breiland[1]; [1]Sandia National Laboratories, MS 0603, Albuquerque, NM 87185 USA

Etching in a metalorganic vapor phase epitaxy (MOVPE) reactor is important for substrate surface cleaning for low interfacial density regrowth. We studied in situ etching of GaAs with $AsCl_3$ in an MOVPE reactor with in situ reflectometry as a function of the $AsCl_3$ flow rate, substrate temperature, and AsH_3 flow rate during etching. A smooth and uniform etched surface was successfully achieved at substrate temperatures above 680 °C. The etch rate was found to be proportional to the flow rate of $AsCl_3$, and exhibited Arrhenius temperature dependence with an activation energy of ~1eV. The etching was also found to be very selective toward the Al composition in AlGaAs, and stopped abruptly on AlGaAs with an Al composition as low as 0.05. This process has applications for MOVPE regrowth on an AlGaAs surface after a selective in situ etch of the GaAs cap layer. We will demonstrate the successful regrowth on $Al_{0.5}Ga_{0.5}As$ for novel vertical-cavity surface-emitting lasers at 850-nm wavelength after ex situ processing steps and in situ selective removal of GaAs cap layer. The research was performed at Sandia National Laboratories, a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under contract No. DE-AC04-94AL85000.

12:00 PM

Single Wavelength In-Situ Laser Reflectometry for Fabrication of Reproducible High Performance Vertical Cavity Surface Emitting Lasers: WON-JIN CHOI[1]; Aaron E. Bond[1]; Chao-Kun Lin[1]; P. Daniel Dapkus[1]; [1]University of Southern California, Department of Electrical Engineering, University Park, Los Angeles, CA 90089-0271 USA

We report on the reproducibility of high performance vertical cavity surface emitting lasers grown by MOCVD using single wavelength in-situ laser reflectometry for monitoring growth rates. Single wavelength reflectometry is used to calculate growth rates of alloys as well as binary materials, eliminating the need for multiple wavelength systems in acquiring growth rates. By using a linear combination of the growth rates from binary materials, the growth rate of an alloy can be derived accurately. We report on the method and results used to calibrate $Al_xGa_{1-x}As$, GaAs, and AlAs epilayers. Reproducibility, uniformity, and device results will also be presented.

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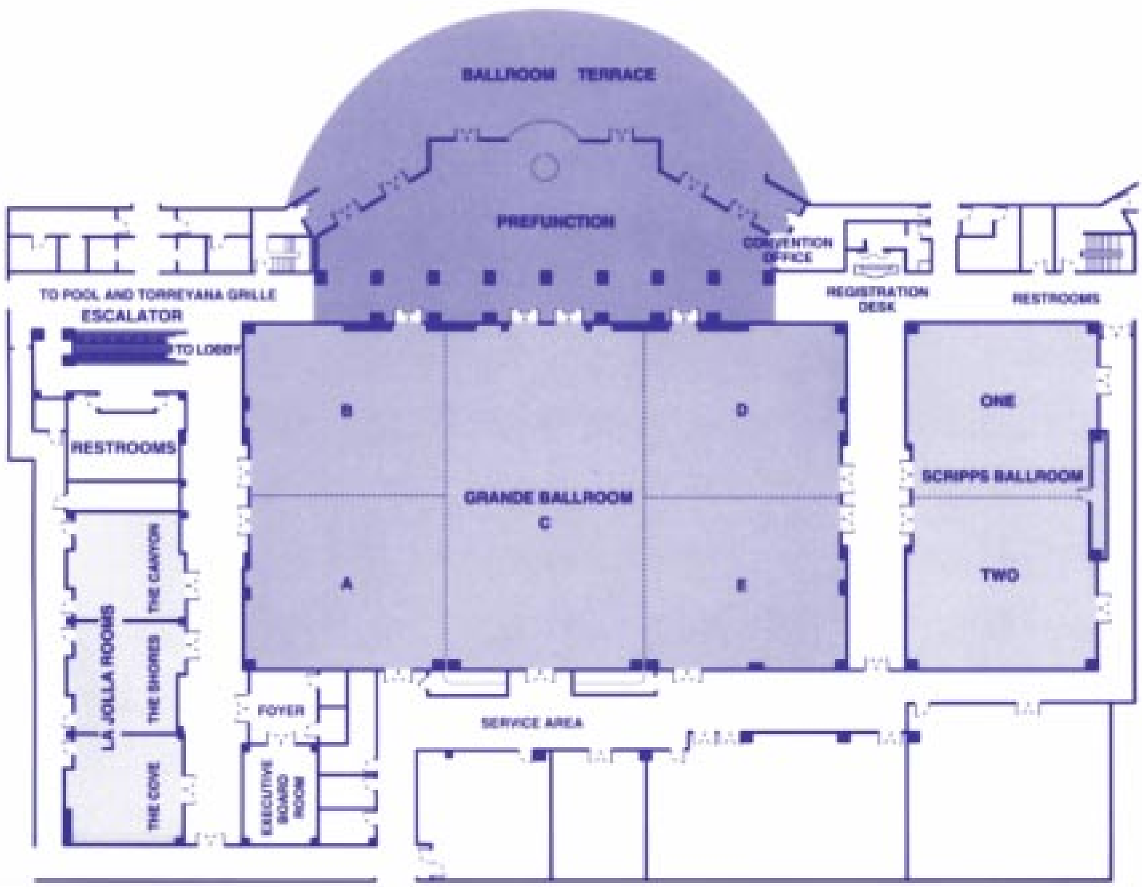

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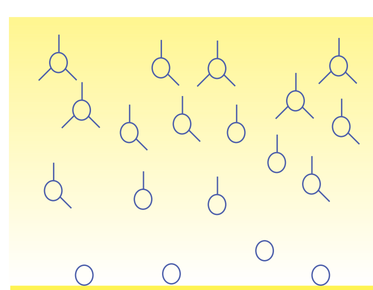

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