



Strasbourg (France)

E-MRS Spring Meeting 2004  
May 24-28, 2004

## SYMPOSIUM M

Dilute nitride and related mismatched  
semiconductor alloys

Symposium Organizers:

Eoin O'Reilly, NMRC, Cork, Ireland

Naci Balkan, University of Essex, U.K.

Henning Riechert, Infineon Technologies, München, Germany

Irina Buyanova, University of Linköping, Sweden

Xavier Marie, LPMC, Toulouse, France

# E-MRS 2004 SPRING MEETING

## SYMPOSIUM M

Tuesday, May 25, 2004

Morning

Session I : Growth 1

Session Chair: James Harris

- M-I.01** 09:00 -Invited- EPITAXY AND CHARACTERIZATION OF DILUTE III-As<sub>1-y</sub>N<sub>y</sub> ON GaAs AND InP  
**K. Köhler**, J. Wagner, P. Ganser, D. Serries, T. Geppert, M. Maier and L. Kirste, Fraunhofer Institut für Angewandte Festkörperphysik, Tullastrasse 72, 79108 Freiburg, Germany  
Epitaxial growth and characterization of dilute Ga<sub>1-x</sub>In<sub>x</sub>As<sub>1-y</sub>N<sub>y</sub> films and quantum wells are presented. Starting with the epitaxy on GaAs, recent results on the local bonding of nitrogen in Ga<sub>1-x</sub>In<sub>x</sub>As<sub>1-y</sub>N<sub>y</sub> are reviewed, revealing that bonding of nitrogen is controlled by an interplay between bond cohesive energy and reduction of local strain. Thus, III-N bonding in Ga<sub>1-x</sub>In<sub>x</sub>As<sub>1-y</sub>N<sub>y</sub> can be changed from Ga-N to In-N by post-growth thermal annealing. We then adopted this concept for the epitaxy on InP substrates, which is equivalent to a drastic increase in In content of the Ga<sub>1-x</sub>In<sub>x</sub>As<sub>1-y</sub>N<sub>y</sub> system and thus an extension to longer wavelengths. We will show the feasibility of high In containing III-AsN structures using InP-based pseudomorphic Ga<sub>1-x</sub>In<sub>x</sub>As<sub>1-y</sub>N<sub>y</sub> quantum wells. The deterioration of the PL properties in terms of reduced peak intensity and increased linewidth with increasing nitrogen incorporation can be partially compensated by rapid thermal annealing, which is accompanied by a blue-shift with respect to the as-grown samples. Within the resolution limits of our SIMS experiments, no annealing-induced loss of nitrogen was observed even for the high In-content Ga<sub>1-x</sub>In<sub>x</sub>As<sub>1-y</sub>N<sub>y</sub> quantum well structures. The results on indium-rich highly strained Ga<sub>0.22</sub>In<sub>0.78</sub>As<sub>0.99</sub>N<sub>0.01</sub> quantum wells on InP substrate are reported, showing room-temperature photoluminescence at wavelengths up to 2.3µm. We finally conclude with the demonstration of multi quantum well lasers emitting at wavelengths beyond 2 µm.
- M-I.02** 09:40 ELECTRON SPECTROSCOPY OF GaNAs ALLOYS  
**C.F. McConville**, I. Mahboob and T.D. Veal, Department of Physics, University of Warwick, Coventry CV4 7AL, U.K., **M. Hopkinson**, Department of Electronic and Electrical Engineering, University of Sheffield, Mappin Street, Sheffield S1 3JD, U.K.  
The nitrogen bonding configurations in GaN<sub>x</sub>As<sub>1-x</sub> alloys with 0.07 < x < 0.11 have been studied using x-ray photoelectron spectroscopy (XPS). In contrast to previous studies of alloys with x > 0.03, the nitrogen is found to exist in a single bonding configuration - the Ga-N bond; no interstitial nitrogen complexes are present. The amount of nitrogen in the alloys is estimated from the XPS using the N 1s photoelectron and Ga LMM Auger lines and is found to be in agreement with the composition determined by x-ray diffraction. Additionally, the surface optical phonon spectra of these GaN<sub>x</sub>As<sub>1-x</sub> alloys have been measured using high-resolution electron-energy-loss spectroscopy (HREELS). Multiple excitations of both the GaAs-like and GaN-like Fuchs-Kliewer phonons were observed. Comparison is made with surface optical phonon spectra obtained from GaAs and GaN, semi-classical dielectric theory calculations and previous Raman scattering measurements from bulk GaN<sub>x</sub>As<sub>1-x</sub> alloys.
- M-I.03** 10:00 EFFECTS OF ELECTRON IRRADIATION ON PHOTOLUMINESCENCE FROM GaInNAs/GaAs MULTIQUANTUM WELLS SUBJECT TO THERMAL ANNEALING  
**E.-M. Pavelescu**(a), **M. Dumitrescu**(a), **A. Gheorghiu**(b), **R. Kudrawiec**(c), **J. Misiewicz**(c), **N. Tkachenko**(d), **V.D.S. Dhaka**(d), **H. Lemmetyinen**(d), **T. Jouhti**(a), and **M. Pessa**(a), (a)Optoelectronics Research Centre, Tampere University of Technology, P.O.Box 692, 33101 Tampere, Finland, (b)Hyperion University, Calea Calarasi 169, 74118 Bucuresti, Romania, (c)Institute of Physics, Wrocław University of Technology Wybrzeze Wyspiaskiego 27, 50-370 Wrocław, Poland, (d)Institute of Materials Chemistry, Tampere University of Technology, P.O. Box 541, 33101 Tampere, Finland  
The PL intensity enhancement induced by annealing in GaInNAs/GaAs quantum wells is significantly increased by applying 7-MeV electron irradiation to the dose of 2x10<sup>16</sup> cm<sup>-2</sup> prior to annealing. The phenomenon is accompanied by a small additional blueshift as compared with the sample that was not irradiated. The additional blueshift disappears when the dose is decreased to 2x10<sup>15</sup> cm<sup>-2</sup>, but the increase in annealing-induced PL intensity enhancement with respect to the sample that was not irradiated remains, although it is reduced. The total blueshift, including the additional blueshift due to the irradiation, was found to occur without noticeable changes in the alloy macroscopic composition or quantum-well structure within the accuracy of x-ray diffraction. Photoreflectance measurements indicate that the blueshift is due to In-N bonds formation. This suggests that the irradiation enhances the annealing-induced In-N bonds formation subsequent to the irradiation. Possible mechanisms of electron irradiation influence on annealing-induced increase in In-N coordination are qualitatively discussed.

10:20

**BREAK**

## Session II: Growth 2

Session Chair: Henning Riechert

- M-II.01** 10:40 -Invited- MOVPE GROWTH OF DILUTE NITRIDES ON GaAs AND InP SUBSTRATES FOR DEVICE APPLICATIONS  
**F. Alexandre**, ALCATEL Research & Innovation, OPTO+, route de Nozay, 91460 Marcoussis, France  
The development during the 90s of the dilute nitride semiconductor family such as GaInAsN alloy has opened a new opportunity to extend the bandgap engineering capabilities of III-V semiconductor compounds. First, due to the large band gap bowing parameter of this alloy, the incorporation of Nitrogen in small amounts into Ga(In)As induces an important red-shift of the emission wavelength. This has been particularly applied to get lasers on GaAs substrate with an emission wavelength up to the telecommunication standards of 1.3  $\mu\text{m}$  and more recently 1.5 $\mu\text{m}$ . This alloy can also be grown on InP substrates in order to cover the whole C- and L-band emission, using tensile strained quantum wells (QW) or to extend the emission wavelength range further into the infra-red, using compressive strained QWs structure. A second interesting feature of N-containing alloys is the large electron confinement with other N-free alloys as barriers, which is of interest for improving the high temperature performance of lasers. However, it has been widely reported that a specific degradation of the photoluminescence properties of GaInAsN QWs occurs with increasing N incorporation. This degradation results in higher lasing threshold of GaInAsN-based lasers in comparison with the N-free GaInAs QW lasers. So far, the most important improvements in N-containing material quality as well as in laser performances have been mainly obtained by MBE while MOVPE grown structures appeared to be a step behind. In this work, we have investigated in detail the growth by MOVPE of GaInAsN on GaAs and InP substrates, using dimethylhydrazine (DMHy) as Nitrogen precursor. We have established that optimized growth conditions can lead to a strong improvement of both photoluminescence (PL) and lasing characteristics. The low growth temperature regime as well as the use of a reactive Nitrogen precursor lead also to specific conditions in order to grow high quality heterointerfaces between GaInAsN well and arsenides or phosphides barriers. These growth features as well as material properties and laser characteristics will be illustrated by results obtained on 1.3 $\mu\text{m}$  GaAs-based edge-emitting lasers and by PL results of tensile strained GaInAsN QWs grown on InP.
- M-II.02** 11:20 IMPROVING OPTICAL PROPERTIES OF 1550 nm GaInNAs/GaAs MULTIPLE QUANTUM WELLS BY GaInNAs QUATERNARY BARRIER AND SPACER LAYER  
**H.Y. Liu**, M. Hopkinson, P. Navaretti, M. Gutierrez, J.S. Ng and, J.P.R. David, Department of Electronic & Electrical Engineering, EPSRC National Centre for III-V Technologies, University of Sheffield, Sheffield S1 3JD, U.K., H.D. Sun, A.H. Clark, M.D. Dawson, Institute of Photonics, University of Strathclyde, 106 Rottenrow, Glasgow, G4 0NW, U.K.  
The GaInNAs (GINA) semiconductors have recently attracted considerable attention due to their unique physical properties and potential application for the long-wavelength GaAs-based laser diodes operating in the 1300-1600 nm telecommunication-wavelength range. As a low N content is preferred, the operation wavelength of most devices so far reported utilizing GaInNAs/GaAs multiple quantum well (MQW) is still limited to around 1300 nm. Here, we present the 1550-nm GaInNAs/GaAs MQW heterostructures with GaNAs or GaInNAs barrier and spacer layer (BSL). The stronger improvement of photoluminescence efficiency has been observed with increasing N concentration in GaNAs BSL, instead of increasing N composition in GaInNAs QWs, to achieve room-temperature emission above 1500 nm for GaInNAs/GaAs multiple QW structure, when the nitrogen concentration in GaInNAs QW is as high as 3%. However, the strain at the QW/BSL interface is accumulated by the increasing N concentration in GaNAs layer, possibly resulting in deteriorating the structural and optical properties. Consequently, the GINA quaternary BSL is finally proposed to reduce the strain at the QW/BSL interface. RT emission at 1560nm with linewidth of 39.7 meV (15.7 meV at 10 K) was achieved from the sample with Ga<sub>0.977</sub>In<sub>0.023</sub>N<sub>0.01</sub>As<sub>0.99</sub> quaternary BSL. The remarkable improvements of GINA QW optical characteristics are also revealed by detailed spectroscopic measurements including selectively excited photoluminescence (PL), temperature dependent PL, high-resolution XRD measurements and PL excitation (PLE) spectra. These results present to us a variable approach to further developing GaAs-based light sources in the telecommunication wavelength range near 1550 nm.
- M-II.03** 11:40 GROWTH OF Ga<sub>x</sub>As<sub>1-x</sub> ATOMIC MONOLAYERS ( $x < 0.1$ ) AND THEIR INSERTION IN THE VICINITY OF GaInAs QWs  
**M. Le Dû**, J.C. Harmand, K. Meunier, Laboratoire de Photonique et de Nanostructures, Route de Nozay, 91460 Marcoussis, France  
It has been reported that the introduction of N shortens the carrier lifetimes of III-V alloys. Beyond a N composition of 2-3%, the optical properties of III-V-N alloys are degraded, likely due to the presence of traps and non-radiative centers related to nitrogen. This short carrier lifetime can be attractive to design structures for high speed optical devices. To this aim, we have investigated the deposition of GaNAs atomic monolayers with N composition up to 10%. This is obtained by an exposure of a GaAs surface to a RF plasma source during a growth interruption at 400°C in molecular beam epitaxy. The N accumulation was confirmed and evaluated by secondary ion mass spectroscopy. This process is compatible with regrowth, as in situ monitored by reflection high energy electron diffraction. The photoluminescence of such a GaNAs monolayer embedded in GaAs exhibits broad emissions below the GaAs band gap. It shows that a wide distribution of deep energy levels is created by the GaNAs monolayer. Then we have inserted two of these GaNAs monolayers in GaAs barriers on each side of a single 8 nm GaInAs quantum well (QW). In a series of samples, the distance between the QW and the N plans was varied from 1 to 10 nm. A drastic effect of the N plans on the QW luminescence intensity is observed, with a strong influence of the spacer thickness. Carrier recombination dynamics studied by a time resolved PL analysis of these samples will be presented. This kind of structure is (anticipated as) a flexible mean to control the carrier lifetime in a QW.

12:00

**LUNCH**

Tuesday, May 25, 2004

Afternoon

Session III: Structure

Session Chair: Wlodek Walukiewicz

- M-III.01** 14:00 -Invited- COMPOSITIONAL FLUCTUATIONS AND OPTICAL PROPERTIES OF InGaAsN QUANTUM WELLS ANALYSED BY TRANSMISSION ELECTRON MICROSCOPY  
**M. Albrecht**, T. Remmele, H.P. Strunk, University of Erlangen-Nuremberg, Department of Materials Science and Engineering, Institute of Microcharacterisation, Cauerstr. 6, 91058 Erlangen, Germany, L. Geelhaar, Gh. Dumitras, H. Riechert, Infineon Technologies, Corporate Research Photonics, 81730 München, Germany  
InGaAsN is a solid solution with a large size mismatch of the constituents on the group-V-sublattice. This size mismatch leads to carrier localisation. Up to now it is not known, which localization mechanism dominates the optical properties of the alloy for which range of composition. Formation of quantum dot like structures, N and In-clustering and short range order have been evidenced. However, the reported values of localization energies, Stokes shift and photoluminescence line width vary over a large range even for comparable In and N concentrations. Thus, quantitative analysis of structural and optical properties of InGaAsN dependent on N and In concentration is needed.  
In this paper we will show that transmission electron microscopy can give valuable information and allow to correlate optical and structural properties of InGaAsN quantum wells. We use both, high resolution transmission electron microscopy and energy selective imaging to reveal compositional and well width fluctuations. These methods allow to determine In and N concentration fluctuations with a spatial resolution of 1 nm. Monochromatic cathodoluminescence images are obtained in the scanning transmission electron microscope and are directly correlated to structural properties of the material. Our analysis yields that InGaAsN exhibits two different localization mechanisms: In fluctuations on a mesoscopic length scale lead to strong carrier localization while N fluctuations lead to weak localization and broadens the line width up to 20 meV. Moreover our measurements show, that addition of N influences the growth mode of the layer: under the presence of N the quantum wells tend to grow three dimensional with increasing growth temperature.
- M-III.02** 14:40 NITROGEN INCORPORATION INTO DILUTE GaAsN ALLOYS  
M. Reason, H. McKay, X. Weng, N. Rudawski, and R.S. Goldman, Department of Materials Science and Engineering, University of Michigan, Ann Arbor MI 48109-2136, USA, V. Rotberg, Department of Nuclear Engineering and Radiological Sciences, University of Michigan, Ann Arbor MI 48109, USA  
Dilute nitride semiconductor alloys have shown significant promise for a wide range of applications including long-wavelength light-emitters, high-performance electronic devices, and high efficiency solar cells. In the case of dilute GaAsN alloys, conflicting results have been reported regarding the mechanism of N incorporation, and the effect of doping on N incorporation in GaAsN has apparently not been considered. We have investigated N incorporation in dilute GaAsN alloys grown by plasma-assisted molecular beam epitaxy using a variety of in-situ and ex-situ measurements. A comparison of Nuclear Reaction Analysis and Rutherford Backscattering Spectrometry in channeling and non-channeling conditions reveals significant composition-dependent non-substitutional incorporation of N, presumably as either N-N or N-As split interstitials. The incorporation of N into interstitial vs. substitutional sites apparently leads to less significant band gap bowing. For Si-doped GaAsN alloys, the concentration of interstitial N may be greater than that of substitutional N, depending on the growth conditions. It is well known that Si doping of GaAs often leads to the formation of charged Si-Vacancy pairs [1]. Thus, it is likely that an electrostatic interaction between the charged Si-Vacancy pairs and charged N-N or N-As split interstitials lead to the enhanced interstitial N incorporation for certain Si-doped GaAsN films. In-situ scanning tunneling microscopy studies suggest that interstitial N incorporation begins to occur at the early stages of growth.  
[1] J. E. Northrop and S.B. Zhang, Phys. Rev. B 47, 6791 (1993).
- M-III.03** 15:00 DETECTION OF STRAIN FIELDS IN METASTABLE (GaIn)(NAs) INVESTIGATED BY DARK FIELD TEM  
T. Torunski, W. Stolz and K. Volz, Materials Sciences Centre, Central Technology Lab., Philipps University Marburg, Hans-Meerwein Strasse, 35032 Marburg, Germany  
(GaIn)(NAs) alloy systems have attracted a great deal of attention due to their interesting properties such as an extremely large band gap bowing for a wide range of applications e.g. solar cells and optoelectronic devices. But the optical properties of (GaIn)(NAs)/GaAs MQWs show several anomalies obtained in materials and structures with inherent strong carrier localisation for example. From the point of view of electronic devices surprisingly low minority carrier diffusion length have been observed. The detailed reasons for those deteriorated optical and electronic properties are unknown up to now.  
We carried out in depth TEM investigations on the quaternary as well as both ternary materials ((GaIn)As and Ga(NAs)), which have been grown by metal organic vapor phase epitaxy (MOVPE). The high structural quality of the samples is shown by using HRTEM and Dark Field TEM with the chemical sensitive (200) reflection. However by using a combination of Dark Field Imaging with different reflections we detected specific inhomogeneous strain fields in all the N containing materials, which depend on N-content and growth conditions. Results depending on different N-concentrations and comparisons between annealed and nonannealed structures are presented. Possible causes as well as impacts on optical and electronic properties are discussed.
- M-III.04** 15:20 FURTHER INSIGHT INTO THE GROWTH TEMPERATURE INFLUENCE OF 1.3µm GaInNAs/GaAs QWS ON THEIR PROPERTIES  
D. Jahan, G. Patriarche, V. Sallet, J.C. Harmand, LPN-CNRS, Route De Nozay, 91460 Marcoussis, France

The potential of GaInNAs quantum wells (QWs) for 1.3 $\mu$ m photonic devices on GaAs is now well established. Their usual growth temperature,  $T_g$ , in molecular beam epitaxy is ranging between 400°C and 450°C, and thermal annealing is generally performed to optimise their photoluminescence (PL) characteristics. However, there is no clear agreement on the optimal annealing temperature,  $T_a$ , to be used. In this work, we further investigate the influence of  $T_g$ , and we show that  $T_g$  and  $T_a$  are not independent. 7nm thick GaInNAs QWs were grown with  $T_g$  ranging from 400°C to 470°C with 10°C increments. As a first result, transmission electron microscopy clearly showed that flat interfaces are obtained for  $T_g$  lower than 450°C. Beyond this temperature, the upper interface of the QW starts to undulate. Then the series of QWs was annealed at different temperatures. The PL emission of the QWs was blue shifted and narrowed (down to 22 meV), as generally observed. However, we noticed that these evolutions occurred at a lower  $T_a$ , when a lower  $T_g$  was used for the growth.

Even though the PL energies of the different as-grown-QWs were the same, this observation tends to show that the nano-texture of the GaInNAs alloys depends on  $T_g$  in the range of temperatures investigated here. The texture obtained at low  $T_g$  is more easily rearranged by annealing, into a more stable configuration. This results in an important consequence for the growth of GaInNAs QW laser structures. By using the lowest  $T_g$  for the GaInNAs QWs, the AlGaAs cladding layer growth temperature (usually around 620°C) is high enough to optimise the QW quality by its annealing effect.

15:40

**BREAK**

## Session IV: Defects 1

Session Chair: Irina Buyanova

**M-IV.01** 16:00 -Invited-

### THE PHYSICS OF DEFECTS AND HYDROGEN IN DILUTE NITRIDES

**S.B. Zhang**, National Renewable Energy Laboratory, Golden CO 80401, USA

First-principles theory is capable of unveiling physical properties of the various defects in dilute nitrides. In this talk, I will discuss some of our recent results [1-4] for native defects, N-N pairs, as well as for hydrogen in GaAsN and GaPN. Our studies showed that defect physics of dilute nitrides is *qualitatively* different from conventional semiconductors due to the involvement of nitrogen. This leads to a number of phenomena ranging from the existence of a new class of intrinsic traps such as the N-N split interstitials,  $P_{Ga-N}$  and  $V_{Ga-N}$  pairs, to a surprising modification of the fundamental band gap by hydrogen. If time permits, I will also discuss some of the recent calculations on the Fermi contact for defects and complexes, in light of the recent interesting experimental observations.

Work was in collaboration with A. Janotti, S.-H. Wei, C. G. Van de Walle, S. Kurtz, and S. Limpijumnong.

1. S. B. Zhang and S.-H. Wei (2001) *Phys. Rev. Lett.* **86**, 1789.

2. A. Janotti, S. B. Zhang, and S.-H. Wei (2002) *Phys. Rev. Lett.* **88**, 125506.

3. A. Janotti, S. B. Zhang, S.-H. Wei, and C. G. Van de Walle (2002) *Phys. Rev. Lett.* **89**, 086403.

4. A. Janotti, Su-Huai Wei, S. B. Zhang, Sarah Kurtz, and C. G. Van de Walle (2003) *Phys. Rev. B* **67** (Rapid Comm.), 161201.

**M-IV.02** 16:40

### MUTUAL PASSIVATION EFFECTS IN HIGHLY MISMATCHED GROUP III-V-N ALLOYS

J. Wu, K.M. Yu and W. Walukiewicz, Materials Sciences Division, Lawrence Berkeley National Laboratory, Berkeley CA 94720, USA

We have recently discovered a new effect in the dilute InGaAsN alloy system in which electrically active substitutional Si donors and isoelectronic N atoms passivate each other's activity [1]. The passivation of the shallow donors and the N atoms manifests itself in a drastic reduction of the free electron concentration and, simultaneously, an increase in the fundamental bandgap. The mutual passivation effect has been also observed in Ge doped GaAsN [2] and Si doped InGaPN alloys [3].

We have performed systematic studies of the mutual passivation effect in Si doped InGaAsN alloys. We show that the passivation process is controlled by the diffusion of Si to the nearest neighbors of N occupied sites, forming nearest neighbor Si-N pairs. Analytical calculations and a Monte Carlo simulation of the passivation process based on Ga vacancies mediated diffusion show good agreement with the experimental results [4]. We show that the mutual passivation provides a method to precisely control electrical properties of InGaAsN:Si. Through a judicious choice of the annealing conditions we were able to change the electron concentration by more than two orders of magnitude. This provides a unique system to investigate scattering mechanisms limiting electron mobility in InGaAsN alloys. Our studies indicate that the mutual passivation is a general phenomenon controlling the dopant activation efficiency in highly mismatched alloys.

[1] K. M. Yu et. al. *Nature Materials* **1**, 185 (2002).

[2] K. M. Yu, et. al., *Appl. Phys. Lett.*, **83**, 2844 (2003).

[3] Y. G. Hong, et. al., *Appl. Phys. Lett.*, **83**, 5446 (2003).

[4] J. Wu et. al., *Phys. Rev. B* **68**, 195202 (2003).

**M-IV.03** 17:00

### CARRIER RECOMBINATION PROCESSES IN (In)GaAsN: FROM THE DILUTE LIMIT TO ALLOYING

R. Intartaglia, T. Taliercio, P. Valvin, P. Lefebvre, T. Bretagnon, T. Guillet, B. Gil, Groupe d'Etude des Semiconducteurs, UMR5650 CNRS-Université Montpellier II, CC074, 34095 Montpellier Cedex 5, France, M.A. Pinault, Centre de Recherche sur l'Hétéro-Epitaxie et ses Applications, Centre National de la Recherche Scientifique (CRHEA/CNRS), Rue Bernard Grégory, Parc Sophia Antipolis, 06560 Valbonne, France, E. Tournie, CEM2 CNRS UMR 5507, Université Montpellier II, CC067, 34095 Montpellier Cedex 5, France

The nature, energy and dynamics of radiative carrier recombination in Ga<sub>1-y</sub>In<sub>y</sub>As<sub>1-x</sub>N<sub>x</sub> strongly depend on the nitrogen composition. To study this dependence, we used low temperature (10 K) time-resolved photoluminescence (TR-PL) experiments with a time resolution of 10 ps. The epitaxial layers were grown on (001) GaAs substrates by solid source molecular beam epitaxy, using solid sources for group-III and As elements, and a radio-frequency plasma source precursor for N. The nitrogen content, measured by secondary ion mass spectroscopy, ranged from 5 10<sup>-5</sup> to 7 10<sup>-2</sup>. PL spectra are dominated by the emission from discrete

nitrogen clusters for the very low x regime (around  $5 \cdot 10^{-5}$ ), and from a continuum of states originating from nitrogen clusters for higher x (larger than  $5 \cdot 10^{-4}$ ). Our TR-PL results show that, when N clusters created discrete bound states, the PL time-decays are exponential, whereas nonexponential decays are obtained when N clusters create a continuum of states. We show that these PL decays involve complex carrier transfers between the various available states. Changing the nitrogen content changes the recombination mechanism by changing the distance between the clusters.

**M-IV.04** 17:20

**THERMAL ANNEALING EFFECT ON 1.3  $\mu\text{m}$  GaInNAs/GaAs QUANTUM WELL STRUCTURES CAPPED WITH DIELECTRIC FILMS**

Hongfei Liu, Changsi Peng, Tomi Jouhti, Suvi Karirinne, Janne Konttinen, and Markus Pessa, Optoelectronic Research Center, Tampere University of Technology, P.O. Box 692, Tampere 33101, Finland

Blue-shift in photoluminescence (PL) spectra upon thermal annealing is a remarkable and complex phenomenon in GaInNAs/GaAs quantum well (QW) structures; reorganization of the nearest neighbors of nitrogen in short-range-order N-InmGa4-m ( $0 \leq m \leq 4$ ) clusters and interdiffusions of In/Ga/N atoms across the QW interfaces are the two main argued mechanics that cause the blue-shift. Selective modification of the band gap of GaInNAs/GaAs by dielectric films is important for a wide range of photonic integrated circuit and advanced device application. We have used PL, X-ray diffraction (XRD), and Secondary-ion-mass-spectrometry (SIMS) to study post-growth annealing effect on GaInNAs/GaAs single QW grown by molecular beam epitaxy. The QW structures were un-capped or capped by  $\sim 100$ -nm-thick SiO<sub>2</sub> or Si<sub>3</sub>N<sub>4</sub> dielectric films. The results indicate that during annealing, SiO<sub>2</sub> encapsulates enhance the Ga/In interdiffusion across the QW interfaces, hence promote the blue-shift in PL emission, while Si<sub>3</sub>N<sub>4</sub> encapsulates prevent the PL peak blue-shift. After annealing at 750 oC for 25 minutes a difference of band gap shifts over 60 meV has been obtained between SiO<sub>2</sub> and Si<sub>3</sub>N<sub>4</sub> coated samples. This spectacular blue-shift inhibition effect of Si<sub>3</sub>N<sub>4</sub> cap layer cannot stem from diffusion phenomena directly. By comparing the Ga-N bonds density in the QWs after annealing, we found that Si<sub>3</sub>N<sub>4</sub> caps effectively suppressed the Ga-N bonds decreasing while SiO<sub>2</sub> caps improved it. The detail of the mechanics is still on investigating.

Wednesday, May 26, 2004

Afternoon

Session V : Devices

Session Chair: François Alexandre

- M-V.01** 14:00 -Invited- GaInNAs(Sb) LONG WAVELENGTH COMMUNICATIONS LASERS  
**James Harris**, Department of Electrical Engineering, Stanford University, Stanford, CA 94305, USA
- M-V.02** 14:40 HIGH FREQUENCY PERFORMANCE OF 3-QUANTUM WELL GaInNAs/GaAs RIDGE WAVEGUIDE LASERS EMITTING AT 1.35  $\mu\text{m}$   
A. Martinez, V. Sallet, D. Jahan, L. Ferlazzo, J.-C. Harmand, A. Ramdane, CNRS-Laboratoire de Photonique et de Nanostructures, Route de Nozay, 91460 Marcoussis, France and J.-G. Provost, J. Landreau, O. Le Gouezigou, B. Dagens, ALCATEL/ OPTO+, Route de Nozay, 91460 Marcoussis, France  
We report on high frequency characterization of GaInNAs/GaAs laser diode emitting at 1.35 $\mu\text{m}$ . Optimized Molecular Beam Epitaxy growth has allowed the achievement of a 3-quantum well stack for improved dynamic properties. Broad area lasers exhibit a transparency current density of 614A/cm<sup>2</sup> at 20°C under pulsed operation and a characteristic temperature T<sub>0</sub> of 80K. Single mode narrow ridge waveguide devices emitting at 1.34 $\mu\text{m}$  demonstrate a low threshold current of 26mA under CW operation at 25°C for an as-cleaved/HR cavity. The maximum output power reaches 15mW with a slope efficiency of 0.22W/A. Intrinsic dynamic properties of the devices have been evaluated through relative intensity noise (RIN) measurements and small signal modulation. The dependence of the relaxation frequency on the bias current shows a slope of 0.92 GHz/mA<sup>1/2</sup>. The evolution of the damping factor versus the squared relaxation frequency gives a K factor of 0.44ns. RIN measurements yield a record relaxation frequency of 7.4GHz for this 3-QW device. Small signal modulation shows a 3dB bandwidth of 9.7GHz for this new material system, compatible with 10Gbit/s applications.
- M-V.03** 15:00 INFLUENCE OF GROWTH CONDITIONS ON CARRIER RECOMBINATION IN GaInNAs-BASED LASERS  
R. Fehse(a), S.J. Sweeney(a), A.R. Adams(a), D. McConville(a), L. Geelhaar(b), H. Riechert(b), (a)Advanced Technology Institute, University of Surrey, Guildford, Surrey GU2 7XH, U.K., (b)Infineon Technologies AG, Corporate Research, 81730 Munich, Germany  
Over the past few years the reported threshold current densities ( $J_{th}$ ) of 1.3 $\mu\text{m}$  GaInNAs-based lasers have decreased significantly albeit at the expense of poorer thermal characteristics. Relatively small changes in growth parameters, such as the active layer growth temperature, have been shown to have dramatic effects on  $J_{th}$  for GaInNAs-based lasers. In this paper we consider the influence of different growth parameters on the contribution of defect related current to  $J_{th}$  for nominally identical structures. The two sets of devices used in this study are nominally identical 1.3 $\mu\text{m}$  GaInNAs SQW edge-emitting lasers grown under different conditions. We find that the different growth conditions have a strong effect on  $J_{th}$  for the devices. We observe a factor of two difference in  $J_{th}$  between the two sets of lasers. To determine the process responsible for this increase we measure the light emitted from a window in the substrate contact of the devices as a function of current and temperature, which yields the absolute magnitudes of the defect-, radiative- and Auger-related recombination processes at threshold. The results show that the strong increase in  $J_{th}$  with changing growth conditions can be entirely explained by an increase in the monomolecular recombination coefficient, A, yielding a larger defect related current contribution. Furthermore, the extracted radiative- and Auger-related current paths in the two devices are of very similar magnitude. This is strong evidence that the change in growth conditions does not affect the internal losses of the devices, as the threshold carrier density,  $n_{th}$ , appears to be unchanged.
- M-V.04** 15:20 GaInNAs SESAMS PASSIVELY MODE-LOCKING 1.3- $\mu\text{m}$  SOLID-STATE LASERS  
V. Liverini, S. Schön, R. Grange, M. Haiml, S. Zeller, U. Keller, ETH Zurich, Switzerland  
We demonstrate for the first time stable self-starting passive cw mode locking of a solid-state laser at about 1.3  $\mu\text{m}$  using a GaInNAs semiconductor saturable absorber mirror (SESAM). The incorporation of about 2.2% nitrogen into InGaAs redshifts the absorption edge above 1330 nm and reduces the strain in the saturable absorber grown on a GaAs/AlAs Bragg mirror. Final absorption edge adjustments have been made with thermal annealing which blueshifts the absorption edge. GaInNAs SESAMs show negligible nonsaturable losses, low saturation fluences (11  $\mu\text{J}/\text{cm}^2$ ) and picosecond decay times which make them well-suited for self-starting and stable cw mode locking. The SESAM was based on a standard antiresonant design with a GaInNAs SQW as the saturable absorber. From optical characterization we could extract the material's saturation fluence of  $3.5 \pm 0.5 \mu\text{J}/\text{cm}^2$  for the 10-nm GaInNAs QW close to the band edge. Using our antiresonant GaInNAs SESAM we obtained self-starting stable cw mode locking with 6.7-ps pulses at 1314 nm. The average output power of the laser was very high due to the low nonsaturable losses and the SESAM proved to be robust by working in cw mode-locked operation over several hours at the maximum average output power of 580 mW.
- 15:40 **BREAK**
- 16:00 – 18:30 POSTER SESSION

## Session VI: Band structure

Session Chair: Shengbai Zhang

**M-VL01** 09:00 -Invited-**DILUTE GaAsN: AN "UNUSUAL" ALLOY BAND STRUCTURE PROBED BY MAGNETO-TUNNELLING SPECTROSCOPY**

**A. Patanè**, J. Endicott, J. Ibáñez, L. Eaves, School of Physics and Astronomy, University of Nottingham, Nottingham NG7 2RD, U.K., M. Hopkinson, R. Airey, and G. Hill, Dept. of Electronic and Electrical Engineering, University of Sheffield, S3 3JD Sheffield, U.K.

We use magneto-tunnelling spectroscopy [1] to investigate the nature of the N-induced states (band- and impurity-like) in GaAs<sub>1-y</sub>Ny alloys. In our resonant tunnelling diodes (RTDs), a quantum well (QW) layer of GaAs<sub>1-y</sub>Ny ( $y < 2\%$ ) is embedded between two Al<sub>0.4</sub>Ga<sub>0.6</sub>As tunnel barriers.

Undoped GaAs spacer layers separate the barriers from two contact layers with *n*-type doping. These devices are designed to act as RTDs in which electrons can tunnel from the doped GaAs layers into the N states: resonant tunnelling through a particular state in the QW leads to a resonant feature in the current-voltage  $I(V)$  plot whenever the energy of the state is resonant with a filled state in the negatively biased emitter layer.

We find that the  $I(V)$  are profoundly affected by the incorporation of low N content. When *y* is increased from 0 to 0.1%, the resonance due to electrons tunnelling through the ground state of the QW splits into two main features,  $E^-$  and  $E^+$  corresponding to electron tunneling into the N-induced hybridised subbands of the GaAs<sub>1-y</sub>Ny layer. [2] A further increase of *y* smears out the resonance and strongly quenches the current due to electron trapping on strongly localised N-levels.

A magnetic field, *B*, applied perpendicular to the current direction, is used to probe in detail the nature of the N-states. In our experiment, the

magnetic field imparts to the tunnelling electron a change of the in-plane wave vector  $\hbar / eBs k = s$ , where *s* is the tunnelling distance from the emitter to the QW [1]. Varying *B* allows us to tune an electron to tunnel into a given *k*-state of the well; the voltage tunes the energy so that we can map out the energy-momentum dispersion curve  $\epsilon(k)$  of the

$-E$  and  $E^+$  subbands over a wide range of *k* values.

The data reveal that for a small N-content ( $y = 0.1\%$ ) the  $-E$  and  $E^+$  subbands are highly nonparabolic and that the heavy effective mass  $E^+$

states have a significant  $\Gamma$ -conduction band character even at  $k = 0$  [3]. Our results indicate that the dispersion curves of the hybridised subbands of GaAs<sub>1-y</sub>Ny QW layers have a very well-defined character and suggest that the highly non-parabolic dispersion of  $-E$  and  $E^+$  could be tailored by the quantum well confinement and exploited to design novel band-structure engineered devices with negative differential velocity characteristics, similar to those occurring in semiconductor superlattices or Gunn diodes.

[1] R. K. Hayden et al., Phys. Rev. Lett. 66, 1749 (1991).

[2] W. Shan et al., Phys. Rev. Lett. 82, 1221 (1999).

[3] J. Endicott et al., Phys. Rev. Lett. 91, 126802 (2003).

**M-VL02** 09:40**MAGNETOPHOTOLUMINESCENCE STUDIES OF In<sub>x</sub>Ga<sub>1-x</sub>As<sub>1-y</sub>Ny: A MEASUREMENT OF THE ELECTRON EFFECTIVE MASS, EXCITON SIZE, AND CARRIER LOCALIZATION DEGREE**

**A. Polimeni**, F. Masia, G. Baldassarri Höger von Högersthal, F. Mari, A. Frova, and M. Capizzi, INFN-Dipartimento di Fisica, Università di Roma "La Sapienza", P.le A. Moro 2, 00185 Roma, Italy, P.J. Klar and W. Stolz, Department of Physics and Material Sciences Center, Philipps-University, Renthof 5, 35032 Marburg, Germany

We report on a comprehensive study of the effects of a magnetic field on the photoluminescence (PL) of In<sub>x</sub>Ga<sub>1-x</sub>As<sub>1-y</sub>Ny/GaAs heterostructures. Our study is aimed at the measurement of the properties of the bottom of the conduction band (both curvature and localization degree) of N-containing samples. We describe first the evolution of the electron effective mass,  $m_e$  and exciton radius,  $r_{exc}$ , in GaAs<sub>1-y</sub>Ny epilayers with N concentration varying from  $y < 0.01\%$  to  $y = 0.5\%$ . In particular, by exploiting the capability of post-growth hydrogen irradiation to tune finely the electronic properties of GaAs<sub>1-y</sub>Ny, we are able to assess that a major change in  $m_e$  and in  $r_{exc}$  takes place within a very narrow concentration interval centred at  $y = 0.1\%$ . We consider then the magneto-PL properties of In<sub>x</sub>Ga<sub>1-x</sub>As<sub>1-y</sub>Ny/GaAs quantum wells, QWs, having  $x \sim 30\%$  and  $y = (0.7-5.2)\%$ . For these samples, the electron effective mass (exciton radius) increases (decreases) with *y* up to a N concentration equal to 1%, namely, an order of magnitude higher than that found in In-free samples. Both the values of  $m_e$  and  $r_{exc}$  display a saturation for  $y > 1\%$ . Finally, magneto-PL sheds new light on the origin of the states from which carriers recombine at low temperature in In<sub>x</sub>Ga<sub>1-x</sub>As<sub>1-y</sub>Ny samples in the alloy limit. Indeed, the shift of the PL bands induced by *B* decreases sizably and changes its dependence on *B* from linear to quadratic on going from low to high *T*. These findings indicate that the PL emission at low temperature is not excitonic in character and it is determined, instead, by the recombination of loosely bound electron-hole pairs in which one carrier (electron) is localized by N-induced potential fluctuations and the other carrier (hole) is delocalised.

**M-VL03** 10:00**BOUNDARY CONDITIONS FOR THE ELECTRON WAVE FUNCTION IN GaInNAs-BASED QUANTUM WELLS AND MODELLING OF THE TEMPERATURE-DEPENDENT BAND GAP**

**M. Hetterich**(a), A. Grau(a), A.Yu. Egorov(b) and H. Riechert(b), (a)Institut für Angewandte Physik and Center for Functional Nanostructures (CFN), Universität Karlsruhe (TH), 76131 Karlsruhe, Germany, (b)Infineon Technologies, 81730 München, Germany

In our contribution we firstly derive and discuss the boundary conditions for the electron wave function in general GaInNAs-based heterostructures described by the band anticrossing (BAC) model. The use of these boundary conditions greatly simplifies the calculation of, e.g., transition energies in quantum wells. We then apply the derived equations to model the electronic states in GaInNAs/GaAs quantum well structures with various In concentrations as well as the temperature dependence of the lowest e1-hh1 transition in these

structures. From a fit to our experimental photoreflectance data we find evidence that the effective nitrogen level in the BAC Hamiltonian, measured with respect to the valence band edge, shifts significantly to higher energies with decreasing temperature. This supports and extends a similar result reported recently in the literature for low indium content epilayers.

10:20

**BREAK**

Session VII: Electronic disorder

Session Chair: Naci Balkan

**M-VII.01** 10:40 -Invited-

**EXCITON LOCALIZATION IN InGaAsN AND GaAsSbN OBSERVED BY NEAR-FIELD MAGNETOLUMINESCENCE AND SCANNING OPTICAL MICROSCOPY (NSOM)**

**James L. Merz**, Alexander M. Mintairov, and Thomas Kosel, Department of Electrical Engineering, University of Notre Dame, Notre Dame IN 46556, USA, Victor M. Ustinov, Ioffe Physico-Technical Institute, St. Petersburg, Russia, Gregory Peake, Sandia National Laboratory, Albuquerque NM 87185, USA Dilute nitride alloys have recently attracted considerable attention as promising materials for laser diodes in the 1.3 -1.5 micrometers range as well as for more efficient solar cells. We have used near-field optical spectroscopy to investigate clustering and consequent exciton localization in epitaxial layers of GaAsN and InGaAsN, and in a quantum well (QW) of GaAsSbN. These were grown by solid source molecular beam epitaxy and by metal-organic vapor phase epitaxy, respectively.

Near-field magnetoluminescence was used to investigate the structural and optical properties of quantum-dot (QD)-like compositional fluctuations in GaAsN and InGaAsN alloys [1]. The diamagnetic shifts of the sharp spectral lines originating from these dots was used to determine their size ( $r \sim 6-18$  nm), density ( $\sim 100 \mu\text{m}^{-3}$ ), and nitrogen composition. Monochromatic images produced by near-field scanning optical microscopy (NSOM) of these epi-layers consist of a series of bright spots having spatial extent of 300-600 nm, demonstrating a strong lateral inhomogeneity of the layers on the length scale of 1000 nm. Little effect was observed from the presence or absence of indium.

For the GaAsSbN QW the images of the individual clusters consist of bright stripes having width 400-600 nm oriented along one of the  $\{110\}$  directions. The separation between the stripes is  $\sim 300$  nm and their length is greater than 2000 nm. Plan-view transmission electron microscopy measurements showed the presence of composition modulation along the  $[110]$  direction having a wavelength  $\sim 100$  nm. The orientation and the lateral dimensions of the composition modulation stripes observed in TEM agree well with NSOM images. However as the NSOM data are related to the emission of individual clusters, the stripe character of the images can be related to the diffusion of photo-generated carriers along the quantum-wire-like channels created by As and Sb phase separation. The effect of sample annealing on these images will be reported.

[1] A. M. Mintairov et al, Phys. Rev. Lett. **87**, 244701 (2001).

**M-VII.02** 11:20

**MAGNETOTRANSPORT IN DOPED GaAsN AND GaInNAs LAYERS**

Jörg Teubert, Peter J. Klar, Wolfram Heimbrodt, Peter Thomas, Kerstin Volz, Wolfgang Stolz, Dept. Physics and Materials Science Center, Philipps-University Marburg, Renthof 5, 35032 Marburg, Germany

Incorporation of small amounts of nitrogen into GaAs and GaInAs results in large changes of the electronic properties of these materials. Whereas the optical properties are already extensively studied, there is only little knowledge about the effects of nitrogen incorporation onto the electronic transport behaviour of these III-V alloys. Magnetoresistance (MR) and Hall measurements at temperatures between 2 and 280 K and fields up to 10 T show large negative MR effects and anomalous Hall effects for n-type samples whereas p-type samples behave like conventional III-V alloys. This can be explained qualitatively with the energetic and spatial disorder induced by N in the conduction band. We present first magnetotransport measurements under hydrostatic pressure up to 20 kbar for n-type GaNAs samples with low N concentrations. In these samples applying hydrostatic pressure allows one to tune the energetic positions of the localized N-cluster states with respect to the conduction band edge. The effects on the transport properties are discussed.

**M-VII.03** 11:40

**INTRINSIC LIMITS ON ELECTRON MOBILITY IN DISORDERED DILUTE NITRIDE SEMICONDUCTOR ALLOYS**

**S. Fahy**, Department of Physics and NMRC, University College Cork, Ireland, A. Lindsay and E.P. O'Reilly, NMRC, University College, Lee Maltings, Prospect Row, Cork, Ireland

We have previously shown using the band-anti-crossing (BAC) model that there is a fundamental connection between the composition-dependence of the conduction-band-edge energy and the n-type carrier scattering cross-section in dilute alloys, imposing general limits on the electron mobility in Ga(In)NAs alloys and heterostructures. We derived a simple general expression for scattering in the dilute regime, showing that the scattering rate in the BAC model is proportional to  $|dE_c/dx|^2$ , the square of the initial variation of the conduction band edge energy with alloy composition,  $x$ . The mobility estimated in  $\text{Ga}_{1-x}\text{As}_x$  using the two-level BAC model is of the right magnitude ( $\sim 1000 \text{ cm}^2/\text{Vs}$ ) but still larger than typical experimental values. We consider here the effects of disorder in the N distribution, including the formation of N-N pairs (where a single Ga atom has two N neighbours), and more complex clusters. We show that the inclusion of such complexes plays a major role in further limiting the calculated mobility, giving values comparable to experiment. We conclude that random alloy scattering, rather than film quality or other factors, dominates the carrier mobility and is an intrinsic limiting factor in these materials.

12:00

**LUNCH**

Thursday, May 27, 2004

Afternoon

Session VIII: Mismatched alloys

Session Chair: Xavier Marie

**M-VIII.01** 14:00 -Invited-

**SYNTHESIS AND PROPERTIES OF HIGHLY MISMATCHED II-O-VI ALLOYS**

K. M. Yu(a), **W. Walukiewicz**(a), M.A. Scarpulla(a,b), O.D. Dubon(a,b), W. Shan(a), J. Wu(a), J.W. Beeman(a) and P. Becla(c), (a)Materials Sciences Division, Lawrence Berkeley National Laboratory, Berkeley CA 94720, USA, (b)Materials Sciences Division, Lawrence Berkeley National Laboratory, and Department of Materials Science and Engineering, University of California, Berkeley CA 94720, USA, (c)Department of Materials Science and Engineering, Massachusetts Institute of Technology, Cambridge MA 02139, USA

Group II-O-VI semiconductors with the anions partially replaced by highly electronegative isoelectronic O atoms are a direct analog of the extensively studied diluted nitrides. The electronic band structure of such highly mismatched alloys (HMAs) is determined by the anticrossing interaction between localized O or N states and the extended states of the semiconductor matrix. The interaction splits the conduction band into two nonparabolic subbands leading to a variety of unusual optical and electrical properties of the alloys. We have synthesized ternary and quaternary diluted II-VI oxides using a highly non-equilibrium method: the combination of O ion implantation and pulsed-laser melting. We have produced CdOxTe1-x thin films with x up to 0.015 and with the energy gap reduced by 0.15 eV. Optical transitions corresponding to both the lower (E-) and upper (E+) conduction subbands resulting from the anticrossing interaction between the localized O states and the extended conduction states of the matrix are clearly observed in quaternary Cd0.6Mn0.4OxTe1-x and Zn0.88Mn0.12OxTe1-x layers. These results have important implications for the existing theoretical models of the electronic structure of the highly mismatched alloys. In Zn1-xMnxTe, where the O level lies below the conduction band edge, we demonstrate that incorporation of a small amount of oxygen leads to the formation of a narrow, oxygen-derived band of extended states located well below the conduction band edge of the ZnMnTe matrix [1]. The three absorption edges of this material (~0.73, 1.83 and 2.56 eV) cover the entire solar spectrum providing a material envisioned for the multi-band, single junction, high efficiency photovoltaic devices.

[1] K. M. Yu et al., Phys. Rev. Lett. 91, 246203 (2003).

**M-VIII.02** 14:40

**ORIGIN OF BANDGAP BOWING IN GaNP ALLOYS**

I.A. Buyanova, M. Izadifard, W.M. Chen, Department of Physics and Measurement Technology, Linköping University, 581 83 Linköping, Sweden, and H.P. Xin, C.W. Tu, Department of Electrical and Computer Engineering, University of California, La Jolla, USA

GaNxP1-x alloys belong to a novel material system of dilute nitride semiconductors that have recently attracted considerable interest due to their fascinating fundamental properties attractive for optoelectronic applications. Incorporation of N in GaAs and GaP compounds induces a giant band gap bowing, often considered as a fingerprint of dilute nitrides. The exact physical mechanism behind the observed modifications of the electronic structure, however, is still rather contentious in spite of extensive theoretical and experimental efforts.

In this work, by employing photoluminescence excitation (PLE) spectroscopy, we shall provide direct evidence for N-induced strong coupling of host conduction band (CB) states in GaNxP1-x. This strong coupling is manifested as 1) a drastic change in the ratio of oscillator strengths between the optical transition near Eg and the CB minimum (CBM); 2) a strong blue shift of the a1 state with increasing N composition accompanying a red shift of the CBM; 3) pinning of the energies of the N-related levels; 4) the appearance of t2(L) or t2(X3) upon N incorporation of which the energy position is insensitive to N compositions. These findings shed new light on the controversial issue of the dominant mechanism responsible for the giant bandgap bowing of dilute nitrides.

**M-VIII.03** 15:00

**EFFECT OF LATTICE IONICITY ON HYDROGEN ACTIVITY IN II-VI MATERIALS CONTAINING ISOELECTRONIC OXYGEN IMPURITIES**

A. Polimeni, M. Felici, V. Cesari, A. Frova and M. Capizzi, INFN-Dipartimento di Fisica, Università di Roma "La Sapienza", P.le A. Moro 2, 00185 Roma, Italy, Y. Nabetani, Y. Ito, T. Okuno, T. Kato, T. Matsumoto and T. Hirai Department of Electrical and Electronic Engineering, University of Yamanashi, Takeda 4-3-11, Kofu 400-8511, Japan, Yong Dae Choi, Department of Physics, Mokwon University, Taejeon 302-729, Korea, Byung-sung O and Young-Moon Yu, Department of Physics, Chungnam National University, Taejeon 305-764, Korea, I.K. Sou, W.K. Ge, Department of Physics, The Hong Kong University of Science and Technology, Clear Water Bay, Hong Kong, China

We report on the effects of atomic hydrogen irradiation in ZnTe, ZnTe1-ySy (y = 1.5%), and ZnSe1-xOx (x = 0.35 - 1.3 %) epilayers. Photoluminescence (PL) measurements show the full passivation of O-related recombination bands in ZnTe and ZnTe0.985S0.015 samples slightly doped with oxygen. However, hydrogen irradiation does not affect the band gap reduction ensuing O incorporation in ZnSe1-xOx alloys, in contrast to the case of nitrogen-containing GaAs1-zNz and GaP1-zNz lattices where the GaAs and GaP band gap has been recovered upon H irradiation. Such lack of interaction between O and H in ZnSe1-xOx indicates a scarce localized character in the ZnSe1-xOx band edges. This is well supported by the study of the temperature dependence of the band gap in ZnSe1-xOx. Indeed, the rate at which the band gap of ZnSe1-xOx decreases with T does not depend on O concentration and it is equal, instead, to that of the ZnSe host in contrast with the strong dependence on N concentration observed in GaAs1-zNz and GaP1-zNz. We rationalize these diversity of behaviors of H in different II-VI and III-V compounds and alloys in terms of the different degree of the materials' ionicity.

15:20

**BREAK**

Session IX: Defects 2  
Session Chair: Eoin O'Reilly

- M-IX.01** 16:00 -Invited- DEFECTS IN DILUTE NITRIDES: SIGNIFICANCE AND EXPERIMENTAL SIGNATURES  
**W.M. Chen** and I.A. Buyanova, Department of Physics and Measurement Technology, Linköping University, 581 83 Linköping, Sweden  
In this talk, we shall provide an overview of our present knowledge and understanding of defects in dilute nitrides and will underline their important roles in determining the success of this novel material system for optoelectronic device applications. A brief summary of experimental results of defects in dilute nitrides by various techniques reported so far in the literature will be given. Our recent results from optically detected magnetic resonance studies of grown-in non-radiative defects in Ga(In)NAs and Ga(Al,In)NP will be discussed in some detail, in an effort to provide chemical identification and experimental signatures of defects. Among them, intrinsic defects such as antisites and self-interstitials have been positively identified and effects of growth conditions, chemical compositions and post-growth processing on formation of the defects were studied. The information retrieved from the experimental findings is expected to provide useful guidance for designing strategies to eliminate defects that are harmful to device performance.
- M-IX.02** 16:40 C INCORPORATION IN (GaIn)(NAs) AND ITS DEPENDENCE ON GROWTH CONDITIONS AND INFLUENCE ON LASING CHARACTERISTICS  
K. Volz, S. Nau, B. Kunert, S. Reinhard, W. Stolz, Material Sciences Center - Central Technology Laboratory, Philipps University Marburg, 35032 Marburg, Germany  
Mixed III-V nitride semiconductor alloys have a theoretically predicted and experimentally observed large bandgap bowing, which allows to realize 1.3 to 1.55  $\mu\text{m}$  wavelength emission on GaAs substrates. These wavelength regimes are extremely interesting for telecommunication applications, implying appropriate characteristics of the lasers grown from these materials.  
Due to its metastability, the quaternary (GaIn)(NAs) has to be grown at low substrate temperatures. We have deposited the material with metal organic vapor phase epitaxy (MOVPE) using the more efficiently decomposing group V and group III precursors tertiarybutylarsine, 1,1 dimethylhydrazine, trimethylindium and triethylgallium. From these precursors - as well as from hydrocarbon contaminations in the vacuum chamber during molecular beam epitaxy growth - carbon can be incorporated into active material of the laser structures. We varied growth conditions, e.g. V/V, V/III ratios, growth rate, temperature and In content of the material over a wide range, always fixing the emission wavelength to 1.3  $\mu\text{m}$ . The C content in the multi quantum well structures has been measured by secondary ion mass spectroscopy. From the samples edge emitting laser structures have been processed and the laser characteristics have been determined. It will be shown that there is a clear dependency of the threshold current densities of the lasers on the C content in the active material. Controlling the C incorporation during the MOVPE growth results in a reduction of the threshold current densities and hence a drastic improvement of the laser characteristics.
- M-IX.03** 17:00 EFFECT OF FAST THERMAL ANNEALING ON THE OPTICAL SPECTROSCOPY IN MBE AND CBE GROWN GaInNAs/GaAs QWS: BLUE SHIFT VERSUS RED SHIFT  
N. Balkan(a), S. Mazzucato(b), A. Erol(c), C.J. Hepburn(a), R.J. Potter(d), A. Boland-Thoms(a), A.J. Vickers(a), (a)University of Essex, Department of Electronic Systems Engineering, Colchester, Essex CO4 3SQ, U.K., (b)Dipartimento di Fisica, Universita' degli Studi di Roma "La Sapienza", Piazzale Aldo Moro 2, 00185 Roma, Italy, (c)Istanbul University, Department of Physics, 34459 Vezneciler, Istanbul, Turkey, (d)University of Liverpool, Department Material Science & Engineering, Liverpool L69 3BX, U.K.  
We present an investigation of thermal annealing effects on spectral photoconductivity photoluminescence and in-plane photovoltage in sequentially grown GaInNAs/GaAs and GaInAs/GaAs quantum well structures. Experiments have been carried out at temperatures between 30K and 300K. The results indicate that thermal annealing improves the optical quality of GaInNAs, but may causes either a blue shift as commonly observed by other groups, or a red shift depending on the growth technique. The anneal-induced blue shift behaviour can be explained in terms of two competing mechanisms involving the redistribution of nearest neighbour configuration and the change of quantum well profile. The red shift is explained in terms of hydrogen induced chemical effects.