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SYMPOSIUM M

N-containing III-V semiconductors fundamentals and applications

Symposium Organizers:

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E-MRS 2002 SPRING MEETING

SYMPOSIUM M

Tuesday, June 18, 2002 — Morning
Mardi 18 juin 2002 — Matin

Session I: Diluted Nitrides: New Materials
Session Chair: C.W.Tu

09:00 **M-I.1**

DISLOCATION-FREE III-V-N COMPOUND-Si LAYERS GROWN ON Si SUBSTRATE AND THEIR POTENTIAL APPLICATIONS

Hiroo Yonezu, Department of Electrical and Electronic Engineering, Toyohashi University of Technology, Hibarigaoka, Tempaku-cho, Toyohashi, Aichi, 441-8580, Japan

The heteroepitaxial growth of dislocation-free III-V compound semiconductors on Si substrates has been prevented by the following three problems; (1) a hetero-interface between column III-V and IV crystals, (2) a large lattice-mismatch and (3) a large difference in thermal expansion coefficients. We have succeeded in breaking these problems with the sequential growth of a very thin GaP initial layer, a GaPN layer lattice-matched to Si and a Si capping layer. As a result, a dislocation-free GaPN layer was successfully grown on the Si substrate.
A GaAsPN/GaPN strained quantum well structure lattice-matched to Si was grown on the Si substrate. In addition, a Si/GaPN/Si structure, which is a basic structure for novel OEICs, was grown. Close lattice-matching to Si was confirmed by XRD. The FWHMs of rocking curves of the grown layers were close to that of Si substrates. Neither threading dislocations nor misfit dislocations were observed in the grown layers and hetero-interfaces by TEM.
The increase in N compositions is a current issue since it expands the variety of band engineering for novel optoelectronic and microwave devices and circuits lattice-matched to Si.

09:40 **M-I.2**

InSbN GROWTH AND DEVICES

Tim Ashley, T.M. Burke, G.J. Pryce, QinetiQ, Malvern Technology centre, St. Andrew's Road, Malvern, Worcestershire WR14 3PS, UK, A.R. Adams, A.D. Andreev, B.N. Murdin, University of Surrey, Guildford, Surrey GU2 7XH, UK, E.P. O'Reilly, National Microelectronics Research Centre, University College, Lee Maltings, Prospect Row, Cork, Ireland

InSb has the smallest energy-gap of any of the binary III-V materials, leading to a cut-off wavelength of 7μm at 300K. The addition of small proportions of N to InSb offers the prospect of extending the response wavelength into the 8 – 12μm range, which is important for thermal imaging in that atmospheric transmission window and because it encompasses the absorption lines of several environmentally important gases and can therefore be used for monitoring the gases. We report on the growth, by a combination of MBE and a nitrogen plasma source, of InSbN with up to 10% nitrogen. Structural characterisation techniques of TEM, AFM and SIMS have enabled some optimisation of material quality to be demonstrated by biasing the sample during growth. Measurements on light emitting diodes comprising a superlattice of $InSb_{0.945}N_{0.055}$/InSb show an emission wavelength of 10.5μm, which is confirmed by free electron laser assessment. Comparison with tight-binding band-structure calculations indicate that approximately 10% of the nitrogen is active. Hall effect measurements of 1μm thick bulk layers indicate an increasing n-type behaviour, the degeneracy effects of which mean, however, that this is only a lower limit.

10:20 **BREAK**

Session II: Diluted Nitrides: Growth
Session Chair: H. Yonezu

10:40 **M-II.1**

INTEREST OF THE (111) ORIENTATION FOR GaInAsN / GaAs QUANTUM WELLS GROWN BY MOLECULAR BEAM EPITAXY

S. Blanc, A. Arnoult, H. Carrère, E. Bedel, G. Lacoste and C. Fontaine, LAAS-CNRS, 7, Avenue du Colonel Roche, 31077 Toulouse cedex 4, France

The(111) orientation has been shown to have some interesting properties for MBE growth of strained zincblende materials. In particular, this orientation is piezoelectric and allows to increase the critical thickness for strain relaxation relatively to the (100) case. As a consequence, 10nm thick (111)B(Ga,In)As wells of high In contents (up to 30-32%) can routinely be obtained at a standard temperature (520°).

We have investigated MBE growth of (Ga,In)(As,N)wells on (111)B GaAs. The objective was to determine wether the use of this novel orientation could be beneficial for these quaternaries. We will present our first results on the effect of growth conditions on the N incorporation efficiency, and the optical properties of these(Ga,In)(As,N) wells grown on (111)B GaAs. We will compare (111)B and (100) characteristics and conclude on the interest of these novel wells to extend the wavelengths reachable for GaAs optoelectronics.

11:00 **M-II.2**

PROPERTIES OF 1.3µm InGaNAs LASER MATERIAL GROWN BY MBE USING A N2/Ar RF PLASMA

J.A. Gupta(a), Z.R. Wasilewski(a), B.J. Riel(a,b), J. Ramsey(a,b), R.L. Williams(a,b), G.C. Aers(a), P.J. Barrios(a), G.I. Sproule(a), A. Perovic(c) and D.D. Perovic(c), (a)Institute for Microstructural Sciences, National Research Council of Canada, Ottawa, Canada K1A 0R6, (b)Physics Department, University of Ottawa, Ottawa, Canada K1N 6N5, (c)Department of Materials Science and Engineering, University of Toronto, Toronto, Canada M5S 3E4

Increasingly, the development of InGaNAs-based laser diodes on GaAs substrates is being directed towards the 1.3um wavelength regime because of its importance in Metropolitan Area Networks. In this presentation we will describe the growth and material characteristics of InGaNAs quantum well structures grown by molecular beam epitaxy (MBE) using dilute N2/Ar gas mixtures with an RF plasma cell. Ar gas dilution facilitates the plasma ignition and enhances the control of nitrogen solid composition, which varies according to the fraction of N2 in the gas mixture. Single and multiple quantum wells grown by this technique have excellent structural quality as shown by high resolution X-ray diffraction, atomic force microscopy, transmission electron microscopy and photoluminescence (PL) spectroscopy. We will also discuss the PL results and the effects of post-deposition rapid thermal annealing (RTA) on the structural and optical properties. Room temperature PL emission beyond 1.3um was achieved from as-deposited InGaNAs quantum wells with GaNAs barriers. After optimized RTA, bright and narrow room temperature emission at 1.3um was achieved. These results confirm the suitability of the dilution plasma approach for producing laser diode active regions at telecommunications wavelengths.

11:20 **M-II.3**

EFFECT OF INCREASED N INCORPORATION ON GROWTH AND MICROSTRUCTURE OF GaInNAs/GaAs FILMS

T.J. Bullough, S. Davies, S. White, S. Thomas, P.R. Chalker and T.B. Joyce, Materials Science and Engineering, Department of Engineering, The University of Liverpool, Liverpool, L69 3GH, UK

We compare in-situ reflection anisotropy spectroscopy (RAS) acquired during the CBE growth (with an atomic-N beam) of GaInNAs/GaAs(001) films containing N below and above the solubility limit, and corresponding post-deposition STEM EDX chemical composition analysis from cross-section samples. RAS is used to show any anisotropy above ~0.1% in the optical reflectivity from the surface, associated with surface reconstructions and/or the near-surface optical anisotropy of the bulk. During growth at low N levels (below the solubility limit of N in InGaAs), RAS shows the surface (As-dimer) reconstructions are somewhat comparable with InGaAs growth, although nitridation of the surface results at low arsenic overpressures. However at higher N levels the normal (As-dimer) reconstructed surface is lost during the first few monolayers of growth, and bulk optical anisotropy of the order 1% develops as the reflectivity decreases by up to 70% due partly to surface roughening. These observations are compared with post-deposition STEM EDX from cross-sections which show the low-N films to be homogeneous and of uniform thickness, whereas the high-N films are segregated with ~100nm InGaAs(N) volumes separated by layers of a ~10nm thick GaN-like phase. The segregated microstructure is anisotropic when viewed along the [110] and [-110] directions, which correlates with the observed RAS optical anisotropy.

11:40 **M-II.4**

NITROGEN-PLASMA STUDY FOR PLASMA-ASSISTED MBE GROWTH OF 1.3µm LASER DIODES

Hélène Carrère(a), Alexandre Arnoult(a), André Ricard(b), Eléna Bedel-Pereira(a), (a)LAAS-CNRS, Toulouse, France, (b)CPAT-UPS, Toulouse, France

In recent years, (Ga, In)(As, N) alloys, with low N contents, have attracted increasing attention. In particular, GaInAsN has appeared to be a very interesting candidate for 1.3µm emitting devices; thus standard laser diodes and VCSELs have been fabricated. However, growth of these alloys remains problematic in terms of N incorporation control and material quality.
We have studied plasma-assisted molecular beam epitaxy growth of GaAsN and GaInAsN using a RF plasma cell to provide reactive nitrogen from ultrapure N2. Plasma emission spectroscopy has been performed in order to identify its different species (N, N2, N2+,…) and their concentration evolution as a function of N2 flow rate and RF power. These results have been related to N concentration in GaAsN bulk material and GaxIn1-xAs1-yNy/GaAs quantum wells (QW). N2+ ions emission has been investigated in order to minimize their concentration and consequently to limit the deterioration of the growing surface.
On the other hand, we have studied the incorporation of impurities due to the RF plasma cell. Oxygen, generally responsible for low photoluminescence performance, has been observed and its incorporation reduced, allowing growth of 1.3µm emitting QWs at room temperature. Other impurities, less affecting optical properties, have been detected and related to growth conditions.
These studies allowed us to define optimal conditions for RF plasma cell utilization, leading to the growth of 1.3µm laser diodes.

12:00 **LUNCH**

Tuesday, June 18, 2002 — Afternoon
Mardi 18 juin 2002 — Après-midi

Session III: Diluted Nitrides: Band Structure I
Session Chair: E. O'Reilly

14:00 **M-III.1**

BAND ANTICROSSING IN HIGHLY MISMATCHED COMPOUND SEMICONDUCTOR ALLOYS

W. Walukiewicz, Materials Sciences Division, Lawrence Berkeley National Laboratory, Berkeley CA 94720, USA

Highly mismatched alloys (HMAs) of compound semiconductors are formed when electronegative atoms partially replace more metallic anions. Group $IIIN_xV_{1-x}$ alloys with a small concentration of electronegative N substituting the more metallic column V elements has been the most extensively studied class of HMAs. We have shown that many of the unusual properties of the $IIIN_xV_{1-x}$ alloys can be well explained by the Band Anticrossing (BAC) model that describes the electronic structure in terms of an interaction between highly localized levels of substitutional N and the extended states of the host semiconductor matrix [1]. The model has not only explained a large variety of the effects observed in the group $IIIN_xV_{1-x}$ alloys but has also predicted new phenomena. For example, experiments have fully confirmed the theoretically predicted effective mass enhancement [2] and the greatly improved donor activation efficiency [3] in InGaNAs alloys and also the N-induced transition from indirect to direct band gap in GaNP [4]. Recently we have demonstrated the broad applicability of the BAC model to other HMAs including ZnS_xTe_{1-x}, $ZnSe_yTe_{1-y}$ [5] as well as extreme case of $Cd_{1-y}Mn_yO_xTe_{1-x}$ alloys [6].

[1] W. Shan, et. al., Phys. Rev. Lett., 82, 1221 (1999),.[2] C. Skierbiszewski, et. al., Appl. Phys. Lett. 76, 2409, (2000), [3] K. M. Yu, et. al., Phys. Rev. B61, R13337 (2000)), [4] W. Shan, et. al., Appl. Phys. Lett., 76, 3251 (2000), [5] W. Walukiewicz, et. al., Phys. Rev. Lett., 85, 1552 (2000), [6] K. M. Yu, et. al., Appl. Phys. Lett., to be published

14:40 **M-III.2**

MONITORING THE STRONG NON-PARABOLICITY OF THE CONDUCTION BAND IN (Ga,In)(N,As)/GaAs QUANTUM WELLS

H. Grüning, P.J. Klar, W. Heimbrodt, J. Koch and W. Stolz, Department of Physics and Material Sciences Center, Philipps-University, Renthof 5, 35032 Marburg, Germany, S. Tomic, Department of Physics, University of Surrey, Guildford GU2 5XH, Surrey, UK and E.P. O'Reilly, National Microelectronics Research Centre, University College Cork, Lee Maltings, Prospect Row, Cork, Ireland

(Ga,In)(N,As) as well as Ga(N,As) alloys are employed in the active region of GaAs-based lasers for 1.3 and 1.55µm applications. However, these alloys differ considerably from conventional amalgamation-type III-V alloys such as (Al,Ga)As commonly employed in III-V device structures and exhibit striking new properties. Dramatic changes of the electronic band structure occur when only incorporating a small fraction of N into GaAs or (Ga,In)As. One important implication of the N-incorporation is a strong non-parabolicity of the conduction band yielding already for x about 1% an increase of the electron effective mass by about a factor of 2 for k=0 and a strong variation of the electron effective mass with increasing k-vector. We demonstrate how this N-induced non-parabolic dispersion of the conduction band in Ga(N,As) and (Ga,In)(N,As) can be monitored in hydrostatic pressure experiments of the interband transitions of (Ga,In)(N,As) based quantum wells Photomodulated reflectance experiments were carried out at 300K and hydrostatic pressures up to 20kbar. The PR spectra were fitted using derivative-like line shapes to extract the energy positions of the interband transitions. These were compared with theoretical values calculated using a 10-band k.p model including the effects of nitrogen. The good agreement between experiment and theory allows one to extract the conduction band dispersion and hence the change of the effective mass.

15:00 **M-III.3**

EXOTIC ELECTRONIC PROPERTIES OF III-V NITRIDE ALLOYS: CLUSTERING, LOCALIZATION AND AMALGAMATION

Alex Zunger, National Renewable Energy Laboratory, Golden CO, USA

Although nitrogen is an isovalent substitution in GaAs or GaP, it leads to very unusual optical properties, which I will review first. Using the empirical pseudopotential method and large atomistically relaxed supercells we have systematically studied the evolution of the electronic structure of GaPN and GaAsN, from the dilute nitrogen impurity regime to the nascent nitride alloy. We show how substitutional nitrogen forms Perturbed Host States (PHS) inside the conduction band whereas small nitrogen aggregates from localized Cluster States (CS) in the band gap. As the nitrogen composition increases, the energy of the CS is pinned while the energy of the PHS plunges down as the nitrogen composition increases. Strongly localized wave functions, low-pressure coefficients, and sharp emission lines from the CS characterize the impurity limit (PHS above CS). We do not find support to the formation of impurity bands, as the CS-CS interaction is much weaker than the PHS-CS interaction. The amalgamation limit (PHS overtake the CS) is characterized by a coexistence of localized states (leading to high effective mass, exciton localization, Stoke's shift in emission vs. absorption) overlapping delocalized PHS (leading to asymmetrically broadened states, low temperature coefficient, delocalized E+ band at higher energies). The alloy limit (PHS well below CS) may not have been reached experimentally, but is predicted to be characterized by conventional extended states.

15:40 **BREAK**

Session IV: Diluted Nitrides: Charaterization

Session Chair: A. Zunger

16:00 **M-IV.1**

HYDROGEN AS A PROBE FOR STUDYING THE ELECTRONIC PROPERTIES OF (INGA)(ASN)/GAAS HETEROSTRUCTURES

M. Bissiri, G. Baldassarri Höger von Högersthal, **A. Polimeni** and M. Capizzi, Istituto Nazionale di Fisica della Materia and Dipartimento di Fisica, Universita degli Studi di Roma "La Sapienza", Piazzale A. Moro 2, 00185 Roma, Italy, M. Fischer, M. Reinhardt and A. Forchel Universität Würzburg, Technische Physik, Am Hubland, 97074 Würzburg, Germany

Recently, we have shown that H irradiation leads to a passivation of the electronic activity of N in (InGa)(AsN)/GaAs heterostructures, a rather surprising effect for an alloy and/or an isoelectronic impurity as nitrogen. Such passivation is due to the formation of N-H bonds and manifests itself as: (i) a quenching of the exciton recombination in N-related complexes in the N dilute limit; (ii) a blue-shift of the (InGa)(AsN) gap toward that of the N-free material in the alloy limit.
At all N concentrations, a thermal annealing leads to a complete recovery of the electronic properties (InGa)(AsN) had before H irradiation. In the dilute limit, the activation energy, Ea, for the release of the H atoms increases from 2.0 eV to more than 2.4 eV with increasing the number of N atoms in complexes such as N clusters and/or chains. This allows a microscopic characterization of the many N related luminescence lines observed so far in Ga(AsN)/GaAs heterostructures. In the alloy limit, annealing data show the presence of a bi- (or tri-) modal gaussian distribution of Ea's, suggesting that different N complexes contribute to the giant optical bowing observed in the dependence on N content of the (InGa)(AsN) energy gap.
Finally, we show that hydrogen affects the dependence of the material electronic properties on temperature and provides an estimate of the tensile strain contribution to the band gap of Ga(AsN)/GaAs quantum wells.

16:40 **M-IV.2**

THE In AND N DISTRIBUTION IN InGaAsN QUANTUM WELLS ANALYSED BY HIGH RESOLUTION TRANSMISSION ELECTRON MICROSCOPY

M. Albrecht, Th. Remmele, V. Grillo, H.P. Strunk, Universität Erlangen, Department of Materials Science and Engineering, Institute of Microcharacterisation, Cauerstr. 6, 91058 Erlangen, Germany, A.Yu. Egorov, H. Riechert, Infineon Technologies, Corporate Research Photonics, Otto-Hahn-Ring 6, 81730 München, Germany

Despite the detailed knowledge of the optical properties of InGaAsN quantum wells, the structural origin of the localisation centres is not well understood. In principle these centres can be caused by local fluctuations of (i) well width, (ii) strain and (iii) composition (In as well as N) or a combination of them. To analyse which of these effect is predominant requires the analysis of the In and N atoms in the quaternary alloy with high spatial resolution. In this paper we propose a method, that solves the problem of the independent determination of the indium and nitrogen concentrations in a strained quaternary InGaAsN superlattice, by measuring lattice strain and the intensity of the chemical sensitive (002) reflection
As an example we evaluate InGaAsN quantum wells with a nominal N concentration of 1.7% and with In concentrations of 10%, 20% or 35%. We reveal local fluctuations of the In and N concentrations over distances down to 4 nm with a sensitivity of 0.1% for N and 1% in for In fluctuations in this distance range. From a comparison of annealed and as grown samples we find, that optical properties of as grown samples are dominated by In concentration fluctuations on a length scale of 20 nm with a broad size distribution. These In fluctuations lead to carrier localisation and low energy tail in the photoluminescence. Annealing homogenises the In distribution and leads to diffusion of N out of the quantum well.

17:00 **M-IV.3**

BONDING OF NITROGEN IN DILUTE GaInAsN AND AlGaAsN STUDIED BY RAMAN SPECTROSCOPY

J. Wagner, T. Geppert, K. Köhler, P. Ganser, and M. Maier, Fraunhofer-Institut für Angewandte Festkörperphysik, Tullastrasse 72, 79108 Freiburg, Germany

Recently the dilute III-V nitrides, such as GaAsN and GaInAsN containing a few percent of nitrogen, have attracted considerable interest. For the understanding of the physics of these alloys with highly dissimilar group V constituents it is important to gain information on the local bonding of the nitrogen. For that purpose, the bonding of nitrogen in $Ga_{1-x}In_xAs_{1-y}N_y$ with x 0.12 and y 0.04 and $Al_xGa_{1-x}As_{1-y}N_y$ with x 0.05 and y 0.04 has been studied by Raman spectroscopy. When proceeding from GaAsN to GaInAsN the nitrogen-induced vibrational mode near 470 cm^{-1} observed in GaAsN was found to split into up to three components, with one of the In-N related modes at higher and the other at lower frequencies than the Ga-N mode. Upon thermal annealing, the relative mode intensities were found to change in favor of the In-N related modes, indicating a redistribution of III-N bonds. For AlGaAsN, in contrast, the almost exclusive formation of complexes with Al-to-N bonding was observed already for a low Al content of x=0.05 at a nitrogen concentration of y=0.01, as seen from a complete switch in mode intensity from the Ga-N mode at 470 cm^{-1} to a new Al-N related mode near 450 cm^{-1} and a concomitant reduction of the intensity of the AlAs-like mode. Upon thermal annealing no redistribution in mode intensities was observed, reflecting the much larger cohesive energy of the Al-N bond as compared to that of the Ga-N and In-N bond.

Wednesday, June 19, 2002 Afternoon
Mercredi 19 juin 2002 Après-midi

Session V: Diluted Nitrides: Characterization
Session Chair: W. Walukiewicz

14:00 **M-V.1**

RECOMBINATION PROCESSES IN N-CONTAINING III-V TERNARY ALLOYS
I.A. Buyanova and W.M. Chen, Department of Physics and Measurement Technology, Linköping University, 581 83 Linköping, Sweden, C.W. Tu, Department of Electrical and Computer Engineering, University of California, La Jolla CA 92093-0407, USA
Nitrogen containing III-N-V alloys, such as Ga(In)NAs and GaNP have in recent years emerged as a subject of considerable theoretical and experimental research interest, due to their very unique physical properties and a wide range of possible device applications. In this paper we review our results from optical and magnetooptical studies which have allowed identification of the dominant recombination processes in the alloys and related quantum structures. The dominant mechanism for photoluminescence (PL) in Ga(In)NAs is determined as being due to recombination of excitons trapped by potential fluctuations of the bandedge, induced by composition disorder and strain nonuniformity of the alloy. The alloy fluctuations are shown to be largely related to non-optimised growth conditions and can be suppressed by increasing growth temperature or using post-growth rapid thermal annealing (RTA). On the other hand, for GaNP alloy the PL emission is shown to occur within deep states likely related to N clusters. With increasing N composition these states are shown to become resonant with conduction band of the alloy and thus optically inactive, leading to the apparent red shift of the PL maximum position. The first available experimental information on the chemical identity of the non-radiative defects in the Ga(In)NAs alloys, reducing the radiative efficiency, and mechanism for their formation is also presented.

14:40 **M-V.2**

PHOTOLUMINESCENCE SPECTROSCOPY OF Ga(In)NAs QUANTUM WELLS FOR EMISSION AT 1.5 μm
M.-A. Pinault and E. Tournié, Centre National de la Recherche Scientifique, Centre de Recherche sur l'Hétéro-Epitaxie et ses Applications (CNRS/CRHEA), rue Bernard Grégory, Parc Sophia-Antipolis, 06560 Valbonne, France
Ga(In)NAs-based materials and quantum-wells (QWs) heterostructures are attracting increasing attention because of their peculiar properties, and because of the potential of GaInNAs for telecom applications. Up to now, most research work has focused on the development of GaInNAs QWs for emission at 1.3 μm which can be achieved by incorporating as low as ~1% N into GaInAs. Impressive results have indeed been reported. Still, the possibility to reach 1.5 μm, the other wavelength of interest for telecommunications, is not yet clear. In fact, this requires to increase the In and N contents in the 40% and 3% range, respectively, which in turn results in degraded properties.
In this work we have investigated by photoluminescence (PL) spectroscopy the optical properties of GaInNAs QWs for emission at 1.5 μm. The samples have been grown by solid-source molecular-beam epitaxy. We show that the low radiative efficiency of as-grown samples arises mainly from the low growth-temperature which has to be used to prevent alloy decomposition. In addition, by varying the sample design we show that the strong blue shift of the PL line observed upon post-growth annealing results from a re-organization of the local N-bond configuration inside the GaInNAs QW. This, in turn, strongly affects the carrier localization which is detected in as-grown samples. Finally, we show that a careful adjustment of both the growth conditions and annealing parameters allow to achieve high PL efficiency at 1.5 μm.

15:00 **M-V.3**

ELECTRON TRAPS IN GaAs:N AND Ga(As,N) GROWN BY MOLECULAR BEAM EPITAXY
P. Krispin(a), V. Gambin(b) J.S. Harris(b) and K.H. Ploog(a), (a)Paul-Drude-Institut für Festkörperelektronik, Hausvogteiplatz 5-7, 10117 Berlin, Germany, (b)Solid State and Photonics Laboratory, Stanford University, Stanford CA 94305, USA
Crystal quality and luminescence efficiency of Ga(As,N) layers deteriorate for larger GaN mole fractions. Both can be remarkably improved by postgrowth heat treatment. The degradation and anneal mechanisms are however still controversially discussed. Further, it is not clear, why the doping efficiency of Si is poor for Ga(As,N). Deep-level defects are often proposed as compensating and non-radiative recombination centers, but have not been identified yet in Ga(As,N). We therefore study the generation of electron traps in the alloy region [Ga(As,N)] and in the dilute N limit [GaAs:N] by capacitance-voltage measurements, admittance spectroscopy, and deep-level transient Fourier spectroscopy on 500 nm thick layers with N contents of about 0.5% and below 0.1%, respectively. We find at low reverse biases for all layers an electron depletion and a strong admittance dispersion, both of which can be ascribed to deep traps in a region close to the surface. The thickness of the defective region changes with the Si concentration, but does not depend on the amount of N. The admittance dispersion can be remarkably reduced by annealing. For each of the investigated GaAs:N and Ga(As,N) layers, a dominant electron trap is observed, the gap level of which is 0.59 and 0.30 eV below the conduction band edge, respectively. The nature of these deep-level defects will be discussed.

15:20 **BREAK**

15:40-18:00 POSTER SESSION

Session Chair: W. Chen, E. O'Reilly, A. Forchel, C.W. Tu

Diluted Nitrides

M/P01 CHEMICAL BEAM EPITAXY (CBE) OF INDIUM GALLIUM NITRIDE ARSENIDE (InGaNAs) FOR 1.3 MM PHOTOLUMINESCENCE

J.O. Maclean, K.J. Nash, P.D.J. Calcott and E.T. Chidley, QinetiQ Ltd., Malvern Technology Centre, St. Andrew's Road, Malvern, Worcestershire WR14 3PS, UK

GaAs-based dilute nitride devices have the potential to reduce the cost of optical communications modules. 1.3µm dilute nitride VCSEL's, grown by Molecular Beam Epitaxy (MBE) using a plasma source of nitrogen, are being tranferred to production[1]. However, the use of an alkyl precursor as the nitrogen source may well allow relatively simpler scale-up. Nevertheless, Metalorganic Vapour Phase Epitaxy (MOVPE) growth of 1.3. µm InGaNAs using 1,1-Dimethylhydrazine (DMHy) as the nitrogen precursor is challenging because the nitrogen incorporation efficency is low. We report the epitaxy and photoluminescence of InGaNAs quantum wells by CBE using trimethylindium, triethylgallium, arsine and DMHy. This builds on previously demonstrated very high nitrogen incorporation into gallium arsenide (up to 7%) [2]. The growth temperature, and V:III ratios have been varied for a range of InGaNAs compositions. Epitaxy optimisation resulted in an intensity enhancement of 10 K PL by several orders of magnitude, significantly beyond 1.1 µm.

[1] K.D. Choquette, J.F. Klem, A.J. Fischer, O. Blum, A.A. Allerman, I.J. Fritz, S.R. Kurts, W.G. Breiland, R. Sieg, K.M. Geib, J.W. Scott and R.L. Naone, Electronics Lett., 36(16) (2000) 1388-1390.
[2] J.O. Maclean, D.J. Wallis, T. Martin, M.R. Houlton and A.J. Simons, J.Cryst. Growth, 231 (2001) 31-40.

M/P02 CHEMICAL BEAM EPITAXIAL GROWTH OF (GA,IN) (AS,N) SEMICONDUCTING ALLOYS

J L. Castano, P.L. Pernas and B.J. Garcia, Laboratorio de Microelectronica, Departamento de Fisica Aplicada C-XII, Universidad Autonoma de Madrid, Cantoblanco 28029 Madrid, Spain

Nitrogen containing III-V semiconducting alloys have received increasing attention due to their potential application on infrared optoelectronic devices. It is well known that the incorporation of small amounts of nitrogen into GaAs dramatically decreases the band gap energy.

The limitations on grown thickness or N mole fraction imposed by the tensile stress of the GaAs1-xNx layers grown on a GaAs substrate can be overcome if indium is added to the alloy, allowing the growth of Ga1-yInyAs1-xNx layers lattice-matched to GaAs or InP substrates.

Several growth techniques, including low or high pressure vapour phase epitaxy, that use organic gases or hydrides as precursors (MOCVD, MOVPE), ultra high vacuum techniques (UHV) using solid sources and plasma N sources (MBE), either organic precursors or hydrides (MOMBE, GSMBE) have demonstrated their ability to grow III-V-N alloys. In this work we present preliminary results on the growth of III-V-N alloys by Chemical Beam Epitaxy (CBE) using organic gases as precursors for all elements: triethylgallium (TEGa), trimethyindium (TMIn), tertiarybutylarsine (TBAs) and dimethylhidrazine (DMHy).

Although other groups have previously used these four precursors on MOCVD reactors, or some of them in UHV techniques (MOCVD, GSMBE) combined with other sources (plasma N, NH3, AsH3...), their simultaneous use in a UHV system is described here.

M/P03 OPTICAL PROPERTIES OF GaInNAs/GaAs QUANTUM WELLS

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We report the results of our studies of optical and electro-optic properties of GaInAsN /GaAs single quantum wells and heterojunctions grown by Gas Source MBE. Scanning transmission electron microscopy and energy dispersive X-ray analysis confirm that the quantum wells are of uniform composition, thickness and good crystalline quality.

Photoluminescence (PL) measurements from sequentially grown GaInAs and GaInNAs quantum wells were carried out between 2K and room temperature. A significant difference in the temperature dependence of GaInNAs bandgap compared to nitrogen free GaInAs is observed. Photo-modulated reflectance spectroscopy and the PL results are used to determine the interband transition energies. The results are compared with the theoretical values obtained using the band-anticrossing model. When the device is illuminated with monochromatic or broad band light a finite photovoltage (PV) develops in the plane of the quantum wells due to Fermi level fluctuations. Photovoltage transients measured as a function of temperature are used to extract information about the potential fluctuations and non-radiative centres in the GaInNAs QWs.

M/P04 LO PHONON-PLASMON COUPLING AND MECHANICAL DISORDER-INDUCED EFFECT IN THE RAMAN SPECTRA OF GaNAs ALLOYS

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We report LO-allowed Raman spectra from GaN(x)As(1-x) alloys with N-content close to the solubility limit, i.e. ~3%.
One attractive characteristic, yet unexplored, of N-based III-V ternary alloys is that they consist in mixed crystals with a sharp contrast in the bulk modulus of the two constituents. Raman scattering is well-suited for its investigation because it addresses the force constant of the bond, which depends on the mechanical properties of the host matrix. In the Ga-N region, we observe a mode at 425cm-1, i.e. below the local mode of N in GaAs at 471cm-1. This mode has degenerated LO and TO components and grows at fixed frequency with x. From a direct comparison with Be-chalcogenide alloys [1], which exhibit a similar mechanical contrast, it is attributed to Ga-N vibrations in hard-like N-rich bounded regions, dispersed within the soft-like Ga-rich matrix.
In the Ga-As region we use Si-doping as a sensitive probe to investigate the structural quality close to the solubility limit. At large doping rate (n>1018cm-3), we observe similar phonon LO-plasmon (LO-P) coupling as in GaAs:Si. Unexpectedly LO-P coupling disappears at lower n values, while it persists in GaAs:Si. When n decreases, the LO and theoretically forbidden-TO modes, which substitute for LO-P, exhibit antagonist shifts and asymmetries towards the center of the optical band. The whole of this suggests an improvement in the alloy quality with Si-doping.

1 O. Pagès et Al., Phys. Rev. B, to be published.

M/P05 DERIVATION OF A 10-BAND K.P MODEL FOR DILUTE NITRIDE SEMICONDUCTORS

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There still exists controversy as to the validity of the band anti-crossing model (BAC) [1] used to describe the electronic structure of GaInNAs [2]. We have developed a simple, quantitative tight-binding model [3] for GaN_xAs_{1-x}. Because it employs a basis of localised atomic orbitals, we can confirm that N forms a resonant defect level above the conduction band edge in GaAs. We then use a Green's function model to derive explicitly that the resonance becomes delocalised and spread over several energy states as x increases, and show that the two-level BAC still provides an excellent description of the behaviour of the conduction band edge in ordered supercells. We discuss its modification when disorder is included. We extend the Green function model to derive that the band structure of GaNAs/GaAs and related heterostructures can be calculated using the k.p method, but the conventional 8-band k.p Hamiltonian must be modified to include two extra spin-degenerate nitrogen states, giving a 10-band model. We explicitly identify and track the resonant level even to alloy compositions as large as x =0.25. The picture established for GaN_xAs_{1-x}, including the formation of a localised resonant level, can be applied to any alloy, providing a simple but accurate technique to account for the observed band-gap bowing across a wide range of semiconductors.

[1] W. Shan *et al.*, Phys. Rev. Lett. 82 1221 (1999)
[2] E.D. Jones *et al.*, Phys. Rev. B 60, 4430 (1999); T. Mattila, S.H. Wei, A. Zunger, Phys. Rev. B 60, R11245 (1999); Y. Zhang and A. Mascarenhas, Phys. Rev. B 61, 15562 (2000); P.R.C. Kent and A. Zunger, Phys. Rev. B 64, 115208 (2001)
[3] A. Lindsay and E.P. O'Reilly, Solid State Commun. 112 443 (1999)

M/P06 EXCITONS LOCALIZATION EFFECTS IN GaAsN/GaAs EPILAYERS GROWN BY MOCVD

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Optical studies of GaAs1-xNx/GaAs epilayers grown by metal-organic chemical vapour deposition (MOCVD), with low nitrogen concentration (1.65% and 2.2%), have been achieved by a number of optical techniques such as photoluminescence (PL) , photoreflectance (PR) spectroscopies and time-resolved PL (TR-PL) measurements in the nanosecond range. It has been shown that the increase of the nitrogen fraction causes a red shift of the PL emission band compared to the GaAs one. TR-PL results at 12 K reveal that the decay time is clearly dependent on the emission energy. It increases for lower emission energy. From the temperature PL decay lifetime study we suggest that PL emission is dominated by the recombination of localized excitons trapped by potential fluctuations of the near-band-edge induced by compositional fluctuations in GaAsN epilayer .

M/P07 PLASMA ETCHING OF InGaAs(N) THIN FILMS FOR LASER STRUCTURES

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Progress in the development of the semiconductor quaternary GaInNAs/GaAs has led to the production of 1.3mm laser diodes and solar cells using this alloy. Efficiency of these devices, which is still limited, is due to both material and laser structure quality. Plasma etching has a capability of producing high quality opto-devices, with very fast etch rates.
We have grown continuous thin films (~250nm) of In0.22Ga0.78As and In0.22Ga0.78As0.99N0.01, which has a 1.3mm emission in quantum well form, on GaAs [001] in a UHV chemical beam epitaxy system. These materials were then etched using an STS inductively coupled plasma (ICP) system; SiCl4 was used as the etchant and varying etch rates between 0.1mm and 0.5mm per minute were investigated.
Electron microscopy, scanning and transmission (SEM and TEM), and atomic force microscopy (AFM) has revealed high quality isotropic etching of InGaAs(N), producing ~90°sidewalls on very small, 1mm, features with no mask undercut. No re-deposition of removed material is seen as often evident in plasma systems and the addition of nitrogen to the InGaAs alloy changes only the material etch rate. In this paper we present a summary of the effects of N addition to the plasma etching process of InGaAs(N).

M/P08 BAND OFFSET MEASUREMENT OF QW STRUCTURES USING SURFACE PHOTOVOLTAGE: APPLICATION TO THE InGaAsN/GaAs QW SYSTEM

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A novel method allowing to determine the band alignment/band offsets for quantum well structures is presented. The method is based on surface photovoltage, is simple and direct: no fitting procedure is needed and standard experimental equipment is used. The samples have a simple structure, no contact is needed. The experimental setup and sample structure is described and a model of the photovoltage generation mechanism is presented. Then it is shown how the surface photovoltage spectra can be used to determine the band alignment (type I or II) and the band offsets of QW structures. Spectra of type I and type II QW structures have different typical features. Finally the method is applied to determine the band offsets of two type I QW structures: InGaAs/GaAs and InGaAsN/GaAs. For InGaAs a percent ratio conduction/valence band offset of 60/40 is obtained, in agreement with other results from literature. For InGaAsN the result is 78/22.

M/P09 MEDIUM ENERGY ION SCATTERING STUDIES OF AS-GROWN AND ANNEALED GaInNAs/GaAs QUANTUM WELLS

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The post-growth thermal annealing of GaInNAs quantum well (QW) based lasers has been widely employed to achieve the desired laser emission wavelength although the mechanism for this process is uncertain. The observation of dot-like structures in as-grown GaInNAs quantum wells has been previously reported and it has been noted that annealing of these layers causes a significant enhancement of cathodoluminescence intensity due to the disappearance of a non uniform dot-like regions.
In this paper we investigate the distribution of indium within as-grown and annealed GaInNAs QW’s characterised by medium energy ion scattering (MEIS). The ion scattering data are compared with Raman spectra and scanning transmission electron microscopy cross-sectional images of the quantum well structures, which indicate long range uniformity of the GaInNAs composition and crystallinity. Differences between channeling and randomly scattering MEIS geometries indicates the aggregation of indium in the as-grown quantum wells occurs on the nanoscale but can be ameliorated by a short period of annealing.

M/P10 INFLUENCE OF NITROGEN ON THE EXCITON BINDING ENERGY IN GaInNAs/GaAs QUANTUM WELL

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The binding energy of ground state exciton in GaInNAs/GaAs single quantum well is studied theoretically. We have calculated the exciton binding energy by a variational envelope function procedure using simple two-band model, including strains and the difference in dielectric constants between well and barrier materials. The influence of the well width and nitrogen and indium mole fractions on the value of binding energy has been analyzed. It has been observed that incorporation of small amounts of nitrogen (up to 5%) induces significant changes of the exciton binding energy. We have calculated binding energy of the ground state heavy-hole exciton in a GaInNAs/GaAs single quantum well as a function of the well thickness, for various In and N concentrations. The dependence of the binding energy on In content is qualitatively the same as in a GaInAs/GaAs structures. Higher nitrogen mole fraction causes larger band gap difference between well and barrier and therefore deeper potential well, resulting in the increase of the binding energy.

M/P11 OBSERVATION OF LIGHT HOLE AND HEAVY HOLE EXCITONS IN DILUTE GaAsN ALLOY

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Several physical properties are not very well known in GaNAs semiconductor alloy. Recently, measure of Photoluminescence excitation has realised on GaNAs alloy and demonstrated the excitonic origin of the fundamental transition of GaNAs. Surprisingly no splitting of the fundamental level was observed. Such splitting should arise from the bi-axial strain induced by the lattice mismatch with the GaAs substrate. In our work, we have performed absorption and photoluminescence measurements of as-grown GaAsN layers on GaAs substrates. The absorption shows an energy splitting of the fundamental transition and an increase of the splitting with an increase of the N concentration [N]. This indicates the presence of a strain, which lifts the light- and heavy-hole valence band degeneracy. The measure of the energy splitting between light and heavy hole yields the distortion, the lattice parameter and the strain-free excitonic band gap of the GaNAs layer. This excitonic absorption proves the existence of a GaNAs alloy and shows that the band gap reduction of GaNAs start at very low [N]. The photoluminescence results provide information about change, with the [N], of the "impurity levels" (N pairs and clusters) in the band gap of GaNAs. Our results are consistent with the picture of "perturbed host states" as discussed in Ref. [1], in the general context of III-nitride ternary alloys.

[1] P.R.C. Kent and Alex Zunger, Phys. Rev. Lett. 86, p2613 (2001).

M/P12 OPTICAL INVESTIGATIONS OF InGaAsN/GaAs SINGLE QUANTUM WELL STRUCTURES

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We have investigated a number of InGaAsN/GaAs SQW with N concentrations up to 5% and high In concentrations (up to 40%). The width of quantum well ranges from 6.5 to 9.0 nm. To investigate the optical properties of InGaAsN/GaAs single quantum well (SQW) structures the photoreflectance (PR) and the photoluminescence (PL) measurements were performed. PR data were taken at room temperature. For all structures besides of high-energy transition originating from GaAs, the 11H optical transition originating from SQW was observed. For some structures higher energy QW optical transitions are visible at the spectra, too. The identification of optical transitions was possible due to the theoretical calculations based on the envelope function model applied to structures being under study. With increasing nitrogen content, we observed the relatively high red shift of the optical transition energies. PL measurements were performed to study the temperature dependence of 11H transition energy. Experimental data were fitted using the empirical Varshni model. We found that for structures with higher N content the temperature dependence of 11H transition energy is weaker in comparison to the structures with lower N content. Fitting with Varshni model to PL data showed that carriers are almost fully delocalised. Only at low temperatures a localisation of the carriers is present. At low temperatures we can observe S-shaped energy peak behaviour for structures with high nitrogen content.

M/P13 EFFECT OF ANNEALING ON AN InGaP/InGaAsN/GaAs NpN DOUBLE HETEROJUNCTION BIPOLAR TRANSISTOR

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We have characterized an InGaP/InGaAsN/GaAs NpN double heterojunction bipolar transistor on the effects of rapid thermal annealing. The use of a quaternary InGaAsN material system takes advantage of a low energy bandgap in the base to reduce operating voltages in GaAs-based HBT. The base layer was made of p+ In(0.03)Ga(0.97)As(0.99)N(0.01) with a band gap of ~ 1.2 eV which is lattice matched to GaAs. RTA has been demonstrated to improve the photoluminescence (PL) intensity, the internal quantum efficiency of solar cells, and the hole mobility. Therefore, RTA is also performed on our samples to investigate its effect on device performance. The samples before and after RTA were characterized by x-ray, PL, and SIMS. By using RTA at 650 and 700C for 15, 30, and 45 seconds, the dc device performance was studied as function of the base hydrogen concentration.

M/P14 TIME RESOLVED STUDIES OF PHOTOLUMINESCENCE IN GaNP EPILAYERS AND MULTIPLE QUANTUM WELL STRUCTURES

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We report on time-resolved studies of low temperature photoluminescence (PL) in GaNP alloys with N composition up to 4%. The PL is attributed to radiative recombination within deep localized states related to N pairs and clusters, and its decay is found to contain two components. The fast component is suggested to be due to contribution of non-radiative (NR) transitions and energy transfer within N-related defects. The decrease in the NR decay time from about 100 ns for N < 0.24% down to 10-20 ns for N > 0.6% likely reflects increasing concentration of competing NR defects. On the other hand, the slow decay component is believed to represent radiative decay, i.e. intrinsic to the PL emission. The abrupt shortening of this component from 700 ns to 100-200 ns is revealed when N > 0.6%. Interestingly, this occurs within the same range of N compositions as the appearance of the direct-bandgap-like transitions in the photo-modulated transmission spectra of GaNP [1]. Thus the change in the character of the extended band states seems to affect the oscillator strength of optical transitions at N-induced localised states, due to e.g. interaction between the localized and extended states. Moreover, the PL decay time is spectral dependent and decreases at the high energy side of the PL spectrum. Such behaviour can be explained by increasing communication of the higher energy localised states with the extended band states.

[1]W. Shan et al. Appl. Phys. Lett. 76, 3251 (2000)

M/P15 TEMPERATURE BEHAVIOUR OF GaNP BANDGAP ENERGY

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Incorporation of a small amount of nitrogen in GaP has been found to cause significant changes of the conduction band (CB) states of the resulting alloy leading, e.g., to a transition from indirect to direct band gap. This transition has been attributed either to an anticrossing between the Gamma-minimum of the CB and localized N states or to admixing of the Gamma-character to the CB states. Both mechanisms should also affect the temperature dependence of the GaNP band gap energy. The anticrossing with the N states is expected to slow down the reduction of the bandgap energy with increasing temperature, whereas an opposite trend should be observed if the admixing of the Gamma-states dominates the CB formation. We report experimental results from temperature dependence studies of the optical absorption edge of the GaNP alloy with N composition up to 3.1 %. The observed increase in absorption coefficient with increasing N content, as well as the spectral shape of the absorption edge incline towards direct bandgap for the alloy, in agreement with previous studies. Temperature variation of the GaNP band gap, however, is found to be rather similar to the parental GaP. We thus suggest that both contributions from the anticrossing with the localized states and the increasing Gamma-character to the CB states are important to the alloy formation.

M/P16 LATTICE DISTORTIONS EFFECT ON EXCITON BOUND TO NITROGEN IN GAP-RICH A3B5 ALLOYS

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Effects of microscopic inhomogeneties of GaP-rich A3B5 solid solutions on exciton bound to isolated nitrogen impurity are investigated. Calculated densities of states are compared with experimental data.
The bound exciton ground state sustains an energy shift induced by atomic substitution. Amount of this shift depends on local environment of the nitrogen atoms and is defined by the difference of atomic potentials. Alloys with substitution in both sublattices are under consideration.
Caused by nitrogen atoms crystal lattice deformations are taken into account by Harrison bonding orbital method. Lattice relaxation to the equilibrium state changes interatomic distances: the N-host atom distance is not equal to N-substitution atom distance. This difference causes an increase of the energy shift and leads to redistribution of spectral line components intensities.
Interatomic distance dispersion, caused by substitutional atoms, was taken into account by quasicontinual model. It leads to broadening of bound exciton ground state energy levels. The dependence of energy level width on alloy composition is obtained. However lattice distortions cannot explain the asymmetry of the spectral line, observed in luminescence excitation data. We suppose that the asymmetry of the spectral line is determined by exciton ground state splitting due to intrinsic piezoelectric effect.

M/P17 ELECTROLUMINESCENCE STUDIES IN FORWARD AND REVERSE BIAS CONDITIONS OF A NITRIDE-RICH GaN(1-x)P(x) SQW STRUCTURE LED GROWN BY LASER-ASSISTED METAL-ORGANIC CHEMICAL VAPOR DEPOSITION

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III-V-nitrides such as GaN(1-x)P(x) have been particularly attractive for optoelectronic devices operating over a wider range of wavelengths from ultraviolet to infrared due to a gigantic bandgap bowing compared with a cation (In) mixed GaN. We fabricated the light emitting diode (LED) of a nitride-rich GaN(1-x)P(x) single quantum well structure grown using a laser-assisted metal-organic chemical vapor deposition. We investigated the electroluminescence (EL) of the LED. In the forward bias condition, the EL of the LED had two main peaks of which energy position were around 2.9 eV called a blue band and 2.2 eV called an yellow band. Furthermore, we observed that the LED emitted at yellow band even reverse bias condition. The peak energy of these emissions shifted towards higher energy with an increase of the drive current. The blue-band shift of increasing current may be explained by a band-filling mechanism, as reported for InGaN LEDs. The current-voltage (I-V) characteristics of LED is not so similar to conventional InGaN LED. The component of current flow consists of ohmic ingredient and exponential ingredient. The equivalent ideal factor n of this LED is over 200, and in reverse bias region, I-V curve has a good linearity rather than exponential component. These results suggest that blue band emission relates to exponential ingredient, and that yellow band emission relates to ohmic ingredient respectively.

M/P17A A NEW METHOD TO SUPPRESS THE IN DIFFUSION OF GaInNAs/GaAs QUANTUM WELLS GROWN BY MOLECULAR BEAM EPITAXY

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Diluted nitride lasers made of GaxIn1-xNyAs1-y exhibit excellent temperature characteristics suggesting that they may operate as Peltier-free light sources in optical data transmitters. In addition, GaInNAs / GaAs has been used to fabricate photovoltaic cells, resonant cavity enhanced photo-detectors, and hetero-junction bipolar transistors. However, the optical properties are rapidly deteriorated with increasing nitrogen incorporation for longer wavelength emission, while the lasing threshold remains relatively high. Although the photoluminescence can be improved significantly by thermal annealing, it can also induce a big blue shift, which is due to the inter-diffusion of In and N (especially for In) between GaInNAs and GaAs(N) during the annealing.
We present a new method to suppress dramatically the In diffusion of GaInNAs / GaAs quantum wells during thermally annealing. By adding very thin strain-mediating layer (SML) between GaInNAs and GaAs(N), both the diffusion of In and photoluminescence (PL) blue shift are decreased significantly and the interfaces of the GaInNAs / GaAs(N) quantum well become much sharper under the same annealing process. With such SMLs, the PL (after the same annealing) peak is shifted 33 nm to longer wavelengths compared to the sample without the SMLs.

Wide Gap Nitrides

M/P18 Er DIFFUSION INTO GALLIUM NITRIDE

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Erbium has been diffused into GaN for the first time. Weak photoluminescence emission can be observed in infrared region. The diffusion coefficient has been measured by Rutherford backscatting spectroscopy (RBS) and secondary ion mass spectrometry to be D=1.8E-12EXP(1.054 eV/kT) cm2/s. Erbium is also implanted into GaN to compared the concentration profile and photoluminescence intensity. To enhance the emission intensity of the Er-diffused GaN, Si, Mg, C and O co-doping by ion-implantation is performed. The enhancement effect of the emission intensity will be discussed.

M/P19

GROWTH AND CHARACTERISATION OF MANGANESE DOPED GaN THIN FILMS PREPARED BY PULSED LASER DEPOSITION

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Thin films (~100nm) of the dilute magnetic semiconductor (DMS) Ga/(1-x) Mn/(x) N, 0.01<x<0.05 were grown by the pulsed laser deposition technique. The films were grown from both a sintered, pressed GaN powder target and a Ga/Mn metal alloy. The influence of plasma assist was investigated using a small anode nitrogen DC plasma source. The growth rate and surface roughness of the film was monitored by in-situ reflectometry. The pressures of the nitrogen atmosphere and substrate temperatures were varied to optimise the growth. The affect of the Mn dopant was investigated using X-ray diffraction and photoluminescence spectroscopy. SQUID magnetometry and electron spin resonance were used to characterise the magnetic properties of the films.

M/P20

CHARACTERISATION OF GaN FILMS GROWN ON SAPPHIRE BY LOW-TEMPERATURE CYCLIC PULSED LASER DEPOSITION / NITROGEN RF PLASMA

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Recently we have proposed a new method for deposition of group-III nitrides from elemental precursors (Ga, N2) [1]. This technique is based on a two-step cyclic process, which alternates Pulsed Laser Deposition (PLD), of a liquid gallium target and nitrogen plasma treatment. Previously, the films have exhibited an increase in the intensity of the X-ray peak (0001) with deposition temperature. In this work, we proceed to detailed characterisation of the films grown by this NH3-free cyclic PLD deposition technique and we study the influence of the deposition temperature on the GaN films. The layers were deposited on pre-nitridated sapphire (0001) substrates at low deposition temperatures (400º C to 600º C) and a nitrogen plasma pressure of 1 mbar.

The cyclic GaN thin films thus obtained are compared in terms of rocking curve quality, photosensitivity and nitrogen incorporation. X-ray diffraction, transient photoconductivity, scanning electron microscopy and energy dispersive spectroscopy are the selected tools used to characterise and compare the deposited films. Optimisation of deposition parameters is suggested to further improve the quality of binary films. Our technique is also applicable to ternary and quaternary alloy systems.

[1] S. Koynov, P. Sanguino, M. Niehus, L. V. Melo, R. Schwarz, Layer-By-Layer Deposition of Group-III Nitrides By Two Step Cyclic Process, to be published in Materials Science & Engineering, 2001.

M/P21

HIGH ALUMINIUM COMPOSITION AlGaN LAYERS GROWN BY LP MOVPE

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AlxGa1-xN films, with various aluminum composition (up to 65%), were elaborated by low pressure metalorganic vapor phase epitaxy (LP MOVPE). The thickness of these layers varies between 1 and 2µm. The aluminum composition increases if decreasing the reactor pressure. It varies from 19.6% to 53.3% for the growth pressure of 50 and 20 mbar, respectively. The x value has been measured by energy dispersion spectroscopy (EDS). Correlation between Al fraction in the vapor phase xv and the fraction in the solid phase xs is investigated. It shows a linear behavior for xv values higher than 20%. The dependence of growth rate on growth conditions is also investigated. Growth rate increases with decreasing the reactor pressure and so parasite reactions. A linear variation of growth rate with partial pressure of the elements III is observed between 3 and 5 10-6 atm. The optical gap of AlxGa1-xN layers is determined as function of alloy composition x by photoluminescence measurements.

M/P22

THE GROWTH OF GaN/Si AND p-TYPE DOPING VIA ION IMPLANTATION

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A simple reactive evaporation technique combined with a two-step growth method was used to grow wurtzite single crystalline GaN on Si (111) substrates.

GaN films had a good crystalline structure. FWHM of XRD was about 30 arcmin. Strong band edge photoluminescence (PL) spectrum was detected at 365nm with FWHM 74 meV at room temperature. The difference of the crystalline quality of GaN/Si between using a low temperature GaN buffer layer and a Si_3N_4 buffer layer was investigated. GaN p-n junction was fabricated by implantation of Mg ions followed with a subsequent annealing in N2 atmosphere. A hole concentration in p-type GaN was 2.70_10^{17} /cm3 , and a hole mobility was 9.39cm^2/Vs.

M/P23

STUDY OF INVERSION DOMAIN PYRAMIDS FORMED DURING THE Mg:GaN GROWTH

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Optical investigation of structural defects induced by the introduction of Mg during the growth of MOCVD GaN is presented. The incorporation of Mg not only induces changes in the stacking sequences but simultaneously inverts the GaN polarity from Ga-face to N-face during the growth. By photoluminescence measurements, several excitonic emissions associated to these inversion domain pyramids are found.

M/P24

ANALYSIS OF THE CURRENT TRANSPORT IN THE METAL/p-GaN:Mg CONTACTS

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The production of reliable ohmic contacts with low contact resistance on p-GaN:Mg still presents a considerable problem which hampers various applications. This is particularly pronounced in the laser diodes where large current densities are needed.

The experimental results of the current transport for several metal contacts on MOCVD p-Gan:Mg samples are analyzed. Temperature dependence of the I-V characteristics is also presented. In some cases ohmic behavior is obtained and in some not. Relevant charge transport mechanisms are analyzed and it is show that the tunneling is the most important transport mechanism. It is further concluded that the surface properties are critical for the ohmic contacts. Providing good surface, the formation of ohmic contacts should not present considerable problem.

In the second part we analyze theoretically the charge transport phenomena for the metal/semiconductor contacts. For that purpose pertinent equations are critically re-examined, all in attempts to obtain a formula that would explain I-V characteristic for the case of two non-ohmic contacts. Furthermore, an attempt is presented to determine the characteristic parameters (energy barrier) even in the case of 2 non-ideal and non-ohmic contacts. The energy band diagram for metal/p-Gan:Mg contacts and an estimated value for contact resistance in ideal case are presented.

M/P25

NON-STATIONARY PHOTOCONDUCTIVITY STUDIES IN GaN THIN FILMS DEPOSITED BY HYBRID PULSED LASER AND PLASMA TECHNIQUE

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Recently we proposed a new method to deposit GaN by layer-by-layer cyclic pulsed laser deposition combined with nitrogen r.f. plasma CVD. In this work we characterize the electrical and optical film properties by means of I-V curves, with and without illumination, optical absorption, photoluminescence, and steady-state and transient photoconductivity under different experimental conditions.

The films were amorphous when deposited on quartz glass substrates. Sharp X-ray peaks indicate oriented film growth already at a low deposition temperature of 600°C on sapphire. Both types of films show photosensitivity for illumination above and below the bandgap. The decay after pulsed excitation is following a power law with index about -0.3, as it is known for GaN and AlGaN [1]. Optical absorption near the band edge indicates a broad trap state distribution. Photoluminescence is used to evaluate the density of deep defects. We interpret the results in terms of multiple trapping (MT) and release of carriers in localized states.

Persistent photoconductivity experiments show that the electronic equilibrium is not reached until hundreds or even thousands of seconds. A broad distribution of lifetimes is also supported by a slow decay of the peak photoconductivity as a function of the chopping frequency.

[1] M. Niehus, R. Schwarz, S. Koynov, P. Sanguino, M. Heuken, and B.K. Meyer, phys. stat. sol. (a) 188 (2001) 845.

M/P26

THERMAL ANNEALING EFFECTS ON THE OPTICAL GAIN OF InGaN/GaN QUANTUM WELL STRUCTURES

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In this work, we analyze the effects of thermal annealing by calculating the optical gain in the InGaN/GaN quantum well for different In composition. The interdiffusion of Ga and In atoms across the interface of the well and the barrier resulted from thermal treatments is assumed to follow Fick’s law. The strong piezoelectric effect in the InGaN/GaN quantum well is considered in the calculation. The maximum optical gain can be obtained as the In diffusion length to be 4 angstrom. This optimum diffusion condition shows an agreement with the results reported in literature.

M/P27

A STUDY OF SAPPHIRE ETCHING CHARACTERISTICS USING BCl3/HBr INDUCTIVELY COUPLED PLASMAS

C.H. Jeong, D.W. Kim, K.N. Kim and G.Y. Yeom, Dept. of Materials Engineering, Sungkyunkwan Univ. Kyungki-do, Suwon, Korea

In this study, BCl3-based inductively coupled plasmas were used to investigate the etch characteristics of (0001) sapphire wafers. The etch characteristics were investigated as a function HBr contents in BCl3/HBr plasmas. Ar was used as an additional additive gas in these gas combinations. Sapphire wafer was etched at 1200 watts of inductive power and –350 volts of DC bias voltage.

The highest sapphire etch rate obtained in BCl3/HBr plasma was about 3700 Å/min and the small addition of Ar increased the sapphire etch rate about 10 %. The etch selectivity over photoresist obtained with this gas mixture was about 0.9. During the etch process in BCl3/HBr plasmas, the etch products were monitored in situ by optical emission spectroscopy(OES) and quadrupole mass spectroscopy(QMS). The improved vertical etch profile with smooth sidewall would be observed by SEM in 90%BCl3/10%HBr plasmas.

M/P28

A STUDY OF GaN ETCHING CHARACTERISTICS USING HBr-BASED INDUCTIVELY COUPLED PLASMAS

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In order to fabricate the GaN-based devices such as light emitting diodes and laser diodes successfully, high etch rates, high etch selectivities, vertical etch profiles, and smooth sidewalls are required in the dry etching process. Many studies showed that the high etch rates could be obtained using BCl3-based and Cl2-based plasmas. However, to obtain highly vertical etch profiles and smooth sidewalls with these gas combinations, hard masks had to be used.

In this study, HBr/BCl3, HBr/HCl, and HBr/Cl2 inductively coupled plasmas were used to etch GaN selectively over photoresist. The GaN etch characteristics such as the etch rates of GaN, etch selectivities over photoresist, and etch profiles, were studied as a function of these gas composition.

In addition, optical emission spectroscopy(OES) and quadrupole mass spectroscopy (QMS) were used to characterize the GaN etching in HBr-based plasmas. In HBr/ BCl3 plasmas, the measured GaN etch rate was about 700 nm/min and over 80 degree of etch profile with smooth sidewall could be obtained with the variation of HBr contents.

M/P29

MICROSTRUCTURE OF PLANAR DEFECTS AND THEIR INTERACTIONS IN WURTZITE GaN FILMS

J. Kioseoglou(a), Ph. Komninou(a), G.P. Dimitrakopulos(a), Th. Kehagias(a), H.M. Polatoglou(a), G. Nouet(b) and Th Karakostas(a), (a)Aristotle University of Thessaloniki, Department of Physics, Solid State Section, 54006 Thessaloniki, Greece, (b)ESCTM - CRISMAT, UMR 6508 CNRS, ISMRA, 6 Boul. Marechal Juin, 14050 Caen Cedex, France

Optoelectronic devices comprising GaN epilayers exhibit satisfactory performance despite a multiplicity of microstructural defects. The electronically inert character of many structural defects in GaN has been attributed to the atomic configurations that are associated with them. For example, the electronically inert character of most inversion domain boundaries (IDBs) has been correlated to a particular relative displacement of the abutting domains leading to elimination of ìwrongî bonds along the IDB plane. Holt IDBs comprise wrong bonds and have been shown to be electrically active and to require a higher formation energy than IDB*s. Nevertheless, they also have been observed experimentally, and a mechanism for their introduction, through interactions of IDB*s with I1 intrinsic stacking faults SFs, has been proposed. In the present work the topological theory of interfacial defects is employed in order to predict the interactions, and a rigorous framework for the a priori topological analysis of defects is applied in order to determine the character of IDBñSF junction lines. By employing a new formulation of Stillinger-Weber potential we calculate the energy of IDBs and SFs as well as the energy of the prismatic translation domain boundaries. We are also able to determine the relaxed structures for the possible atomic configurations of the interactions between IDBs and SFs and compare the simulated images of the relaxed structures with the HREM observations.

M/P30

THE EFFECT OF Al CONTENT ON QUALITY OF GaN EPILAYERS GROWN ON AlxGa1-xN/GaN/Si(111) BY UHVCVD

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Transmission Electron Microscopy (TEM) was conducted on AlxGa1-xN epitaxial layers grown on exact Si (111) substrates by Ultrahigh Vacuum Chemical Vapour Deposition (UHVCVD). Structures grown were 2.5um-GaN/120nm-Al0.5Ga0.5N/20nm-AlN/Si(111) (structure A) and 2 um-GaN/120nm-AlxGa1-xN/0.5um-GaN/120nm-Al0.5Ga0.5N/20nm-AlN/Si(111) (structure B). The AlN buffer layers were grown at 1170C without any prior surface nitridation process to avoid the formation of a silicon nitride phase on the silicon surface. The AlGaN and GaN layers were grown at the same temperature of 1130C. For comparison, three structure B samples were grown with x = 0.06, 0.1 and 0.2 for the AlxGa1-xN layers between the GaN layers. Selected area diffraction patterns (SADPs) were taken from the interface region of cross-sections of all samples studied. The results indicated that all the layers were single crystalline with an epitaxial orientation relationship with respect to the silicon substrate given by: GaN[0002]//Si[111], GaN[-1100]//Si[-112] and GaN[11-20]//Si[110]. In order to study the crystal quality of the top GaN layers and determine the direction of Burgers vector, cross-sectional TEM micrographs were taken near the [11-20] and [-1100] zone axes of the GaN. It was found that the crystal quality of the GaN layers could be improved by growing the GaN layers on the structure of AlxGa1-xN/GaN/AlGaN/AlN/Si(111). The effect of Al content, x, on dislocation densities in the top GaN layers was discussed.

M/P31

STRAIN AND DEFECTS IN Si-DOPED GaN

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We report a study by photoluminescence (PL), Raman scattering, and X-ray diffraction (XRD) of a series of Si-doped GaN layers grown by MOVPE on sapphire (0001) with the carrier concentration of 2.3E17 – 9E18 cm-3. We found that the band-gap reduction deduced from the PL spectra analysis is due to both band-gap narrowing (BGN) effect and relaxation of the thermal residual stress. The XRD spectra show that at high Si-doping levels (>1.6E18 cm-3) the GaN films become under tensile stress. A progressive decrease of the E2 Raman mode frequency with Si concentration confirm this observation. The stress induced E2 mode frequency shift is estimated to 4.4 cm-1/GPa. Atomic Force Microscopy (AFM) is also used to investigate the defect surface structures of GaN:Si layers which are dominated by pinned steps related to threading dislocations. Additionally, dislocation densities are determined by XRD by employing a model that uses the linewidth of X-ray rocking curves. The obtained values (from 8.4E8 to 7.1E9 cm-2) are in agreement with AFM measurements of step termination densities.

M/P32

EFFECT OF STRAIN ON OPTICAL PROPERTIES OF TERNARY III-NITRIDE ALLOYS

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Importance of III-nitride alloys for applications in optoelectronic devices requires their optical properties to be determined as functions of many factors one of which is the presence of strain due to differences of lattice constants of alloy compounds and substrates. This makes theoretical calculation of the optical properties useful in order to provide complete and coherent information for device design and optimization. The peculiarities observed in measured reflectance spectra of InGaN, AlGaN, InAlN thin films grown on sapphire were confirmed by modulation spectra and photosensitivity. The electronic band structure, charge densities, complex dielectric function and reflectivity of InGaN, AlGaN, InAlN were calculated in a pseudopotential approach. The local model empirical pseudopotentials gave good results for bulk binary compounds but failed to explain the experiment for strained alloy films. Thus we used ab initio norm-conserving pseudopotentials as a starting point for our self-consistent calculations with taking into account the biaxial and local strain. This gave us the possibility to qualitatively explain the observed peculiarities of reflectance spectra.

M/P33

MODELLING OF GaN HEMT

V.V. Murav'ev, A.A. Tamelo, E.V. Krivosheev, D.F. Molodkin, BSUIR, 6 P. Brovski, 22027 Minsk, Belarus

Recently due to the achievements in designing and release of powerful microwaves monolithic integrated circuits and discrete transistors becomes pressing question research GaN of the microwave of field transistors with barrier Shotky in a mode of the large signal and development of recommendations for their application.
On the basis of modelling transistors with high mobility of carriers, on temperature model parameters of the equivalent circuit of the GaN field transistor with high mobility o GaN f carriers with submicronic gate in a mode of the large signal are designed.
The field model based on the equations of Macksvell also is applied for researches, allowing to consider behaviour of structure of the transistor at various operating conditions and being sufficient for definitions of key parameters of the equivalent circuit. Carried out researches for two values of a threshold field, and one corresponds to the semiconductor GaAs, the second – GaN.
Dependence of average drift speed electrons from intensity of an electric field in the semiconductor is received. Drift speed electrons and intensity of a field are uniform function of characteristic length of the transistor. At constant increase of intensity of an electric field, drift speed electrons has a maximum on threshold value of a field, and then falls down after an exhibitor.
For more full representation about behaviour of a voltage and a current calculations for several values of resistance of loading of the equivalent circuit with the distributed parameters are carried out. The received functions are used for construction of characteristics.
Change of distribution of concentration of electrons as lengthways are long size is considered, and during an interval of time interesting us. Distributions of concentration electrons lengthways are long size for GaAs and GaN equally and does not depend on characteristics of a field in the researched semiconductor device. The maximal concentration observes on edges of devise, and during other it parts is uniform and on two order less. And in time value of concentration electrons is practically constant.
Dependences of intensity of a field are received from are long size and from time. Value of intensity of a field depends on time, and it has directly proportional linear character. Intensity of a field is constant during all length, however, on the end has rather significant jump.
At the second investigation phase the initial length of the transistor with 3μm was reduced up to 1μm, that corresponds to more perspective development in a millimetric range. Were carried out, similar above-stated, researches for value of a threshold field appropriate to the semiconductor GaN. Change are long has not affected in any way dependence of drift speed electrons from intensity of a field, has not affected distribution of concentration electrons lengthways are long size. However, reduction of length of the transistor has affected behaviour characteristics at the initial moments of time. The basic difference is earlier achievement of threshold size and less intensive oscillatory process.
At the following stage we the temperature model is used. Its basic difference from field model that it is based on Bolzman equation and particularly allows taking into account processes of dispersion in semiconductor layers. This model allows to calculate parameters of the equivalent circuit of the field transistor with high mobility of carriers with submicronic gate in a mode of the big signal, a spectrum of target fluctuations at various frequencies gained signal and also to analyse dynamics of redistribution of density of a current and concentration in valleys of the semiconductor for the period of a signal.
Research of intensity, a voltage of an electric field, concentration of carriers and temperatures of valleys are carried out depending on length of the semiconductor and time of course of a current. The opportunity of realisation of models of devices is shown by numerical modelling by a method of Monte Carlo of frequencies of dispersion, characteristics, noise parameters of GaN field transistors.

M/P34

BINARY AND TERNARY III-V SEMICONDUCTORS FOR UV AND VIS SOLAR MONITORING

Petro S. Smertenko, Tamara Ya. Gorbach, Ludmila A. Matveeva, Vitaly P. Kostylyov, Institute of Semiconductors Physics NASU, prospekt Nauki 45, 252028 Kyiv, Ukraine, Marian Kuzma, Institute of Physics, Higher Pedagogical School, Rejtana 16a, 35-309 Rzeszow, Poland; Ryshard Ciach, Institute of Metallurgy and Material Science, Polish Academy of Sciences, Reymonta 25, 30-059 Cracow, Poland.

GaP, GaN and AlGaAs p-n junctions were characterised by photo and dark I-V data, photocurrent spectral response and electroreflectance spectroscopy the morphological design, the variation in photosensitivity, wave length peak position recombination and band gap parameters induced by the patterned, doping and heteroepitaxy processing and their influence for achieving of successful solar irradiance detection have been analyses and discussed. A comparison of the spectral photoresponse was shown that GaP and AlGaAs p-n junction are good for detection MUV and VIS and GaN p-n junction may be recommended for NUV and MUV without filters.

M/P35

SELECTIVE PHOTODETECTORS ON THE BASE OF GaAlAs/GaAs, GaP/GaAs, GaN/GaInN HETEROSTRUCTURES

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Barrier heterostructure allow to increase the internal quantum efficiency and selectivity of photodetectors. Hereby a variation of geometrical and electrophysical parameters of contact layers promotes to matching of photodetector spectral sensitivity and the spectra of irradiance registered. The integral (I-V, C-V), kinetic and spectral characteristics of GaAlAs/GaAs, GaP/GaAs, GaN/GaInN photodetectors developed were investigated. The correlation betweeen shortwave boundary of photosensitivity and heterojunction depth has been established. The shortwave boundary is shown to be shifted to longwave region with increase of heterojunction depth (hereby the longwave boundary does not be shifted). In the case of enough big diffusion length and moderate heterojunction depth the curve of spectral photosensitivity has the constant photosensitivty in wide range. At = $_{max}$ the monochromatic photosensitivity is in the range of 0.1-0.7 A/Wt (GaAlAs/GaAs), 0.15 A/Wt (GaN/GaInN) and 0.1 A/Wt (GaP/GaAs).

M/P36

GaN/GaAs/GaN HETEROSTRUCTRES GROWN BY MBE

H. Kim, A. Trampert and T.G. Andersson, Mina, Chalmers, 31296 Göteborg, Sweden

Heterostructures of GaN/GaAs/GaN were grown by MBE on sapphire substrates using RF-activated nitrogen. Such heterostrctures have potential interest as a low band gap material embedded in GaN. The layers can be grown by epitaxial techniques but little is known about the layer quality. There are three main problems with the growth of such heterostructures. The growth temperatures of GaN and GaAs are different, their lattice constant and lattice structures (wurtzite and zincblende) are very different and the growth of GaN on GaAs substrates may result in degradation of the GaAs due to the reactive nitrogen. GaAs layers with thicknesses from 1 to 100 nm were grown at different temperatures on thick GaN. The effect of the growth parameters on the GaAs thickness and composition, were studied by SIMS, TEM and RHEED. The growth of the thin GaAs resulted in an overlayer of arsenic. This excess arsenic was minimised by a certain annealing after terminating the GaAs growth. Layers were also direct grown, i.e. without growth interuption. It was found the GaAs layers had defects and the GaN cap layer contained arsenic. The actual GaAs layer thickness was found to depend on the growth parameters. If the temperature was kept below ~750 °C the physical thickness was nearly the same as the intended one. The GaN cap layer contained arsenic especially it the temperature had been too high. The first interface was generally smoother than the upper one.

M/P37

NEXAFS AND PHOTOEMISSION INVESTIGATION OF LOW-ENERGY ION BEAM ASSISTED NITRIDATION OF III-V SEMICONDUCTOR SURFACES

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The subject of this work is the investigation of surface nitridation using in situ X-ray absorption and photoemission measurements. GaAs, InAs, InP and InSb (100) surfaces were nitrided using low-energy N2+ bombardment at different ion beam parameters and substrate temperatures. A detailed analysis of the N 1s core level peaks reveals the presence of nitrides and interstitial nitrogen. NEXAFS measurements in total electron yield mode were performed at the nitrogen K-edge in order to probe the chemical bonding of the implanted nitrogen species. A sharp and characteristic spectral feature at 401 eV is assigned to interstitial molecular nitrogen. Multiple scattering calculations of the NEXAFS using the FEFF-8 code support this assignment.

N 1s core level and valence band spectra were recorded at different excitation energies and in particular near the 1s-Pi* absorption energy of molecular nitrogen. Valence band spectra taken at resonance conditions reveal a strong enhancement of a feature that may be attributed to an occupied MO of N2, and therefore provide new evidence for a processinherent implantation of interstitial molecular nitrogen (Ni). The spectral features corresponding to Ni are subject of a strong time-dependent effect, which may be due to radiation induced diffusion caused by the intense photon flux at the U49/2 undulator beamline at BESSY II. Extended photoemission studies permit the proposal of a model that describes the surface nitridation.

Thursday, June 20, 2002 — Morning
Jeudi 20 juin 2002 — Matin

Session VI: Diluted Nitrides: Devices I
Session Chair: S. Koch

09:00 **M-VI.1**

InGaAsN: MATERIALS ASPECTS AND APPLICATION IN 1300NM VCSELS

Henning Riechert, Infineon Technology, Corporate Research Photonics, 81730 Muenchen, Germany

1.3µm vertical-cavity surface-emitting lasers (VCSEL) are highly desireable devices for data transmission over silica fibers. For this purpose, we have chosen the novel alloy InGaAsN, combined with conventional GaAs/AlAs VCSEL technology.
We grow this material by solid source MBE using an RF-coupled plasma source to generate reactive nitrogen. Particularities of InGaAsN/GaAs quantum wells, compared to InGaAs, are large changes in band offsets and electron mass, and unusually large fluctuations in composition, which cause carrier localisation almost like in pure nitride alloys. Irrespective of growth process, post-growth thermal annealing is neccessary to achieve laser quality InGaAsN. To study the effects of thermal anneals and to obtain a comprehensive picture of InGaAsN properties, we correlate results from optical and electrical measurements with TEM imaging of the atomic composition along and across the quantum wells.
Material-related performance data of edge-emitting lasers will be given, along with a comparison of lasers based on InGaAsP and on InGaAsN and we will present results for InGaAsN-based VCSELs on GaAs. Our devices emit more than 1 mW, slightly beyond 1300nm, in room-temperature cw operation and data transmission with 10 Gbit/s has been demonstrated.

09:40 **M-VI.2**

CARRIER RECOMBINATION PROCESSES IN 1.3µm GaInNAs EDGE-EMITTING LASERS

R. Fehse(a), S.Tomic(a), A. Andreev(a), S.J. Sweeney(a), A.R. Adams(a), E.P. O'Reilly(a)*, H. Riechert(b), S. Illek(b) and A. Yu. Egorov(b)**; (a)Department of Physics, University of Surrey, Guildford, Surrey, GU2 7XH, UK; (b)Infineon Technologies AG, Corporate Research, 81730 Munich, Germany; *now at NMRC, University College, Lee Maltings, Prospect Row, Cork, Ireland; **guest scientist at Infineon Technologies

The devices used in this study are various 1.3µm GaInNAs (SQW and MQW) edge-emitting lasers, grown by solid source MBE and MOVPE. We determined I_{th} by measuring the light emitted from the facet and, using an optical fibre and an optical spectrum analyser (OSA), we also monitored the light emitted from a window milled in the n-contact of the laser. In this configuration the integrated pure spontaneous emission rate L_{sp} is directly proportional to the radiative current I_{rad}. The measured characteristic temperature T_o(rad) of the radiative current is much larger than the T_o(tot) of the total current at threshold, so we can conclude that temperature sensitive non-radiative recombination processes must be present in these devices. Detailed studies of L_{sp} as a function of injection current in the temperature range of 130K to 370K have enabled us to show that at room temperature 50% of the threshold current is through defects, 25% was radiative and the remainder was due to Auger processes. Interestingly the spontaneous emission rate has a peak at low temperatures which is tentatively associated with the non-equilibrium condition of carriers. It appeared in both MBE and MOVPE devices and may be an intrinsic property of the GaInNAs material system.

10:00 **M-VI.1**

ENHANCED OPTICAL AND STRUCTURAL PROPERTIES OF STRAIN-COMPENSATED 1.3-µm GaInNAs / GaNAs / GaAs QUANTUM WELL LASER STRUCTURE BY INSERTION OF STRAIN-MEDIATING LAYER

E.-M. Pavelescu(a,b), C.S. Peng(a), T. Jouhti(a), W. Li(a), J. Konttinen(a),M. Dumitrescu(c), P. Laukkanen(d), S. Spanulescu(e) and M. Pessa(a), (a)Optoelectronics Research Centre, Tampere University of Technology, P.O.Box 692, 33101 Tampere, Finland, (b)Faculty of Science, Valahia University, Carol I Avenue 2, 0200, Targoviute, Romania, (c)Memscap Oy, 33720 Tampere, Finland, (d)Applied Physics Department, Turku University, 20014 Turku, Finland, (e)Physics Faculty, University of Bucharest, P.O. Box MG-11, 76900 Magurele, Romania

We report on luminescence and structural properties of strain-compensated 1.3-μm GaInNAs / GaNAs / GaAs quantum well laser structure, grown by solid-source molecular beam epitaxy with an rf-coupled nitrogen plasma source. The layer design consists of a strain-mediating GaInNAs layer sandwiched in between a highly compressive GaInNAs quantum well and a strain-compensating GaNAs layer. Insertion of the strain-mediating layer shifts light emission towards longer wavelengths, increases light emission, and improves structural properties of the quantum well, as deduced from the measurements of photoluminescence and X-ray diffraction.

10:20 **BREAK**

Session VII: Diluted Nitrides: Devices II
Session Chair: H. Riechert

10:40 **M-VII.1**

MICROSCOPIC THEORY OF GAIN AND SPONTANEOUS EMISSION IN GAINNAS LASER MATERIAL

Stephan W. Koch, University Marburg, Germany, Joerg Hader, Jerome Moloney, University Arizona, USA

This talk reviews our microscopic many-body theory for the gain and spontaneous emission in semiconductor laser materials. The theory is applied to the novel metastable iii-v semiconductor laser materials. results are shown for the gainnas/gaas material system.

11:20 **M-VII.2**

AUGER RECOMBINATION IN GaInNAs QUANTUM WELLS

A.D. Andreev, University of Surrey, U.K. and E.P. O'Reilly, NMRC, Cork, Ireland

Non-radiative Auger recombination is known to be one of the main effects responsible for the temperature sensitivity of long-wavelength quantum well lasers. In this paper, we present a theoretical study of Auger recombination processes in GaInNAs/GaAs quantum well structures. The calculations are based on the 10x10 k·p model which incorporates the light, heavy and so-hole bands, as well as the conduction and the nitrogen-induced bands. The following effects are included in the Auger rate calculations: (i) light-heavy hole mixing; (ii) the non-linear dependence of the overlap integrals on the momentum transferred, (iii) the non-parabolicity of the electron and hole energy band dispersions; and (iv) the influence of the N-induced band. The Auger transition matrix elements are calculated explicitly, without introducing any further approximations into the 10-band Hamiltonian used. We consider two main channels of Auger recombination: the process when the energy released from the electron-hole recombination is given to the electron excitation (CHCC process) and the process with hole excitation to the spin-orbit valence band (CHHS process). The CHHS process is shown to be dominant. Good agreement was found when comparing the calculated Auger rates with experimental values [2] of the Auger contribution to the threshold current of GaInNAs quantum well lasers.

[1] A.D. Andreev, *et.al.*, Appl. Phys. Lett, 78, 2640 (2001);
[2] R. Fehse, *et.al.*, oral presentation at 14th annual meeting of the IEEE LEOS, 11-15 November (2001), San-Diego, CA, USA

11:40 **M-VII.3**

ANNEALING CONDITION AND COMPOSITION DEPENDENCE OF THERMAL ANNEALING EFFECT ON 1.3 um GaInNAs/GaAs QUANTUM WELL LASERS GROWN BY CHEMICAL BEAM EPITAXY

Shigeki Makino, Tomoyuki Miyamoto, Takeo Kageyama, Yoshihiko Ikenaga, Masakazu Arai, Fumio Koyama and Kenichi Iga Microsystem Research Center, Precision & Intelligence Laboratory, Tokyo Institute of Technology, Japan

We investigated the annealing effect on 1.3 um GaInNAs/GaAs QWs. The In and N was 35%, 1% and as-grown wavelength was 1.34 um. The optimum annealing time is different for each annealing temperature. Regardless of the annealing temperature, the wavelengths reached about 1.28 um at the condition of PL intensity saturation. The highest PL intensity was obtained at 700°C 30 s and 600°C 45 min. This indicates that mechanism of intensity change and wavelength blue shift is different.

We also investigated the composition dependence. We prepared three samples, In and N were (A) 35%, 1%, (B) 33%, 1.2%, (C) 28%, 1.6%. These as-grown wavelength was 1.34 um. The annealing condition was 600°C 45 min. The PL intensity of A and B increased after annealing, on the other hand, C did not show a noticeable increase. Peak wavelength of A became 1.28 um, however, that of B and C were still above 1.3 um. It is found that a high N prevents an increase of PL intensity, and excessively high In requires a higher N to achieve 1.3 um emission due to a large blue shift.

Three types GaInNAs/GaAs DQW lasers were fabricated. In and N were (I) 37%, 1.1% (II) 34%, 0.9%, (III) 29%, 1.4%. 600°C 45 min in situ annealing was performed. These emission wavelengths were about 1.3 um. Smallest Jth as 2.2 kA/cm2 was obtained by sample II. A small N is better to reduce the threshold. These results indicate the importance of selection of the composition and annealing condition for the objective wavelength.

12:00 **LUNCH**

Thursday, June 20, 2002 — Afternoon
Jeudi 20 juin 2002 — Après-Midi

Session VIII: Wide Gap Nitrides: Growth and Characterization
Session Chair: D. Hommel

14:00 **M-VIII.1**

THE INFLUENCE OF GROWTH TEMPERATURE ON THE CRACK DENSITY OF GaN GROWN ON (111) SILICON SUBSTRATES

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The strain in GaN layers on Si can be substantially reduced by the introduction of additional low temperature (LT) AlN interlayers. All samples presented in this paper were grown in an AIXTRON MOCVD reactor using standard precursors. The growth temperatures of the second LT-AlN interlayer and the sandwiched 350 nm thick high temperature (HT) GaN buffer were varied from 550-720°C and 1070-1170°C, respectively. The density and type of cracks on the surface was statistically evaluated. 635°C for the LT-AlN interlayer and 1120°C for the sandwiched HT-GaN layer were found to yield an optimum and top GaN layers as thick as 1 µm could be grown on these buffers. This result indicates that the critical thickness of the HT-GaN on these buffers could be effectively increased using the above mentioned growth procedure. White light interferometry shows a standard deviation of approx. 4.5% for 1.5 µm thickness of the entire layer stack.

In a seperate growth series AlGaN/GaN HEMT structures on Si have been grown in this study on non-optimized buffers. A unity gain frequency of 20 and 32 GHz and a maximum frequency of oscillation of 22 and 27 GHz were obtained for devices with a gate length of 0.7 and 0.5 µm, respectively. In future series we will investigate the performance of this structure on the novel buffer stack.

14:20 **M-VIII.2**

HUNTING FOR A SINGLE-SOURCE PRECURSOR: TOWARD STOICHIOMETRY CONTROLLED CVD OF 13-15 COMPOSITES

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Recently it has been demonstrated both experimentally (1) and theoretically (2), that formation of oligomer species with group 13-15 element backbone occurs directly in the gas phase during 13-15 CVD. The high stability of cluster oligomers [HMYH]n (M=Al,Ga,In; Y=N,P,As; n=4,6) opens perspective to utilize the mixed clusters as a precursors for the synthesis of 13-15 composites, such as AlxGayIn1-x-yN or AlxGa1-xNzAs1-z. Since the gas phase thermodynamic data for the mixed oligomer species and other important intermediates are not available, computational chemistry appears to be the method of choice. Results of extensive ab initio quantum-chemical modelling of gas phase reactions allow one to predict the most promising precursors for the shoichiometry controlled CVD. As an example, nitrogen-containing tetrahedral clusters H4(AlxGayInz)N4H4 (x+y+z=4) are predicted to be excellent candidates for the AlxGayIn1-x-yN production.

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14:40 **M-VIII.3**

MOCVD-GROWTH AND IN SITU CHARACTERISATION OF GaN AND RELATED TERNARY COMPOUNDS BY MEANS OF SPECTROSCOPIC ELLIPSOMETRY

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At present the method of choice for the growth of commercial III-V nitride structures is Metalorganic Chemical Vapor Deposition (MOCVD) due to its high deposition rates, high throughput and less expensive handling, when compared with e.g. Molecular Beam Epitaxy. However, this method lacks the many diagnostic tools available for ultra-high vacuum epitaxial techniques (e.g. reflection high-energy electron diffraction for MBE), thus for MOCVD applications there is an increasing need for in-situ control, which can ensure better reproducibility and higher yield. A solution to this problem is the application of optical in-situ sensors like Spectroscopic Ellipsometry (SE) for the real time monitoring of growth processes [1,2]. Anyhow, a full investigation and understanding of the optical response of the nitride system, especially at elevated temperatures is mandatory. The set-up used for our investigations consists of a spectroscopic ellispometer attached to a commercial Aixtron MOCVD-reactor to study in situ the individual growth stages of GaN and its ternary compounds (AlGaN, InGaN). As a first step, the formation of the GaN nucleation layer on sapphire substrates and the subsequent annealing steps were characterised and compared with simultanously performed laser reflectometry measurements. Layer growth and SE spectra were then recorded at different temperatures in the growth reactor up to 1200°C and the data related to laser reflectometry and ex situ performed high resolution x-ray diffraction, SIMS and TEM measurements to give a full characterisation of the samples. The obtained dielectric functions of substrate, binary and ternary compounds were subsequently used to develope an algorithm for the real time determination of compound concentration during growth using the virtual interface (VI) model proposed by D. Aspnes [3] for optical absorbing ternary semiconductor crystal layers. The experimental results have been compared with simulated data for different monitoring wavelengths and the calculated error in the determination of the Al concentration in AlGaN was found to be as small as 1% in composition. Growth of AlGaN/GaN superlattice structures and the application of the VI model on these systems complete the study.

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[2] W.Richter, J.-T.Zettler, Appl. Surf. Sci. 100/101, 465 (1996).
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15:00 **M-VIII.4**

PHOTOLUMINESCENCE OF GaN LAYERS STUDIED WITH TWO-COLOR SPECTROSCOPY

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Recently, gallium nitride attracts great attention due to its wide direct energy gap (3.5 eV) and material robustness. Extensive studies were devoted to donor centers, which take part in free carriers recombination and thus influence emission. Dominant donor-related emission lines are due to donor-acceptor pairs (DA) and a donor bound exciton recombination (D^0X). The latter process can also occur with simultaneous excitation of donor center (two-electron transition).
In this paper we report results of two-color spectroscopy in the mid-infrared (MIR) applied to GaN epitaxial layers. In this case band-to-band excitation of free carriers is assisted by mid-infrared radiation from a free electron laser (FEL). The MIR photon energy is tuned to match ionization energy of the donors. Photoluminescence spectra obtained with or without additional infrared illumination are compared, and the dependence on FEL photon energy is investigated. The impact of infrared radiation on the on the donor-related emission lines is discussed, taking into account the effective mass model of donor centers.

15:20 **BREAK**

Session IX: Wide Gap Nitrides: Devices
Session Chair: A. Forchel

15:40 **M-IX.1**

GAIN-GUIDED GaN LASER DIODES GROWN ON SAPPHIRE

D. Hommel, T. Böttcher, S. Figge, R. Kröger, Ch. Petter, University of Bremen, Institute of Solid State Physics, Germany, Ch. Zellweger, H.-J. Bühlmann and M. Ilegems, Swiss Federal Institute of Technology Lausanne, IQEP, Switzerland

Laser diodes grown on (0001)-oriented sapphire are impaired by the generation of extended defects and the difficulty to obtain smooth facets by cleaving. A low dislocation density can be achieved by the control of the high-temperature island growth mode during the overgrowth of the nucleation layer. For the heteroepitaxy on sapphire it is possible to obtain typical dislocation densities on the order of 5 10^8 cm^{-2}, which is low enough for device fabrication.

Another crucial point is to avoid by choosing appropriate growth parameters the commonly found Mg-related pyramidal defects, which hinder the incorporation of the Mg as an acceptor. The formation process of the Mg-related pyramides is described by a rate equation model, which takes the segregation of Mg on the surface into account. Under optimized conditions it is possible to grow defect-free structures with hole concentrations exceeding 1 10^{18} cm^{-3}.

One of the key issues to achieve a high output power in light emitting devices is the design of the active region, which typically consists of InGaN quantum wells (QW) embedded in InGaN or GaN barriers and an AlGaN electron blocking layer. The quantum efficiency of InGaN QWs is largely determined by the well thickness and the Si doping level of the barrier layers.

The production of smooth laser facets by cleaving would require the thinning or the removal of the sapphire substrate, which is technologically demanding. Facets of similar perfection can be realized by a much simpler process, where the mesa is defined by reactive ion etching (RIE) followed by a crystallographic wet etching step. This combination ensures a highly reproducible facet quality, since the process is nearly independent of the RIE parameter set.

Gain-guided laser diodes showed stable operation at 400~nm under pulsed current injection at room temperature. Either one or both facets of the laser diodes were coated by dielectric quarter-wavelength mirrors to reduce the threshold current density. Threshold current densities around 15 kA cm^{-2} at threshold voltages of 20 V with output power up to 110 mW at 10°C were obtained.

16:20 **M-IX.2**

A HIGH POWER AlGaN/GaN HETERO FIELD-EFFECT TRANSISTOR

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III-V nitride semiconductors are very attractive for high-power and high-frequency devices. It should be noted that, the on-state resistance of a GaN field-effect transistor (FET) is expected. In this paper, we report that the on-state resistance of an AlGaN/GaN hetero FET (HFET) is lower than that of a Si-based FET. A undoped Al(0.2)Ga(0.8)N(30 nm)/GaN(2 µm) heterostructure was grown on the sapphire substrate using a gas-source molecular beam epitaxy. The mobility of Al(0.2)Ga(0.8)N/GaN heterostructure was about 1200 cm2/Vs at RT. The undoped GaN layer was a high resistive (above 10 Mohm) and the breakdown field of the undoped layer was about 2 MV/cm. Si-doped GaN with a carrier concentration of 5E19 cm-3 was selectively grown in the source and drain regions for obtaining a very low contact resistance.

After that, an Al0.2Ga0.8N/GaN HFET (chip size: 0.15 cm2) was fabricated. The gate width was 20 cm and the gate length was 2 µm. The ohmic electrode materials were Al/Ti/Au and the Schottky electrodes were Pt/Au. The distance between the source and drain was 6 µm. Multi-electrode structures were also fabricated using SiO2 for isolating the source, drain, and gate electrodes, respectively. The ohmic contact resistance for a source and drain was below 1E-6 ohmcm2 The HFET was operated at a current of over 20 A. The on-state resistance of the HFET was about 2 mohmcm2. The schottky breakdown voltage was over 600 V. Therefore, a high power AlGaN/GaN HFET was thus demonstrated.

16:40 **M-IX.3**

QUATERNARY AlInGaN MATERIALS FOR ELECTRONIC AND OPTOELECTRONIC DEVICES

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A new Strain and Energy Band Engineering approach (SEBE) is used to control the strain and optical and electrical properties of quaternary AlInGaN heterostructures. Quaternary $Al_xIn_yGa_{1-x-y}N$ layers are an excellent choice for fabricating heterojunction devices with controlled strain and/or lattice match to GaN. We have demonstrated that In incorporation in the ternary layers significantly improves their structural and optical properties. The quaternary AlInGaN layers can be lattice matched either to GaN, AlGaN or AlInGaN by a proper selection of alloy compositions. Alternatively, an optimized strain profile can be designed in order to increase the Al molar fraction as needed without sacrificing the materials quality. In this talk, we review our results on epilayer and device design and characterization using quaternary $Al_xIn_yGa_{1-x-y}N$ layers and quaternary AlInGaN based heterostructures for optoelectronic and electronic device applications.

The quaternary AlInGaN layers and heterojunctions were deposited using a unique Pulsed Atomic Layer Epitaxy (PALE) approach. This allows for a precise control of the individual layer compositions and thicknesses. Deep UV light emitting diodes with emission from 285-340 nm have successfully been fabricated using PALE deposited quaternary multiple quantum wells in the active region. To the best of our knowledge our results show the shortest LED emission ever achieved. Emission powers as high as 1 mW at wavelengths as short as 340 nm and 0.2 mW at 315 nm have been demonstrated for stripe-geometry devices over sapphire substrates. We will present detailed characterization results to discuss the role of defects, strain, current crowding and their management via quaternary AlInGaN layers.

Improving the performance of high power electronic devices we proposed a novel double heterostructure AlGaN/InGaN/GaN as an active region for nitride based field effect transistors - the Double Heterostructure FET (DHFET). A thin 50 Å layer of $In_{0.1}Ga_{0.9}N$ sandwiched between the GaN buffer and $Al_{0.25}Ga_{0.75}N$ barrier layers provides an excellent 2D carrier confinement due to combined effect of the bandgap offsets and polarization charges at the interfaces. In contrast to conventional devices, the electric field in the InGaN quantum well remains nearly constant in a wide range of gate bias voltages, since it is mainly controlled by the polarization charges at the heterointerfaces. This reduction of field variation reduces the current collapse. Finally, the InGaN layer compensates the strain in the DHFET AlGaN barrier layer. In the DHFET, the strain in the AlGaN/InGaN bi-layer structure on GaN buffer is close to zero at any gate-voltage due to the lattice matching resulting from the use of In. The characteristics of DHFET can be further improved by depositing a thin SiO_2 layer on top of the AlGaN barrier. This thin insulating film reduces the gate leakage current by about 4 orders of magnitude below that of regular HFETs. By combining the gate isolation and improved carrier confinement result in DHFET structure we have recently reported on a novel high-power OSDHFET devices. Compared to regular AlGaN/GaN HFETs, the MOSDHFETs demonstrate 4 - 6 orders of magnitude lower gate-leakage currents, better linearity and current-collapse free characteristics with stable rf-powers above 7 W/mm.