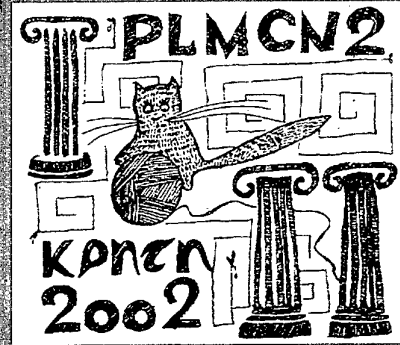
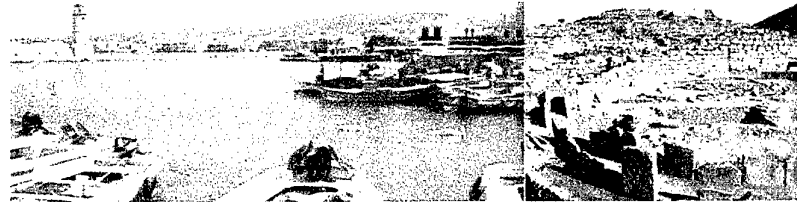


# BOOK OF ABSTRACTS

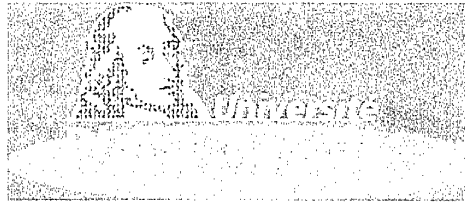
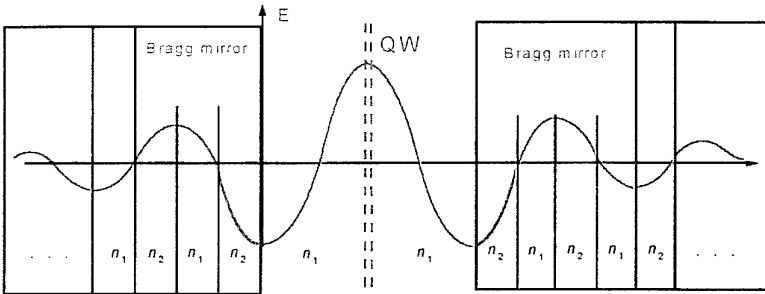


May 25-30, 2002

Grecootel Rithymna Beach  
Rithymnon, Crete, Greece



*International Workshop  
on the  
Physics of Light-Matter  
Coupling in Nitrides - 2*



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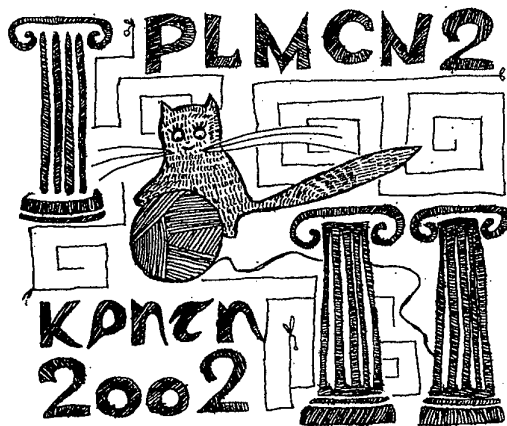
# REPORT DOCUMENTATION PAGE

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<p>ABSTRACT (Maximum 200 words)</p> <p>Contents: The past and the future of heterostructure lasers; Optical Properties of Point Defects in GaN and AlGa<sub>N</sub>; Magneto-Photoluminescence of the Correlated Few-Electron Ground State of Electrostatically Confined Quantum Dots; Scattering of excitons and polaritons by a two dimensional electron gas in GaAs/AlGaAs quantum structures; Optical anisotropy of non-common-atom quantum wells and dots: effects of interface symmetry reduction; Optical Properties of GaN/AlGa<sub>N</sub> Quantum Wells with Inversion Domains; Quantum Dots : Excitons, biexcitons and Charged Excitons; Excitons and trions confined in quantum systems: from low to high injection regimes; Two-dimensional exciton: Unexpected beauty; Fine structure of the quantum-dot trion; Observation of the Fermi Edge Singularity in the Photoluminescence Spectra of Al<sub>x</sub>Ga<sub>1-x</sub>N/GaN Single Heterostructures; Determination of Al<sub>x</sub>Ga<sub>1-x</sub>N refractive indexes at low and room temperature, in the 300 - 600 nm range for the optimization of GaN-based microcavities; Structural and electrical characterization of Schottky barriers on GaN; Homoepitaxial regrowth on free-standing HVPE-GaN quasi-substrates; A Model for Tera-Hertz Radiation from Semiconductor Heterostructures; Exciton Relaxation in Bulk Wurtzite GaN: the Role of Piezoelectric Interaction; Well width dependence of photoluminescence properties of single InGa<sub>N</sub>/GaN quantum wells; Modulation Spectroscopy and Surface Photovoltage Spectroscopy Investigations GaN: Bulk, Thin Films, and Microstructures; Luminescence Properties of III-V-N Type Alloys; Group III Nitride-Based UV Light Emitting Devices; Study of Band Tails in GaN Using Various Optical Probes; Anisotropy and strain effects on lattice dynamics in nitride-based quantum wells and superlattices; EXCURSION: "THE PIRATE BOAT", PIC-NIC; Modeling of Low-Dimensional State of Matter by Excitons in Strong Magnetic Fields; Microscopic investigation of In concentration fluctuation in an InGa<sub>N</sub>/GaN quantum well; Exciton dynamics in InGaAsN/GaAs heterostructures; Molecular beam epitaxy growth of group III-nitrides microcavities optical and structural properties; Stimulated Spin Scattering in Semiconductor Microcavities; Polarization rotation in resonant emission of semiconductor microcavities; The Transition from Strong to Weak Coupling and the Polariton Laser in Semiconductor Microcavities; Polariton Bose condensation in microcavities, thermodynamic and kinetic aspects; Electron-polariton scattering in Semiconductor Microcavities; Elastic Scattering Of Microcavity Polaritons; Atomic Force Microscopy and Electrostatic Force Microscopy observations on Gallium Nitride; High-pressure studies of internal electric fields in nitride quantum structures; Wishful physics: some common misconceptions about InGa<sub>N</sub>; The Anomalous Band Bowing in GaAsN; Energy Gap and Optical Properties of Al<sub>x</sub>Ga<sub>1-x</sub>N; GaN-based Schottky Barrier Photodetectors from near Ultraviolet to Vacuum Ultraviolet (360 - 50nm); Microstructure and the Optical Properties of In<sub>x</sub>Ga<sub>1-x</sub>N and Al<sub>x</sub>Ga<sub>1-x</sub>N Alloys; Disorder-induced modification of the transmission of light in two dimensional photonic crystal; High-Performance AlGa<sub>N</sub>/GaN Solar-Blind Detectors Grown by Metalorganic Chemical Vapor Deposition; GaN-based electronics and opto-electronics in production scale MOCVD systems; Photoluminescence of n-doped InGa<sub>N</sub>/GaN and AlGa<sub>N</sub>/GaN Multiple Quantum Well structures, role of depletion fields and polarization fields.</p>			
14. SUBJECT TERMS  US Army Research, Greece, Heterostructure lasers, Optical properties, Magneto-Photoluminescence, Electrostatically confined quantum dots, Excitons, Biexcitons, Charged excitons, Polaritons, Quantum structures, Quantum wells, Spin scattering, Magnetic fields, Microcavities		15. NUMBER OF PAGES	
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**International Workshop**  
**Physics of Light-Matter Coupling in**  
**Nitrides - 2**



**25 - 30 May 2002**  
**Hotel "Rithymna Beach"**  
**Rithymnon, Crete.**

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This workshop is planned as a high-level scientific meeting connected to the **Research Training Network "CLERMONT" (Physics of Light Matter Coupling in Nitrides)** funded by the Commission of the European Community (Contract No. HPRN-CT-1999-00132). This network is co-ordinated by Alexey Kavokin, professor of Solid State Physics at the University Blaise Pascal in Clermont-Ferrand (UBP-CF), France.

### **IDEA OF PLMCN MEETINGS**

Alexey Kavokin and Bernard Gil (1999)

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All relevant information are available now at:  
<http://www.lasmea.univ-bpclermont.fr/RTN-CLERMONT/PLMCN2.html>

# CONFERENCE PROGRAM

	Sunday 26	Monday 27	Tuesday 28	Wednesday 29
9h00		F. H. Pollak (invited)	R. P. Seysian (invited)	R. D. Dupuis (invited)
		K. Onabe (invited)	J. Gleize (invited)	L. Hirsh (invited)
	<b>OPENING : A. KAVOKIN AND B. GIL</b>		A. Vinattieri	
10h00	E. L. Portnoi (invited)	H. Amano (invited)	D. Byrne	M. Heuken (invited)
	M. Stutzmann (invited)	<i>Coffee break</i>	<i>Coffee break</i>	<i>Coffee break</i>
		T. D. Moustakas (invited)		
11h00	A. S. Plaut (invited)		P. Lagoudakis	B. Monemar
	<i>Coffee break</i>	M. A. Renucci (invited)	A. Kavokin	A. Hoffmann
	E. Cohen (invited)		R. Butté	<b>CLOSING SESSION</b>
12h00	A. A. Toropov (invited)	<b>EXCURSION : "THE PIRATE BOAT" AND PIC-NIC</b>	G. Malpuech	<b>LUNCH AND EXCURSION TO HERAKLION</b>
			M. D. Martin	
	T. V. Shubina		M. Litinskaia	
	<b>LUNCH</b>		<b>LUNCH</b>	
14h30	A. Zunger (invited)		P. Girard (invited)	
15h00	P. Bigenwald (invited)		P. Perlin (invited)	
	M.E. Portnoi		K. P. O'Donnell	
	K. V. Kavokin		U. Tisch	
16h00	N. Akopian		F. Bechstedt (invited)	
	<i>Coffee break</i>		<i>Coffee break</i>	
17h00	<b>POSTER SESSION</b>		K. Hiramatsu (invited)	
			F. A. Ponce (invited)	
18h00			M. A. Kaliteevski	
	<b>CRETE STYLE DINNER</b>	<b>BARBECUE ON THE BEACH</b>	<b>DINNER</b>	<b>BANQUET DINNER</b>

# DETAILED PROGRAM

Sunday, May 26, 2002 :

- 9h40                    **OPENING : A. KAVOKIN, B. GIL**
- 10h00                   **The past and the future of heterostructure lasers**  
E. L. PORTNOI (invited)
- 10h30                   **Optical Properties of Point Defects in GaN and AlGaN**  
M. STUTZMANN (invited)
- 11h00                   **Magneto-Photoluminescence of the Correlated Few-Electron Ground State of Electrostatically Confined Quantum Dots**  
Y.H.ZHANG, A.S.PLAUT, W.G.STALLARD, J.WEIS, J.P.HARBISON,  
L.T.FLOREZ, M.C.HOLLAND AND C.R.STANLEY
- 11h20                   *Coffee Break*
- 11h40                   **Scattering of excitons and polaritons by a two dimensional electron gas in GaAs/AlGaAs quantum structures**  
A. QARRY, G. RAMON, R. RAPAPORT, E. COHEN (invited), A. MANN, ARZARON AND L. N. PFEIFFER
- 12h10                   **Optical anisotropy of non-common-atom quantum wells and dots: effects of interface symmetry reduction**  
A.A. TOROPOV (invited)
- 12h40                   **Optical Properties of GaN/AlGaN Quantum Wells with Inversion Domains**  
T.V. SHUBINA, V.N. JMERIK, M.G. TKACHMAN, V.A. VEKSHIN, A.A. TOROPOV, S.V. IVANOV, J.P. BERGMAN, P. HOLTZ, B. MONEMAR
- 13h00 - 14h30         **LUNCH**
- \*\*\*\*\*
- 14h30                   **Quantum Dots : Excitons, biexcitons and Charged Excitons**  
A. ZUNGER (invited)
- 15h00                   **Excitons and trions confined in quantum systems : from low to high injection regimes**  
P. BIGENWALD (invited), A. KAVOKIN AND B. GIL
- 15h30                   **Two-dimensional exciton: Unexpected beauty**  
M.E. PORTNOI AND D.G.W. PARFITT
- 15h50                   **Fine structure of the quantum-dot trion**  
K.V.KAVOKIN

- 16h10            **Observation of the Fermi Edge Singularity in the Photoluminescence Spectra of  $\text{Al}_x\text{Ga}_{1-x}\text{N}/\text{GaN}$  Single Heterostructures**  
N. AKOPIAN, L. LANGOF, E. LIFSHITZ, D. GERSHONI, C. POBLENTZ, C. R. ELSASS, I. P. SMORCHKOVA AND J. S. SPECK
- 16h30            *Coffee Break*
- 17h00            **POSTER SESSION**
- P-1                **Determination of  $\text{Al}_x\text{Ga}_{1-x}\text{N}$  refractive indexes at low and room temperature, in the 300 – 600 nm range for the optimisation of GaN-based microcavities.**  
N. ANTOINE-VINCENT, F. NATALI, M. MIHAILOVIC, P. DISSEIX, A. VASSON, J. LEYMARIE, F. SEMOND AND J. MASSIES.
- P-2                **Structural and electrical characterization of Schottky barriers on GaN**  
ANNALISA BONFIGLIO, ELISABETTA MACIS, GIOVANNA MURA
- P-3                **Homoepitaxial regrowth on free-standing HVPE-GaN quasi-substrates**  
V. DARAKCHIEVA, T. PASKOVA, P.P. PASKOV, AND B. MONEMAR
- P-4                **A Model for Tera-Hertz Radiation from Semiconductor Heterostructures**  
R. M. GUTIÉRREZ AND A. S. CAMACHO
- P-5                **Exciton Relaxation in Bulk Wurtzite GaN: the Role of Piezoelectric Interaction**  
G. KOKOLAKIS, F. COMPAGNONE, A. DI CARLO, P. LUGLI
- P-6                **Well width dependence of photoluminescence properties of single InGaN/GaN quantum wells**  
S.M. OLAIZOLA, W. FAN, P.J. PARBROOK, A.M. FOX, R. BUTTÉ, AND M.S. SKOLNICK
- 20h00            **CRETE STYLE DINNER**

\*\*\*\*\*

Monday, May 26, 2002 :

- 9h00              **Modulation Spectroscopy and Surface Photovoltage Spectroscopy Investigations GaN: Bulk, Thin Films, and Microstructures**  
F. H. POLLAK (invited)
- 9h30              **Luminescence Properties of III-V-N Type Alloys**  
K. ONABE (invited)
- 10h00            **Group III Nitride-Based UV Light Emitting Devices**  
H. AMANO (invited), S. TAKANAMI, M. IWAYA, S. KAMIYAMA AND I. AKASAKI
- 10h30            *Coffee Break*

- 10h50            **Study of Band Tails in GaN Using Various Optical Probes**  
T. D. MOUSTAKAS (invited)
- 11h20            **Anisotropy and strain effects on lattice dynamics in nitride-based quantum wells and superlattices**  
 J. GLEIZE, J. FRANDON AND M.A. RENUCCI (invited)
- 12h10            **EXCURSION : "THE PIRATE BOAT", PIC-NIC**
- 20h00            **BARBECUE ON THE BEACH**

\*\*\*\*\*

Tuesday, May 27, 2002 :

- 9h00            **Modeling of Low-Dimensional State of Matter by Excitons in Strong Magnetic Fields**  
R.P.SEISYAN (invited)
- 9h30            **Microscopic investigation of In concentration fluctuation in an InGaN/GaN quantum well**  
J. GLEIZE, A. DI CARLO, P. LUGLI<sup>1</sup>, J.-M. JANCU, O. AMBACHER AND M. HERMANN
- 9h50            **Exciton dynamics in InGaAsN/GaAs heterostructures**  
A.VINATTIERI, D.ALDERIGHI , M.COLOCCI , A. POLIMENI , M. CAPIZZI , M. Fischer AND A. FORCHEL
- 10h10           **Molecular beam epitaxy growth of group III-nitrides microcavities : optical and structural properties**  
 F. NATALI, N. ANTOINE-VINCENT, D. BYRNE, F. SEMOND, M. LEROUX, N. GRANDJEAN, J. MASSIES AND J. LEYMARIE.
- 10h30           *Coffee Break*
- 11h00           **Stimulated Spin Scattering in Semiconductor Microcavities**  
 P. LAGOUDAKIS, P. G. SAVVIDIS, D.M. WHITTAKER, J. J. BAUMBERG, R. M. STEVENSON, M. S. SKOLNICK AND J. S. ROBERTS
- 11h20           **Polarisation rotation in resonant emission of semiconductor microcavities**  
A. KAVOKIN, G. MALPUECH, J. J. BAUMBERG, P. LAGOUDAKIS, K. KAVOKIN
- 11h40           **The Transition from Strong to Weak Coupling and the Polariton Laser in Semiconductor Microcavities**  
R. BUTTÉ, G. DELALLEAU, A.I. TARTAKOVSKII, M.S. SKOLNICK, V.N. ASTRATOV, J.J. BAUMBERG, G. MALPUECH, A. DI CARLO, A. V. KAVOKIN, J.S. ROBERTS
- 12h00           **Polariton Bose condensation in microcavities, thermodynamic and kinetic aspects.**  
G. MALPUECH, A. KAVOKIN , F. P. LAUSSY , A. DI CARLO AND J. J. BAUMBERG

- 12h20            **Electron-polariton scattering in Semiconductor Microcavities**  
P. G. LAGOUDAKIS, M. D. MARTIN, G. MALPUECH, J. J. BAUMBERG, E. COHEN,  
L.N. PFEIFFER, R. ANDRE
- 12h40            **Elastic Scattering Of Microcavity Polaritons**  
M. LITINSKAIA, G.C. LA ROCCA, V.M. AGRANOVICH
- 13h00            **LUNCH**
- \*\*\*\*\*
- 14h30            **Atomic Force Microscopy and Electrostatic Force Microscopy  
observations on Gallium Nitride**  
PAUL GIRARD (invited)
- 15h00            **High-pressure studies of internal electric fields in nitride quantum  
structures**  
P. PERLIN (invited)
- 15h30            **Wishful physics: some common misconceptions about InGaN**  
K.P.O'DONNELL, R.W. MARTIN, P.R. EDWARDS, S. PEREIRA AND M.E. WHITE
- 15h50            **The Anomalous Band Bowing in GaAsN**  
U. TISCH, E. FINKMAN, AND J. SALZMAN
- 16h10            **Energy Gap and Optical Properties of  $\text{In}_x\text{Ga}_{1-x}\text{N}$**   
F. BECHSTEDT (invited)
- 16h40            ***Coffee Break***
- 17h10            **GaN-based Schottky Barrier Photodetectors from near Ultraviolet to  
Vacuum Ultraviolet (360 - 50nm)**  
K. HIRAMATSU AND A. MOTOGAITO
- 17h40            **Microstructure and the Optical Properties of  $\text{In}_x\text{Ga}_{1-x}\text{N}$  and  $\text{Al}_x\text{Ga}_{1-x}\text{N}$  Alloys**  
F. A. PONCE (invited)
- 18h10            **Disorder-induced modification of the transmission of light in two  
dimensional photonic crystal**  
M. A. KALITEEVSKI, J. MANZANARES MARTINEZ, D. CASSAGNE, J.P. ALBERT
- 20h00            **DINNER**

\*\*\*\*\*

Wednesday, May 28, 2002 :

- 9h00            **High-Performance AlGaIn/GaN Solar-Blind Detectors Grown by  
Metalorganic Chemical Vapor Deposition**  
R. D. DUPUIS (invited); U. CHOWDHURY; C. J. COLLINS, M. M. WONG; B.  
YANG, J. C. DENYSZYN; AND J. C. CAMPBELL

9h30

L. HIRSH (invited)

10h00

**GaN-based electronics and opto-electronics in production scale MOCVD systems**

M. HEUKEN

10h30

*Coffee Break*

11h00

**Photoluminescence of n-doped InGaN/GaN and AlGaIn/GaN Multiple Quantum Well structures, role of depletion fields and polarization fields**

B. MONEMAR, P P PASKOV, G POZINA, J P BERGMAN, S KAMIYAMA, M IWAYA, H AMANO AND I AKASAKI

11h20

A. HOFFMANN

11h50

**CLOSING SESSION**

\*\*\*\*\*

12h00

**LUNCH AND EXCURSION TO HERAKLION**

20h30

**BANQUET DINNER**

\*\*\*\*\*

9h40            **OPENING : A. KAVOKIN, B. GIL**

S-1 10h00    Invited **The past and the future of heterostructure lasers**  
E. L. PORTNOÏ

S-2 10h30    Invited **Optical Properties of Point Defects in GaN and AlGaN**  
M. STUTZMANN

*Walter Schottky Institut, Technische Universität München, Am Coulombwall  
3, 85748 Garching, Germany*

Whereas optical properties of semiconductors for photon energies close to the fundamental band gap are determined by the overall band structure and excitonic processes, optical transitions below the fundamental gap are related to structural defects and impurities with energy levels in the forbidden gap. A detailed microscopic understanding of such defect-related transitions and the identification of the underlying defects or impurities is not only of general interest for the material under investigation, but also very important for the optimization of electronic and optoelectronic devices. In this presentation, I will try to give a flavour of the interesting and complicated physics of point defects in GaN and AlGaN-alloys using three examples: (i) Mg-related optical transitions in GaN, (ii) the DX-behaviour of Si donors in AlGaN-alloys with a high Al content, and (iii) the energy level scheme of Mn impurities in GaN and AlN.

Mg is the technologically most important acceptor in GaN. Because of the large acceptor ionization energy of about 200 meV, high concentrations of Mg are required in order to obtain a sufficient p-type conductivity e.g. in GaN LEDs. Doping with such high Mg concentrations generally gives rise to considerable changes in the luminescence spectra of GaN, leading to new broad defect-related luminescence bands in the blue, yellow, and red spectral region.

Si is the standard shallow donor in GaN and AlGaN-alloys with low Al concentrations. With increasing Al content, however, the ionization energy of the Si donor increases beyond the expected effective mass value. Eventually, Si becomes a deep donor with a thermal activation energy of 300 meV in AlN. This transition from a shallow to a deep donor is accompanied by the appearance of a pronounced optoelectronic metastability at lower temperatures (< 100 K, DX-behaviour), which is characterized by very complex interplay between optical and thermal transitions.

Quite recently, Mn-doping of GaN has been discussed as a possible route to obtain ferromagnetism in a semiconductor at room temperature, which would be an important achievement towards future "spintronic" devices. Yet, very little is known about the energy levels of the various Mn charge states in the band gap of GaN and AlN.

It will be shown that in all three examples, the coupling of light to the localized states of the different shallow defects or deep impurities helps to illuminate the structural characteristics of the underlying defects and their importance for the optoelectronic properties of the doped crystal.

S-3 11h00    **Magneto-Photoluminescence of the Correlated Few-Electron Ground State of Electrostatically Confined Quantum Dots**

Y.H.ZHANG,<sup>1</sup> A.S.PLAUT,<sup>1</sup> W.G.STALLARD,<sup>1</sup> J.WEIS,<sup>2</sup> J.P.HARBISON,<sup>3</sup>  
L.T.FLOREZ,<sup>3</sup> M.C.HOLLAND,<sup>4</sup> AND C.R.STANLEY<sup>4</sup>

<sup>1</sup> *School of Physics, University of Exeter, Exeter EX4 4QL, UK*

<sup>2</sup> *Max-Planck-Institut für Festkörperforschung, D-70569 Stuttgart, Germany*

<sup>3</sup> *Bellcore, Red Bank, NJ 07701-7040, USA*

<sup>4</sup> *Nanoelectronics Research Centre, Dept. of Electronics and Electrical Engineering, University of Glasgow, Glasgow G12 8QQ, UK*

The ground state of a small number of correlated electrons confined in a quantum dot is expected to undergo magnetically-induced spin and angular momentum transitions [1]. Exact diagonalisation calculations predict a rich phase diagram, but to date, direct measurements of the ground state of such zero-dimensional electron systems by photoluminescence (PL) have not observed these electron-electron interaction induced phase transitions. Since PL probes the entire density of states below the Fermi energy, the magnetic field dependence of the PL is directly related to the total ground state energy of the interacting electrons [1].

Using magneto-PL we have now observed behaviour characteristic of a single-triplet transition in the ground state of quantum dots containing a small number of electrons. The quantum dot arrays are defined by a laterally-structured gate electrode evaporated onto a GaAs-Al<sub>x</sub>Ga<sub>1-x</sub>As n-type heterojunction with a delta-layer of Beryllium in the GaAs to enhance the PL intensity. On application of a bias voltage to the gate, our transport measurements show the two-dimensional electron gas surrounding the quantum dots depleting until eventually conduction in the plane of the dots is completely cut off and the dots become isolated from each other.

We have studied a number of samples with various numbers of electrons per dot. In a sample with around four electrons per dot we observe two PL lines at zero magnetic field, corresponding to the two lowest zero-dimensional subbands. In magnetic field, the higher energy level has a clear negative magnetic field dispersion and eventually these two lowest subbands are observed to anticross. Immediately after, the higher energy level then depletes. This we interpret as the singlet-triplet transition predicted by theory [2]. In a sample with fewer electrons per dot we only observe the ground state energy level of the dot. The photon energy of this level is seen to undergo a discontinuous jump at a particular magnetic field, which is correlated to the number of electrons per dot. Such discrete jumps in the energy of the ground state of the dot are predicted by theory [1] to indicate a singlet to triplet change in the ground state of the correlated electrons within the quantum dot.

These measurements thus constitute not only the first successful magneto-PL measurements from gated quantum dots but also the first successful mapping of the ground state singlet-triplet transition by PL; the size and sign of which can be used as a measure of the electron-electron and final-state interactions within the quantum dot [1].

[1] P. HAWRYLAK AND D. PFANNKUCHE, *Phys. Rev. Lett.* **70**, 485 (1993).

[2] D. PFANNKUCHE, V. GUDMUNDSSON AND P.A. MAKSYM, *Phys. Rev. B* **47**, 2244 (1993).

11h20

*Coffee Break*

S-4

11h40 Invited **Scattering of excitons and polaritons by a two dimensional electron gas in GaAs/AlGaAs quantum structures**

A. QARRY<sup>(a)</sup>, G. RAMON<sup>(b)</sup>, R. RAPAPORT<sup>(c)</sup>, E. COHEN<sup>(a)</sup>, A. MANN<sup>(b)</sup>, ARZARON<sup>(b)</sup> AND L. N. PFEIFFER<sup>(c)</sup>

<sup>(a)</sup> *Solid State Institute, Technion-Israel Institute of Technology, Haifa 32000, Israel*

<sup>(b)</sup> *Department of Physics, Technion-Israel Institute of Technology, Haifa 32000, Israel*

<sup>(c)</sup> *Bell Laboratories, Lucent Technologies, Murray Hill, New Jersey 07974*

We report on a study of the free electron scattering effects on the reflection and photoluminescence (PL) spectra of excitons in bare GaAs/AlAs quantum wells (QW), and of polaritons in a GaAs/AlGaAs microcavity (MC) with an embedded GaAs/AlAs QW. In both systems, a two dimensional electron gas (2DEG) is photogenerated in the QW, and its density is varied in the

(estimated) range of  $10^9 < n_e < 5 \times 10^{10} \text{ cm}^{-2}$ . At low temperatures, and when a 2DEG is present, the polaritons under study are formed by the coupling of the  $X=(e1:hh1)1S$ ,  $X^*=(e1:hh1)1S+e$  and  $X_{hh}=(e1:lh1)1S$  excitons with the confined MC photon [1].

The experimental study consists of measuring the polariton spectra, and from them the energy, intensity and linewidth of all polariton branches, as a function of  $n_e$ , temperature and detuning energy (defined as  $\delta=E_c - E_x$ , where  $E_c$  and  $E_x$  are the confined MC photon and the X exciton energies, respectively). For comparison, the X and X\* PL spectra of bare QW's as a function of  $n_e$  and T are studied. It is observed that throughout the temperature range  $2 < T < 80\text{K}$ , electron-polariton scattering increases the polariton linewidth much more efficiently than acoustic phonon-polariton and polariton-polariton scattering processes do. Non-linear variations in the PL intensity are observed with increasing  $n_e$ , and these variations also depend strongly on  $\delta$  and on T. Since these three parameters determine the charged exciton admixture in the polariton wave function, the experiments indicate that the X\* part in each one of the polariton branches determines their electron scattering rates.

The analysis of the linewidth and the relative intensity of all polariton branches is done by a theoretical model [2] consisting of the following stages: First, the electron - bare exciton direct and exchange interaction matrix elements are calculated for X, X\* and  $X_{hh}$ , in both elastic and inelastic scattering processes. These are then used to calculate the electron scattering rates, as a function of the initial wavevector and energy of the bare excitons. Secondly, the bare exciton lineshape is calculated by convolving its distribution function without a 2DEG, with the energy dependent Lorentzian distribution that results from the electron-exciton scattering processes. Finally, the reflection and PL spectra are calculated by inserting the calculated X, X\* and  $X_{hh}$  lineshapes into the semiclassical linear dispersion model of the QW excitons interacting with the confined MC photon. The PL spectra are calculated as a function of the polariton excitation energy. The results of fitting the theoretical calculations to the experimental spectra will be discussed.

[1] R. RAPAPORT ET AL, *Phys. Rev.* **B63**, 235310 (2001)

[2] G. RAMON ET AL, *Phys. Rev.* **B65**, 085323 (2002)

S-5 12h10 Invited **Optical anisotropy of non-common-atom quantum wells and dots: effects of interface symmetry reduction**

A.A. TOROPOV

*Ioffe Physico-Technical Institute of RAS, St. Petersburg 194021, Russia*

There is increasing interest in the in-plane optical anisotropy induced by breakdown of rotational symmetry at semiconductor interfaces [1]. The point group symmetry  $T_d$  of the zinc-blende lattice is reduced by the presence of an abrupt interface to the much lower  $C_{2v}$  symmetry, which breaks the equivalence of the [110] and [-110] in-plane directions. A quantum well (QW) structure either retains the low  $C_{2v}$  symmetry of a single interface or has the higher  $D_{2d}$  symmetry preserving the in-plane isotropy. The former situation occurs frequently when the well and barrier materials do not share common atoms, which results in specific chemical bonds at the interfaces, or under application of an external electric field. From the theoretical point of view, the anisotropy can be described either in the generalized boundary condition theory [2,3] including in the boundary conditions for hole envelope functions a term mixing heavy- and light holes at normal incidence at the interface, or using the tight-binding approximation [4].

For conventional QWs, the optical anisotropy induced by the interface symmetry reduction, is relatively weak. However, there are two specific cases when the effect can reach almost 100%. First, a dramatic enhancement of the in-plane optical anisotropy (up to ~70%) can take place due to a strong coupling

between excitonic states, e.g. between first light-hole and second heavy-hole levels in a QW, which can be tuned into a resonance by an external electric field [3]. The other case is a type II QW with large band offsets for both electrons and holes, which narrows drastically a region of the electron and hole wave functions overlap in the very vicinity of the type II interface. Hence, the in-plane linear polarization of the interface photoluminescence (PL) directly reflects the dominant orientation of the interface chemical bonds and can reach ~90%, as demonstrated recently for ZnSe/BeTe QWs.

All the results mentioned above concern perfect QWs with ideal abrupt interfaces. Realistic interfaces always contain local defects, like terraces and islands, resulting in the fluctuations of the QW width and chemical composition. The symmetry of the electronic states localized there can differ from the symmetry of ideal QWs, affecting thus the degree of the PL in-plane linear polarization. To address this issue, we have applied the spectroscopy of linearly-polarized PL to the comparative studies of the symmetry properties in ZnSe/BeTe and CdSe/BeTe non-common-atom type II heterostructures grown by molecular beam epitaxy. The former system combines practically lattice-matched compounds and allows the formation of QWs with atomically flat interfaces. The latter one brings together two semiconductors with dramatic lattice-mismatching (~8%), which results in the formation of either rough QWs or self-organized quantum dots (QDs), depending on the growth conditions. Surprisingly, the PL observed in the CdSe/BeTe samples is strongly in-plane linearly polarized (up to 70-80%), approaching thus the maximum PL polarization observed in near-ideal ZnSe/BeTe QWs. This huge in-plane optical anisotropy implies a QW-like flat symmetry as most relevant to each individual localization site, in spite of the 0D nature of the localized electrons.

[1] O. KREBS AND P. VOISIN, *Phys. Rev. Lett.* **77**, 1829 (1996).

[2] E.L. IVCHENKO, A. KAMINSKI, AND U. RÖSSLER, *Phys. Rev. B* **54**, 5852 (1996).

[3] A.A. TOROPOV, E.L. IVCHENKO, O. KREBS, S. CORTEZ, P. VOISIN, J.L. GENTNER, *Phys. Rev. B* **63**, 035302 (2000).

[4] A.V. PLATONOV, V.P. KOCHERESHKO, E.L. IVCHENKO, G.V. MIKHAILOV, D.R. YAKOVLEV, M. KEIM, W. OSSAU, A. WAAG, AND G. LANDWEHR, *Phys. Rev. Lett.* **83**, 3546 (1999).

S-6 12h40

### **Optical Properties of GaN/AlGa<sub>N</sub> Quantum Wells with Inversion Domains**

T.V. SHUBINA (a), V.N. JMERIK (a), M.G. TKACHMAN (a), V.A. VEKSHIN (a), A.A. TOROPOV (a), S.V. IVANOV (a), J.P. BERGMAN (b), P. HOLTZ (b), B. MONEMAR (b)

(a) *Ioffe Physico-Technical Institute, Polyteknicheskaya 26, St.Petersburg 194021, Russia*

(b) *Department of Physics and Measurement Technology, Linköping University, S-581 83 Linköping, Sweden*

*Corresponding author : Phone: +7 812 247 91 24, Fax: +7 812 247 10 17, e-mail : shubina@beam.ioffe.rssi.ru*

Recently it has been recognized that built-in electric fields induced by spontaneous polarization (SP) and piezoelectric (PE) effects in III-nitride-based quantum wells (QWs) result in a strong intensity decrease and red shift of photoluminescence (PL) due to the quantum-confined Stark effect. Most of optical investigations of the phenomenon consider the QW structures as being macroscopically homogeneous, although real samples contain a lot of inversion domains (IDs) of 5-30 nm in diameter, where the polarity and sign of the resultant built-in field is reversed with respect to the rest of the surface. The identity of SP and PE components in the IDs and surrounding area has not been proved up to now. In the paper we focus on manifestation of the IDs in optics of GaN/AlGa<sub>N</sub> QWs. We study GaN/AlGa<sub>N</sub> QW structures with dominant

N-face polarity grown by rf plasma-assisted MBE on (0001) sapphire, without any GaN buffer, that permitted us to measure absorption spectra additionally to reflection, cw and time-resolved PL. Certain gradient of flux ratio and substrate temperature provides variation of morphology and strain from a center of the substrate to a periphery. TEM images reveal plain and perfect QWs at the periphery of a GaN/AlGa<sub>N</sub> (8nm/13nm) MQW sample, while there are a lot of the IDs in the central region. As determined by XRD the center and periphery regions undergo the compressive strain of different values (1.3 and 2.8 GPa, respectively). In spite of the perfect morphology, a PL signal is negligible in the periphery region, whereas in the center the PL is rather bright. Wherever the PL exists, it contains two bands – lower-energy (strong in the center) and higher-energy (dominating at the periphery), separated by ~70-100 meV depending on excitation power density. Both bands decrease in intensity from the center to periphery and survive nearby room temperature. They possess nonexponential decay with different characteristic decay times - 200 ps and 2.2 ns for the higher- and lower-energy bands, respectively. Similar complimented high-energy features are observed in optical spectra of the 3-QWs sample for each QW of different width (2.5, 5 and 8 nm). Absorption spectra measured in the IDs-enriched region of the MQW sample contain a shoulder which is consistent with the lower-energy PL. Micro-PL measurements performed from a facet in points with a varying ID density reveal fluctuations of polarized PL intensities. Since the domains can occupy a significant part of a total area, we assign the bands with the respective absorption edges to transitions taking place inside the IDs and surrounding area.

The difference in energy of emission between the regions with the N- and Ga-polarities is regarded as a result of nanometric-scale fluctuations of strain and built-in electric fields. Possible non-equivalence of interfaces (roughness) in the IDs and around them is taken into account. A role of IDs boundaries - regions, where the fluctuating electric field may be equal zero, is discussed as well.

13h00 - 14h30 LUNCH

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S-7 14h30 Invited **Quantum Dots : Excitons, biexcitons and Charged Excitons**

A. ZUNGER

*National Renewable Energy Laboratory, Golden, Colorado 80401*  
[azunger@nrel.gov](mailto:azunger@nrel.gov)

Single-dot spectroscopy and STM-injection experiments make it now possible to resolve the electronic structure of multi-excitons and charged excitons both in colloidal dots and in self-assembled dots. This talk will focus on our theoretical understanding of these spectra. We find that the traditional continuum (effective-mass-based) approaches miss much of the story here. Instead, we use an atomistic description of the Single-Particle states ("levels"), via the pseudopotential approach, whereas the many-body part is treated with Configuration-Interaction, based on the pseudopotential wavefunctions. I will describe the following effects:

- (a) The quantum-size dependence of the exciton energies in Si, InP, CdSe
- (b) The fine-structure of the mono-exciton (e-h exchange effects), and the emergence of a long-range piece in the exchange.
- (c) The way dot charging shifts exciton energies—both blue and red shifts.
- (d) Bi and multi excitons in InAs/GaAs: the role of correlation
- (e) Charging energies in colloidal dots, violations of Hund's rule and the Aufbau principle.

S-8 15h00 Invited **Excitons and trions confined in quantum systems : from low to high injection regimes**

P. BIGENWALD<sup>(a)</sup>, A. KAVOKIN<sup>(a)</sup> AND B. GIL<sup>(b)</sup>

<sup>(a)</sup> *LASMEA- UMR 6602 CNRS UBP, 24, avenue des Landais, F-63177*  
*AUBIERE CEDEX*

<sup>(b)</sup> *GES – UMR 3407 CNRS Université Montpellier II, CC 077, Place Eugène*  
*Bataillon, F-34095 MONTPELLIER CEDEX 05*  
[pierre.bigenwald@lasmea.univ-bpclermont.fr](mailto:pierre.bigenwald@lasmea.univ-bpclermont.fr)

The achievement of the polariton laser proposed by G. Malpuech et al [1] necessitates the presence of a coolant to bring excited polaritons to their thermodynamic stable states and transfer energy to phonons. This may be achieved via a 2D electron gas (2D EG) present in the structure and a theoretical model based on the resolution of the Boltzmann equations has permitted to propose a critical temperature for the observation of this Bose condensation of excitons-polaritons in a GaAs microcavity [2].

The density of the electron gas is a critical parameter for the phenomenon: if too low, the coolant is inefficient but, if too large, excitons are screened. Injecting a moderate to large density of free carriers also leads to a renormalization of the band to band properties in polarized quantum structures. It also influences strongly the properties of excitons generated in the structure as we previously studied [3].

Moreover, the coexistence of excitons with free electrons leads to the appearance of the charged exciton complex, the X<sup>-</sup> trion. This charged quasiparticle has its own particular properties that will differ dramatically from the exciton ones for moderate to large densities of free electrons in the quantum structure.

Our study is made on AlGaIn-GaN single quantum wells and the chosen approach permits us to describe the effects of the band filling and screening of the dielectric constant for different densities of carriers generated by a doping layer far from the structure.

Our model also provides us with the ability to determine the spin-flip exchange energy separating the singlet from the triplet states of such a trion as a function of the 2D EG density in the well.

[1] G. MALPUECH, A. KAVOKIN, A. DI CARLO ET J.J. BAUMBERG, "Polariton

*Lasing by Exciton-Electron Scattering in Semiconductor Microcavities*", à paraître dans *Phys. Rev. B* (15/04/2002).

[2] G. MALPUECH, A. DI CARLO, A. KAVOKIN, J.J. BAUMBERG, M. ZAMFIRESCU, P. LUGLI, to be published in *Appl. Phys. Lett.*

[3] P. BIGENWALD, A. KAVOKIN, B. GILET P. LEFEBVRE, *Phys. Rev. B* **63**, 035315 (2001)

S-9 15h30

**Two-dimensional exciton: Unexpected beauty**

M.E. PORTNOI AND D.G.W. PARFITT

*School of Physics, University of Exeter, Stocker Road, Exeter EX4 4QL, UK*

*m.e.portnoi@ex.ac.uk*

Non-linear optical properties of semiconductor heterostructures are often governed by excitons and their screening. This is especially important for wide-bandgap semiconductors, where the excitonic binding energy is comparable to room temperature. A recent attempt by Portnoi and Galbraith [1] to build a consistent, tractable theory of a two-dimensional (2D) electron-hole plasma containing screened excitons has led to an unexpected result. Their numerical calculations show that new bound states of a statically screened Coulomb

potential,  $V_s(q) = -2\pi/(q+q_s)$ , appear simultaneously for different values of angular momentum at integer values of the inverse screening wavenumber

$1/q_s$ . The most compact way to formulate this numerical observation is in terms of a homogeneous integral equation:

$$q^2\Psi_q = \frac{\lambda}{\pi} \int \frac{\Psi_{q'}}{|\mathbf{q}-\mathbf{q}'|+1} d^2q' \quad (1)$$

where  $\lambda=1/q_s$  is an eigenvalue. It follows from [1] that  $\Psi_q$  is square

integrable when  $\lambda=(2|m|+n)(2|m|+n+1)/2$ , where  $n=0,1,2,\dots$ , and  $m$  is the internal angular momentum of the exciton. It should be emphasised that this result is of a numerical nature and has not been proven analytically. In an attempt to find such a proof we addressed the problem of an unscreened 2D exciton, which has a well-known solution in real space. Considering this problem in Fourier space reveals a hidden symmetry underlying the well-known degeneracy of the 2D Kepler problem, and may shed some light on the apparent degeneracy of the weakly-bound states in the screened case.

The integral form of the Schrödinger equation for the unscreened problem is given by:

$$(q^2 + q_0^2)\Phi_q = \frac{1}{\pi} \int \frac{\Phi_{q'}}{|\mathbf{q}-\mathbf{q}'|} d^2q', \quad (2)$$

where  $q_0$  is related to the energy eigenvalue via  $q_0^2 = -E$ . Notably, Eq. (2) seems to have the same level of difficulty as Eq. (1). The unscreened problem can be solved by projecting the 2D momentum space onto the surface of a three-dimensional unit sphere. The eigenfunctions are then expanded in terms of

spherical harmonics, and the independence of energy eigenvalues on  $m$  becomes apparent. Transforming the solutions of Eq. (2) into real space and comparing them with the standard real space solutions leads to a previously untabulated integral relation in terms of special functions:

$$\int_0^{\infty} P_n^m \left( \frac{1-y}{1+y} \right) \frac{J_m(x\sqrt{y})}{(1+y)^{3/2}} dy = \frac{(-1)^n (2x)^m e^{-x}}{n+1/2} L_{n-m}^{2m}(2x),$$

$$n, m = 0, 1, 2, \dots; m \leq n, \quad (3)$$

where  $P_n^m(z)$  is an associated Legendre function,  $J_m(z)$  is a Bessel function, and  $L_n^m(z)$  is an associated Laguerre polynomial.

The dynamical symmetry of the unscreened problem is also considered, and it is shown that the two components of the Runge-Lenz vector in real space correspond to the generators of rotations about the respective coordinate axes in momentum space.

[1] M.E. PORTNOI AND I. GALBRAITH, *Phys. Rev. B* **60**, 5570 (1999).

S-10 15h50

### Fine structure of the quantum-dot trion

K. V. KAVOKIN

*School of Physics, University of Exeter, Stocker Road EX4 4QL, Exeter, UK*

Charged excitons, or trions, in quantum dots (QDs) attract a growing interest as principal radiative states of charged QDs. Optical experiments, especially single-dot spectroscopy and time- and polarisation-resolved photoluminescence spectroscopies, reveal a complex structure of levels in excited trion states (the trion ground state is a simple Kramers doublet). Here, I present a theory of the fine structure of the excited state of the QD trion, which is due to spin-spin interactions. In particular, it is shown that the fine structure is universal for both positive (two holes, one electron) and negative (two electrons, one hole) trions. It consists of four doublets, three of them forming a compact group of levels separated from the remaining doublet by the energy of the exchange interaction between identical particles (i.e. between two electrons or two holes). The energy separation between the adjacent doublets in the six-level group is of the order of the much smaller energy of the exchange interaction between particles belonging to different bands, i.e. of the exciton exchange energy. As distinct from the exciton, anisotropy of the exchange interaction does not lift the degeneracy of trion spin doublets; this fact finds its general explanation in the Kramers theorem, since the trion has a half-integer spin. However, the anisotropy does lead to mixture of states belonging to adjacent doublets. This allows, for instance, phonon-assisted spin-flip transitions into the trion ground state, which is important for energy and spin relaxation in charged QDs. Coherent excitation of states with different energy within the fine-structure octet by pulses of polarised light results in quantum beats in the photoluminescence polarisation [1].

[1] I.E.KOZIN, I.V.IGNATIEV, V.G.DAVYDOV, HONG-WEN REN, M.SUGISAKI, K.V.KAVOKIN, A.V.KAVOKIN, G.MALPUECH, "Zero-field spin quantum beats in charged quantum dots", to be published

S-11 16h10 Invited **Observation of the Fermi Edge Singularity in the Photoluminescence Spectra of  $\text{Al}_x\text{Ga}_{1-x}\text{N}/\text{GaN}$  Single Heterostructures**

N. AKOPIAN<sup>(a)</sup>, L. LANGOF<sup>(a)</sup>, E. LIFSHITZ<sup>(a)</sup>, D. GERSHONI<sup>(a)</sup>, C. POBLENTZ<sup>(b)</sup>, C. R. ELSASS<sup>(b)</sup>, I. P. SMORCHKOVA<sup>(b)</sup> AND J. S. SPECK<sup>(b)</sup>

<sup>(a)</sup> *Solid State Institute, Technion, Haifa 32000, Israel*

<sup>(b)</sup> *Materials Department, University of California, Santa Barbara, California 93106, USA*

[dg@physics.technion.ac.il](mailto:dg@physics.technion.ac.il)

$\text{AlGaIn}/\text{GaN}$  single heterostructures (SHs), in which high-density two-dimensional electron gas (2DEG) are formed, are considered to be promising systems for high power, high temperature electronic devices<sup>[1]</sup>. Their properties have been, therefore,

very intensively studied using transport techniques. Optical studies, however, are rather scarce<sup>[2]</sup>. In this study we show, for the first time, that the Fermi energy of the 2DEG can be directly obtained from its photoluminescence (PL) spectrum, and that the spectrum itself gives rise to a pronounced and well-resolved signature of a Fermi Edge singularity<sup>[3]</sup>.

The AlGaIn/GaN heterostructure samples were grown by rf-plasma assisted MBE on 1.5-2  $\mu\text{m}$  thick, n-type (0001) GaN templates grown on sapphire by MOCVD. Approximately 500 nm of unintentionally doped MBE-GaN was grown on the template followed by 33 nm of MBE  $\text{Al}_x\text{Ga}_{1-x}\text{N}$  of various compositions ( $0.08 < x < 0.31$ ). Sheet carrier concentrations and electron mobilities in the structures were determined from temperature dependent Hall measurements.

The optical studies included PL, PL excitation (PLE), and time resolved spectroscopy at various temperatures. Typical PL spectra of one of the samples with  $x=0.17$ , room temperature mobility of  $1000 \text{ cm}^2/\text{V}\cdot\text{sec}$  and 2DEG density of  $2.1 \times 10^{13} \text{ cm}^{-2}$  are presented in Fig. 1, for three different temperatures. The spectrum at 1.4K is composed of a sharp emission line from the GaN template at 3.489 eV, accompanied by two optical phonon replica 86 and 181 meV below it. At higher energies a broad emission band with low energy onset at 3.68 eV, spectral width of 210 meV and a pronounced increase towards its high-energy cutoff at 3.89 eV is seen. This line results from the recombination of the SH channel's electrons with photoinduced holes trapped by acceptors in the AlGaIn/GaN interface, due to the strain induced piezoelectric field in this layer. The localization of these holes, relaxes the crystal momentum conserving optical selection rules, and it permits recombination of holes with electrons throughout the Fermi sea. Using electron mass of  $0.18m_e$ , we calculated from the measured 2DEG density Fermi energy of 280 meV, in agreement with the measured 2DEG band linewidth.

The enhanced PL at the Fermi energy (known also as Fermi-edge singularity<sup>[3]</sup>) is due to multiple electron-hole scattering processes to empty states above the Fermi energy. As expected, this enhancement reduces with the increase in the sample temperature, which relaxes the abrupt Fermi energy cutoff<sup>[3]</sup>.

The PLE spectrum of the 2DEG spectral line is also presented in Fig. 1. The PLE spectra clearly demonstrate the sharp reduction of the absorption cross section at the Fermi edge. A Stokes shift of 100 meV between the PL and PLE peak is expected for these temperatures and carrier concentrations<sup>[4]</sup>.

In the inset to Fig. 1 we present PL transients of the GaN and 2DEG lines. The slower decay of the 2DEG PL band is due to the reduced overlap between the wavefunctions of the 3D localized holes and that of the 2D electrons. The decay time of the PL throughout the 2DEG band is almost energy independent. This indicates that the large width of the spectral line is not due to inhomogeneous broadening<sup>[5-6]</sup>.

- [1] O. AKTAS ET AL, *Appl. Phys. Lett.* **69**, 3872 (1996)
- [2] J. P. BERGMAN ET AL, *Appl. Phys. Lett.* **69**, 3456 (1996)
- [3] M. S. SKOLNICK ET AL, *Phys. Rev. Lett.* **58**, 2130 (1987)
- [4] G. LIVESCU ET AL, *IEEE J. QE* **24**, 1677 (1988)
- [5] I. V. KUKUSHKIN, V.B. TIMOFEEV, *Adv. in Phys.* **45**, 147 (1996)
- [6] E. BERKOWICZ, D. GERSHONI ET AL, *Phys. Rev. B* **61**, 10994 (2000)

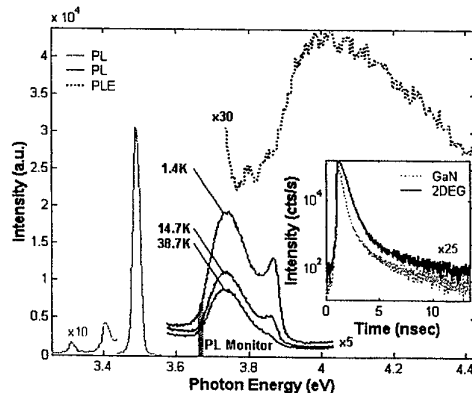


Fig 1 : PL and PLE spectra of the  $x = 0.17$  SH sample. Inset shows PL transients.

17h00

POSTER SESSION

P-1

**Determination of  $\text{Al}_x\text{Ga}_{1-x}\text{N}$  refractive indexes at low and room temperature, in the 300 – 600 nm range for the optimisation of GaN-based microcavities.**

**N. ANTOINE-VINCENT** <sup>1</sup>(<sup>a</sup>), F. NATALI (<sup>b</sup>), M. MIHAILOVIC (<sup>a</sup>), P. DISSEIX (<sup>a</sup>), A. VASSON (<sup>a</sup>), J. LEYMARIE (<sup>a</sup>), F. SEMOND (<sup>b</sup>) AND J. MASSIES (<sup>b</sup>).

<sup>(a)</sup> *LASMEA, Université Blaise Pascal – Clermont-Ferrand II, F-63177 Aubière Cedex, France*

<sup>(b)</sup> *CRHEA – CNRS, rue Bernard Grégory, Sophia-Antipolis, F-06560 Valbonne, France*

<sup>1</sup> *Corresponding author : e-mail : [antoine@lasmea.univ-bpclermont.fr](mailto:antoine@lasmea.univ-bpclermont.fr).*

$\text{Al}_x\text{Ga}_{1-x}\text{N}$  layers ( $x = 0, 0.19, 0.47, 0.675, 0.785, 1$ ) have been grown on (111)Si substrate by molecular beam epitaxy. The Al molar fraction  $x$  is determined both by energy dispersive X-ray spectroscopy and by photoluminescence experiments. The refractive index  $n$  and the extinction coefficient  $K$ , at room temperature, in the 300 – 600 nm range, are extracted from a two-stage procedure based on spectroscopic ellipsometry and reflectivity measurements.

Additional reflectivity experiments are carried out at 5 K in order to extract the corresponding refractive index. The accurate knowledge of the later is essential for the fabrication of optimised GaN-based microcavities. In this purpose, two simulations of microcavities [1,2] with nitride-based distributed Bragg reflectors are presented from the refractive indexes determined in this work at  $T = 5$  K. The first one is constituted by a  $(\lambda/2)$  GaN cavity embedded between two  $\text{Al}_{0.19}\text{Ga}_{0.81}\text{N} / \text{Al}_{0.675}\text{Ga}_{0.325}\text{N}$  distributed Bragg reflectors. In the second one,  $\text{Al}_{0.675}\text{Ga}_{0.325}\text{N}$  alloy is replaced by  $\text{Al}_{0.47}\text{Ga}_{0.53}\text{N}$  in order to reduce the strain effects due to the difference between the lattice parameters.

[1] N. ANTOINE-VINCENT, F. NATALI, F. SEMOND, M. LEROUX, N. GRANDJEAN, J. MASSIES, J. LEYMARIE AND A. VASSON, *Phys. Stat. Sol (a)* **188**, 519 (2001).

[2] N. ANTOINE-VINCENT, F. NATALI, P. DISSEIX, M. MIHAILOVIC, A. VASSON, J. LEYMARIE, F. SEMOND, M. LEROUX AND J. MASSIES, *Phys. Stat. Sol (a)* **190**, 187 (2002).

P-2

**Structural and electrical characterization of Schottky barriers on GaN**

ANNALISA BONFIGLIO\*, ELISABETTA MACIS, GIOVANNA MURA

*INFM – Dept. of Electrical and Electronic Engineering, University of Cagliari, Piazza d'Armi, 09123 Cagliari, Italy*

\* *corresponding author, e-mail address: [annalisa@diee.unica.it](mailto:annalisa@diee.unica.it)*

In this work we have aimed to characterize metal-semiconductor contacts in GaN. The problem is crucial in view of the realization of electronic devices of whatever kind, e.g. fet structures as well as sensors or optoelectronic devices. Therefore we address both the questions of obtaining good quality ohmic contacts, as well as that of measuring the barrier height of Schottky contacts.

To this aim, we employ several characterization techniques, both electrical and structural. Among them, Capacitance vs. Voltage and Current vs. Voltage curves are standard techniques useful for assessing the electrical characteristic of the contact (ohmic or rectifying). At the same time, we are particularly interested in the correlation between electrical parameters and structural features of the metal-semiconductor junction. To this aim, SEM investigation and, in particular, the method known as Electron Beam Induced Current (EBIC) are very well suitable to solve this issue. EBIC, in fact, is a technique that allows to measure, with the resolution allowed by SEM, the efficiency of a rectifying junction, provided it is not too far from the surface scanned by an electron beam. Therefore, in the case of metal-semiconductor rectifying contacts, it is possible to obtain current maps

which, complemented to the information obtained by SEM topographies, allow to correlate the electrical efficiency of a junction with structural characteristics of the investigated samples.

The experimental conditions of realization of the contacts are particularly important: we will present results concerning several metals as well as several deposition conditions (as an example, with and without post-evaporation annealing). The idea is to verify, in the case of GaN, the well-assessed theories about the dependence of barrier height on work functions differences between metals and semiconductors as well as the correlation between barrier height and ionicity of the semiconductor. In this frame, the parallel measurement of the structural features of the obtained junctions and, in particular, of the EBIC signal is particularly important as it allows to fully take into account also the role of technological issues in determining the final behaviour and reproducibility of the contacts.

P-3

### **Homoepitaxial regrowth on free-standing HVPE-GaN quasi-substrates**

V. DARAKCHIEVA, T. PASKOVA, P.P. PASKOV, AND B. MONEMAR

*Department of Physics and Measurement Technology, Linköping University, S-581 83 Linköping, Sweden*

Despite the remarkable progress in III-V Nitrides technology, the lack of a native substrate still hinder further improvement of material crystal quality and reduction of defect density. The hydride vapor phase epitaxy (HVPE) provides the unique opportunity to grow thick GaN layers in a time and cost efficient manner. Free-standing GaN layers can be fabricated by separation from the substrate and further utilized for homoepitaxial regrowth. It has been found that when the laser lift-off process is used to remove the substrate, the free-standing GaN layer exhibits a bowing. The latter could be related to the presence of residual strain in the free-standing GaN layer which might influence the subsequent homoepitaxial growth. Hence, better understanding of the origin and strain evolution in both free-standing and homoepitaxial GaN layers is needed for development of GaN quasi-substrates.

In this work we focus our attention on the determination of residual strain in free-standing and homoepitaxial GaN layers. We study two types of relatively thin GaN free-standing layers with similar thicknesses initially grown: i) directly on a-plane sapphire; ii) by using metalorganic vapor phase deposited GaN buffer layers on c-plane sapphire. Homoepitaxial HVPE-GaN regrown on both type of free-standing layers are studied as well. To evaluate the degree of residual strain we used high-resolution x-ray diffraction measurements. The lattice parameters of GaN are determined from a set of symmetric and asymmetric peaks, using a precise procedure accounting for a possible misalignment of the sample from the center of the goniometer. Refraction correction is also taken into account.

Although there is a significant strain release after substrate removal it is found that the free-standing GaN layers are not totally relaxed. In addition, there is some non-biaxial contribution to the residual strain, which we tentatively attribute to the presence of defects. Furthermore, there is a small increase of the tensile out-of-plane and compressive in-plane strain in the regrown homoepitaxial GaN layers. The blue shift of all photoluminescence peak positions in the near band gap region is consistent with the observed increase of the residual strain in the homoepitaxial GaN layers. Cathodoluminescence (CL) spectroscopy of cross-section of the homoepitaxial GaN layers is performed in order to gain insight into the reason for the small increase of the residual strain. A drastic decrease of the near band gap CL intensity is observed in the interface between the free-standing and the homoepitaxial GaN layers together with a blue shift compared to the near band gap emission in the free-standing GaN layers. The CL intensity is recovered with increasing the thickness of the homoepitaxial

GaN layers, but the blue shift is preserved. We speculate that defect generated in the interfacial region between the free-standing and the homoepitaxial GaN are responsible for the small strain induced in the homoepitaxial layer. It is suggested that a surface processing of the free-standing layer might be beneficial for the subsequent GaN growth, when the homoepitaxy is performed on thin free-standing GaN layers.

P-4

**A Model for Tera-Hertz Radiation from Semiconductor Heterostructures**

R. M. GUTIÉRREZ\* AND A. S. CAMACHO\*\*

\* *Centro de Investigaciones-Universidad Antonio Nariño, Bogotá, Colombia.*

\*\* *Departamento de Física-Universidad de los Andes, Bogotá Colombia.*

We study the dynamics of the carriers population in semiconductor heterostructures represented by a three level asymmetric double quantum well, a-DQW, by combining a classical phenomenological macroscopic description with a microscopic quantum mechanical one. We first perform a detailed microscopic many body calculation of the decay and emission rates in terms of the self-energies associated to the main interaction mechanisms. With the calculated microscopic decay rates we construct a dynamical system for the carrier populations at three energy levels. Our dynamical system exhibits different solutions depending on the microscopically calculated decay and emission rates. These rates depend on several parameters, in particular on the geometry of the a-DQW. For certain time scales the model shows oscillations of the carrier densities which are interpreted as dipole oscillations generating Tera-Hertz radiation.

P-5

**Exciton Relaxation in Bulk Wurtzite GaN: the Role of Piezoelectric Interaction**

G. KOKOLAKIS, F. COMPAGNONE, A. DI CARLO, P. LUGLI

*INFN and Department of Electronics Engineering, University of Rome "Tor Vergata"*

Nitrides exhibit very important electronic and optical properties which make them the ideal candidate materials for the fabrication of semiconductor devices like blue-green laser and light emitting diodes. At the same time their mechanical characteristics makes them promising for the development of high power and high temperature electronic devices. On the other hand, these materials exhibit the largest piezoelectric constants among all the group III-V semiconductors. This pronounced piezoelectric effect enhances the importance of the piezoacoustic scattering which dominates the mobility within a wide temperature range [1].

We focus on the theoretical study of bulk GaN. The energy relaxation of coupled free-carrier and exciton populations in semiconductors after low density, ultra fast optical excitations, are studied through a new kinetic approach. The usual set of semi classical Boltzmann equations for electrons and holes are complemented by an additional equation that accounts for the exciton population. These equations are coupled by reaction terms describing exciton formation and dissociation, mediated by phonons. We employ an Ensemble Monte Carlo simulation technique to solve the resulting rate equation system in the reciprocal space. The relevant scattering mechanisms taken under consideration are so far carrier-carrier, carrier-phonon and exciton-phonon interactions.

In this work, we define in detail the role of the acoustic piezoelectric scattering for the free-carriers and the excitons, showing that this mechanism dominates the relaxation when the LO-phonon scattering is not possible. The individual coupling constants for the electron and holes have been calculated by including the screening effect that is of big importance for the construction of an accurate picture of the dynamical evolution of the system. The corresponding

transition rates of excitons can be calculated rewriting the piezoelectric interaction Hamiltonian in terms of phonon and exciton operators [2]. In this matrix element we include the weighted sum of the individual contributions of the free-carriers.

The scattering rates have been calculated for cubic and wurtzite symmetry, according to the Fermi-Golden rule. The comparison shows a 25% increase from cubic to wurtzite symmetry in the probability of an exciton emitting a piezoacoustic phonon at a temperature of 5K.

This theoretical treatment along with the consideration of carrier-carrier, Fröhlich and the deformation potential interaction with acoustic phonons, implemented into the Monte Carlo simulation, will give us a complete picture of the exciton and free-carrier behaviour in the system.

We present results in the case of bulk wurtzite GaN within the range of fast relaxation processes (i.e. 1 ps to ~ 400 ps), focusing our attention especially on the time evolution of the carriers and exciton populations at different excitation energies.

Detailed analysis of the results show that the efficiency of the exciton formation process and the temporal evolution of the exciton population is strictly related to the excitation energy.

Our theoretical investigation can predict experimental observations making comparison with time resolved exciton relaxation signals possible. The limits and the future extensions of our method are also discussed.

[1] R. GASKA ET AL., *Appl. Phys. Lett.*, **71**, 3673 (1997)

[2] O. MADELUNG, *Introduction to Solid State Theory* (Springer-Verlag, Berlin, 1978)

P-6

### **Well width dependence of photoluminescence properties of single InGaN/GaN quantum wells**

S.M. OLAIZOLA<sup>1</sup>, W. FAN<sup>1</sup>, P.J. PARBROOK<sup>2</sup>, A.M. FOX<sup>1</sup>, R. BUTTÉ<sup>1</sup>, AND M.S. SKOLNICK<sup>1</sup>

<sup>1</sup> *Department of Physics and Astronomy, University of Sheffield, Sheffield S3 7RH, UK*

<sup>2</sup> *Department of Electronic and Electrical Engineering, University of Sheffield, Sheffield S1 3JD, UK*

Continuous wave (cw) and time-resolved (TR) photoluminescence (PL) measurements were performed as a function of temperature (5-270 K) on a set of Si doped single InGaN/GaN quantum wells grown by MOCVD. The samples studied have a well width of 1 nm, 2 nm, 3 nm, 4 nm and 7.5 nm respectively, all other growth parameters being kept identical for the five samples. We find substantial differences between the behaviour of the samples, in particular for the temperature dependence of the PL linewidth and PL energy shift with the well width. These results are explained by a model in which the indium fluctuations across the well and piezoelectric field effects play a dominant role for small and large well widths respectively.

PL measurements performed at 5K show well resolved PL peaks and their LO-phonon replica separated by 91meV underlying the good quality of the wells. By fitting the main peak position an indium concentration of 8% in good agreement with nominal growth values and a piezoelectric field of 400kV/cm have been estimated. The Stokes shift between absorption (PLE) and emission also increases with well width providing strong support for the dominant role of the piezoelectric fields with increasing well thicknesses.

The temperature dependence of the PL peak shift, full width at half maximum (FWHM) and PL efficiency has been measured for temperatures ranging from 5 to 270K. The 1 nm and 2 nm samples exhibit an s-shaped peak shift with temperature indicating localisation effects likely due to potential

fluctuations across the well. For wider quantum wells there is no low energy shift for temperatures below 50K. Linewidth as low as 42 meV was measured at 5 K for the sample with 4 nm well width. The FWHM increases between 50 K and 130 K and remains constant at higher temperatures for the 1 nm and 2 nm samples, the wider SQWs showing by contrast a continuous increase of the FWHM with temperature above 50K. The localisation temperature and the radiative efficiency are found to decrease with increasing well width.

Time-resolved PL measurements show that the decay time increases dramatically with the well width. This is attributed to the reduced electron-hole overlap in the wider wells due to the quantum confined Stark effect caused by the piezoelectric field. As an example, the lifetime in the 3nm sample is found close to 5ns at 5K and decreases to 375ps at 270K due to the activation of non-radiative paths. This is correlated with the decrease of the PL quantum efficiency which drops by about one order of magnitude between 5K and RT.

20h00

**CRETE STYLE DINNER**

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M1 9h00 Invited **Modulation Spectroscopy and Surface Photovoltage Spectroscopy Investigations GaN: Bulk, Thin Films, and Microstructures**

F. H. POLLAK

*Physics Department and New York State Center for Advanced Technology in Ultrafast Photonic Materials and Applications, Btoklyn College, Brooklyn, NY 11210 USA*

M2 9h30 Invited **Luminescence Properties of III-V-N Type Alloys**

K. ONABE

*Department of Advanced Materials Science, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan*

*Phone: +81-3-5841-6841, e-mail: [onabe@k.u-tokyo.ac.jp](mailto:onabe@k.u-tokyo.ac.jp)*

The quaternary InGaAsN and InGaPN alloys may be the quantum-well materials with a large barrier height for the electron confinement in the InGaAsN/GaAs and InGaPN/GaP quantum wells (QWs), respectively. One of the key issues of these III-V-N type alloys is the compositional fluctuation in the microscopic scale, which may be responsible for some anomalous optical properties. In this study, InGaAsN [1] and InGaPN [2] quaternary bulk films and QW structures were grown on GaAs (001) or GaP (001) substrates by metalorganic vapor phase epitaxy (MOVPE). Structural and optical characterizations using photoluminescence (PL), X-ray diffraction (XRD) and transmission electron microscopy (TEM) were done.

For the low-pressure (60 Torr) MOVPE growth, trimethylgallium (TMG), trimethylindium (TMI), AsH<sub>3</sub> (for InGaAsN) or PH<sub>3</sub> (for InGaPN), and dimethylhydrazine (DMHy) were used as the precursors. The growth temperature was chosen at 600 °C for InGaAsN and 630 °C for InGaPN. For the InGaAsN alloy films (In=17%) with N content of 0-2.3% and 250-500 nm in thickness, the grown film surfaces were mirror-like but with a crosshatch pattern for the N contents lower than 1.0% due to the large lattice-mismatch (>0.81%). The low-temperature (11K) PL spectra showed a continuous red shift from 1.3018 eV to 1.0912 eV with increasing N content. The PL properties were excellent with a single near-band-edge emission peak for lower N contents (N<2.3%). In addition, exciton localization induced by compositional fluctuations in the microscopic structure was observed. On the contrary, the InGaAsN alloy film with N content of 2.3% showed that the dominant spectra contain several broad PL bands of unknown origin, in addition to the InGaAsN-related emission. Moreover, the different luminescence emissions from the different regions of the InGaAsN alloy film (In=17%, N=2.3%) were observed. It is indicated that the compositional fluctuation of InGaAsN increases with increasing N concentration. For the InGaPN/GaP (In=5.8%, N=2.2%) single quantum wells (SQWs), where the well thickness is 6.4, 3.2, 2.4 and 1.6 nm, the low-temperature PL spectra have shown a weak blue shift in the wider wells, which may again be attributed to the exciton nature localized at the isolated nitrogen centers. Alternatively, the In segregation, which causes the composition fluctuation, may hinder the manifestation of the quantum-well confinement effect. The efficient quantum confinement of carriers in the narrower (2.4 nm) wells is well confirmed by the fairly survived PL intensity up to higher temperatures than 200 K. The origin of carrier localization in relation to the extended defects and the incorporation of N in the InGaAsN and InGaPN alloy films are discussed.

[1] J. WU, S. SANORPIM, F. NAKAJIMA, K. ONABE AND Y. SHIRAKI, presented at the *International Conference on Nitride Semiconductors*, Denver, 2001

[2] T. KIMURA, N. NAKADAN, J. WU, Y. ITO, S. YOSHIDA, J. KIKAWA, K. ONABE AND Y. SHIRAKI, presented at the *International Conference on Nitride Semiconductors*, Denver, 2001.

- M3 10h00 Invited **Group III Nitride-Based UV Light Emitting Devices**  
H. AMANO, S. TAKANAMI, M. IWAYA, S. KAMIYAMA AND I. AKASAKI  
*Department of Materials Science and Engineering, Meijo University, 1-501  
Shiogamaguchi, Tempaku-ku, Nagoya 468-8502, Japan*  
[amano@ccmfs.meijo-u.ac.jp](mailto:amano@ccmfs.meijo-u.ac.jp)  
Big success of blue and green light emitting diodes and violet laser diodes pushes nitrides forward to UV. At the moment, however, performance of the nitride in the UV region is still far behind that in visible region. The efficiency of nitride LEDs becomes more and more sensitive to the non-radiative recombination center at or around the threading dislocations with shortening of the emission wavelength or decreasing In composition in the well. In order to fabricate high-efficiency UV LED, thick AlGaIn layer is indispensable. Compared to GaN, it is very difficult to grow high-quality, thick AlGaIn on sapphire. Although the crystalline quality of AlGaIn on sapphire is improved by using an LT-buffer layer, it progressively worsens with increasing AlN molar fraction. The crystalline quality is significantly improved when an AlGaIn layer is grown on a high-quality GaN layer, but a crack network originating from the tensile stress induced by the lattice mismatch between AlGaIn and GaN is generated at a high density if the thickness of AlGaIn exceeds a critical value. One of the solutions to the fracture problem in an AlGaIn-on-GaN heterostructure was to insert another LT-AlN layer between the underlying GaN layer and the upper AlGaIn layer, called an "LT-interlayer". The disadvantage of the LT-interlayer technique is that it increases the density of edge dislocations, which are also found to act as non-radiative recombination centers. Therefore, the fabrication of highly luminescent AlGaIn is difficult. Grooved GaN was used to grow low-dislocation-density AlGaIn. UV LED with AlGaIn-based wells was fabricated using LT-interlayer and grooved GaN. A strong and narrow UV emission peaking as short as 323 nm with FWHM as narrow as 6 nm was observed, which is narrower than that of visible nitride LEDs by a factor of two or three. Performance of UV LED will be discussed. We also report on the brand-new metallic and lattice matched substrate for the growth of AlGaIn.
- 10h30 *Coffee Break*
- M4 10h50 Invited **Study of Band Tails in GaN Using Various Optical Probes**  
T. D. MOUSTAKAS  
*Boston University*
- M5 11h20 Invited **Anisotropy and strain effects on lattice dynamics in nitride-based quantum wells and superlattices**  
J. GLEIZE, J. FRANDON AND M.A. RENUCCI\*  
*Laboratoire de Physique des Solides, UMR 5477 CNRS, 118 Route de Narbonne, 31062 Toulouse Cedex 4, France*  
\* Tel. : +33-5-61556158 ; e-mail address : [Marion.Renucci@lpst.ups-tlse.fr](mailto:Marion.Renucci@lpst.ups-tlse.fr)  
Lattice dynamics of layered structures based on III-nitride semiconductors with wurtzite structure are strongly influenced by the anisotropic properties of constitutive materials, and by their ionic character. Both are responsible for large built-in electric fields induced by spontaneous and piezoelectric static polarizations, the latter originating from significant lattice mismatch and difference in thermal coefficients between adjacent layers. Until now, only few reports have been concerned with the optical phonons in GaN/AlN or GaN/(Al,Ga)N quantum wells and superlattices. Moreover, *ab initio* calculations restricted to short period structures can hardly be compared with experiment, as most of the experimental data refer to larger scale systems. [1-4] We present a phenomenological approach to the picture of phonons in more

realistic structures, suitable for the interpretation of experiments. Long wavelength polar phonons are described, within a dielectric continuum model, by the dynamical polarization associated with atomic vibrations. For these  $\mathbf{q} \approx \mathbf{0}$  modes, each type of layers acts as a true band-pass filter for transverse (TO) and longitudinal (LO) phonons, whose frequency width reflects the anisotropy in short range interatomic forces. The propagating modes of the layers show angular dispersion (their frequency depends on the inclination of the phonon wavevector with respect to the c-axis of the layers) and mixed symmetry character. The stop bandwidth between the TO and LO pass bands, on the contrary, is governed by the effects of long range Coulomb forces, dominant in ionic materials as GaN, AlN and their alloys. As a result of both the finite width of pass bands in the layers and their relative positions for the two types of layers, specific dispersive modes are predicted, without any equivalent in structures composed of isotropic materials. These are quasi-confined modes (QC), which oscillate in a given type of materials and can penetrate into the surrounding layers where they decay exponentially, and propagating modes (P), exhibiting an oscillatory character in both types of layers, showing up in GaN/(Al,Ga)N structures with Ga-rich alloys only.

The model requires as input data the  $\mathbf{q} \approx \mathbf{0}$  polar phonon frequencies of constitutive layers in their actual strain state in the structure. As elastic properties are necessarily coupled to electric effects in piezoelectric materials, a macroscopic model has been developed to estimate the influence of static polarizations on the strains in each type of layers in GaN/AlN structures, as a function of their relative thickness. The main effect concerns the strain component along the growth axis, which can greatly be reduced, particularly in the AlN layers. In comparison with that given by a pure elastic theory, a significant increase in the absolute shift of phonon frequencies is predicted for the case of AlN layers lattice-matched to GaN.

Modelling of the angular dispersion of polar phonons was used to interpret Raman measurements we carried out on strained GaN/AlN superlattices, ensuring the control of  $\mathbf{q}$  transfer from photons by varying the scattering geometry in off-resonant conditions.

[1] J.M. WAGNER, J. GLEIZE AND F. BECHSTEDT, IWN 2000, Nagoya, Japan, *IPAP Conf. Series* **1**, 669 (2000)

[2] J. GLEIZE, F.DEMANGEOT, J. FRANDON, M.A.RENUCCI, F. WIDMANN, B. DAUDIN, *Appl. Phys. Lett.*, **74**, 703 (1998)

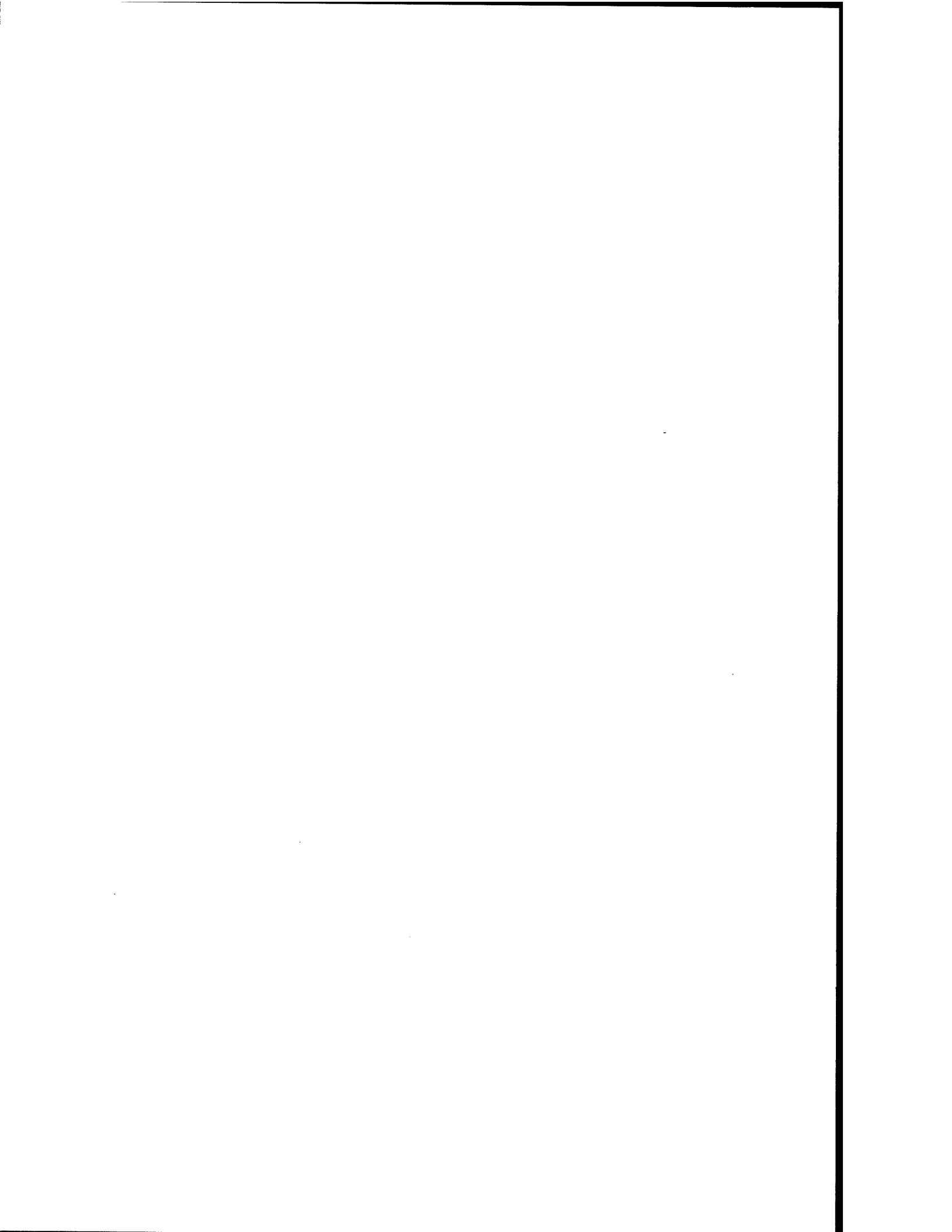
[3] M.SCHUBERT, A.KASCH, T.E.TIWALD, J.A. WOOLLMAN, V.HÄRLE, F. SCHOLZ, *MRS Internet J.NSR* **5** suppl.1 (2000)

[4] V.Y. DAVYDOV ET AL., *Phy. Stat. Sol. (a)* **188**, 863 (2001)

12h10            **EXCURSION : "THE PIRATE BOAT", PIC-NIC**

20h00            **BARBECUE ON THE BEACH**

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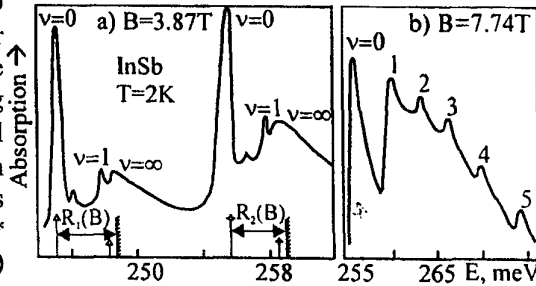


T-1 9h00 Invited Modeling of Low-Dimensional State of Matter by Excitons in Strong Magnetic Fields

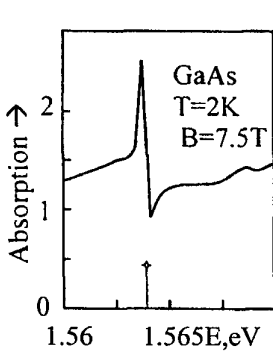
R.P. SEISYAN

A. F. Ioffe Physico-Technical Institute, Politekhnicheskaya 26, 194021, St. Petersburg, Russia, E-mail: rseis@ffm.ioffe.rssi.ru

As known strong field interband magneto-optical ( $\bar{G}\bar{I}$ ) spectra in semiconductors are formed by diamagnetic exciton (DE) series having inter-Landau level transition energies as a dissociation edges (for example, [1]). The main feature of DE states is their quasi-1D character, which is typical for optical behavior of the quantum wires. Strong magnetic field criterion  $\beta \gg 1$  ( $\beta = \hbar\Omega/2Ry^*$ , where  $\Omega$  is sum of the cyclotron frequencies for electrons and holes,  $Ry^*$  is exciton binding energy) can be considered as a



measure of one-dimensionality. It easily reaches  $\beta=10^2$  for narrow gap semiconductors like InSb and MO line shape becomes typical for 1D absorption



(fig. 1a). Here discrete 1D exciton spectrum is followed by distinct continuum, decreasing as  $(E-E(v=\infty))^{-1/2}$ . Top level of the continuum increases at higher magnetic fields and heavy hole ladder fine structure arises on the continuum slope (fig. 1b). More high values of the  $\beta$  are available for PbTe crystals where excitonic nature of magneto-absorption was proved also [1]. This is actual in strong magnetic field for such semimetals as HgTe also. Nevertheless it occurs to be possible to observe well expressed oscillatory magnetoabsorption ( $\bar{I}\bar{G}\bar{A}$ )

spectra in relatively wide gap crystals where strong field criterion does not fulfilled at all. This happens when at least one excited excitonic state ( $n>2$ ) is observable at  $B=0$  and then only  $Ry^*/n^2$  is necessary to satisfy strong field criterion. This is important for quasi-Landau oscillatory spectra arising in GaAs, InP, CdSe, ZnSe, SnO<sub>2</sub> and so on, moreover these spectra have strongly quasi-1 D character and are accompanied with formation of the Fano resonances (fig. 2), as a result of the interaction between discrete DE line with continuum of previous DE of the same ladder. Simulation of the 1D states takes place in pure semiconductor crystals at the conditions which are practically unattainable for real quantum wires due to influence of the interfaces and inevitable inhomogeneous broadening. Moreover, at least in the longwave part of the  $\bar{I}\bar{G}\bar{A}$  we deal with the polaritonic 1D states. Using well developed 2D structures it is possible to simulate OD (quantum dots) situation, arising in the Faraday configuration. Observation of the Fano resonances is also available here. They disappeared when magnetic field becomes stronger and continuum of the states vanishes. Method of magnetoexciton binding energy calculation is well developed [2] and gives a possibility to discriminate continuum of excitonic states being responsible for oscillatory magnetoabsorption formation and to reconstruct the true Landau level positions. It makes possible to recognize such localized states as upper barrier exciton [3], "Coulomb well" exciton oscillatory states [4], and so on. Modeling of low-dimensional systems by strong magnetic field with an exciton also makes possible to simulate behavior of the matter in extremely high magnetic field. Here laboratory field H, multiplied  $\mu/\epsilon^2$  times ( $\mu$  is reduced exciton mass and  $\epsilon$

is dielectric constant), becomes an equivalent of the real field. In the case of PbTe this coefficient occurs to be about  $10^8$ . This makes the laboratory conditions comparable with those on neutron stars.

[1] R.P.SEISYAN, B.P.ZAKHARCHENYA, LANDAU LEVEL SPECTROSCOPY. EDS E.I.RASHBA, G.LANDWEHR, North Holland, 1991, ch.7, pp.345-444. R.P.SEISYAN, Spectroscopy of Diamagnetic Excitons, 1984, Moscow, Nauka, (in Russian).

[2] A.V.KAVOKIN, A.I.NESVIZHSHII, R.P.SEISYAN, *Semiconductors* **27**, 530 (1993)

[3] R.P.SEISYAN, M.E.SASIN, S.I.KOKHANOVSKII, M.R.VLADIMIROVA, A.V.KAVOKIN, M.VA.KALITEEVSKII, V.M.USTINOV, The Physics of Semiconductors, (1996), World Scientific, Singapore, V.3, 2051; JETP Letters, **69**, 779 (1999).

[4] R.P.SEISYAN, A.V.KAVOKIN, S.I.KOKHANOVSKII, A.I.NESVIZHSHII, M.E.SASIN, M.A.SINITSYN, B.S.YAVICH, *Semicond. Sci. Technol.* **10**, 611 (1995).

T-2 9h30

**Microscopic investigation of In concentration fluctuation in an InGaN/GaN quantum well**

J. GLEIZE, A. DI CARLO, P. LUGLI <sup>(a)</sup>, J.-M. JANCU <sup>(b)</sup>, O. AMBACHER AND M. HERMANN <sup>(c)</sup>

<sup>(a)</sup> *INFIM-Dipartimento di Ingegneria Elettronica, Università di Roma "Tor Vergata", Roma, Italy*

<sup>(b)</sup> *INFIM-Scuola Normale Superiore, Pisa, Italy*

<sup>(c)</sup> *Walter Schottky Institut, Technische Universität München, Garching, Germany*

The physical properties of InGaN based heterostructures are influenced by the Indium segregation which can occur in such systems, leading to the formation of Indium-rich regions inside the InGaN layers. It has been shown that, optical properties of InGaN based heterostructures are correlated to these fluctuations [1]. Moreover, experimental values of the polarization fields in InGaN/GaN devices differ significantly from the theoretical ones, which assume a uniform Indium concentration in the InGaN layers.

In order to address this problem, the electronic band structure of an InGaN/GaN quantum well was calculated under a tight-binding approach. Excited  $s^*$  and  $d$  states were taken into account by using a  $sp^3s^*d^5$  basis for nearest neighbors interactions. A new parameterization of InGaN has been developed in order to reproduce correct strain related properties. We included in our simulation the effect of the fluctuation of the local Indium concentration by using the results of recent transmission electron microscopy measurements performed on a real InGaN/GaN device. In this study the quantum well is described with a three-dimensional supercell with imposed periodic boundary conditions. In the growth direction the supercell is thick enough to achieve the situation of isolated quantum well. In the in-plane direction the supercell was large enough to account for the proper distribution of atoms according to the Indium concentration map. The total number of simulated atoms is of the order of  $10^5$ . Efficient diagonalization routines are used to solve the Schrödinger equation in this localized basis. The calculated band structure we obtained is compared to that of an homogeneous InGaN/GaN system, with an Indium concentration corresponding to the average of the actual device. The interplay between polarization field, strain and indium fluctuations are carried out and discussed in this report.

[1] K. P. O'DONNELL, R. W. MARTIN AND P. G. MIDDLETON, *Phys. Rev. Lett.* **82** (1), 237, 1999

T-3 9h50

**Exciton dynamics in InGaAsN/GaAs heterostructures**

A. VINATTIERI<sup>(a)</sup>, D. ALDERIGHI<sup>(a)</sup>, M. COLOCCI<sup>(a)</sup>, A. POLIMENI<sup>(b)</sup>, M. CAPIZZI<sup>(b)</sup>, M. FISCHER<sup>(c)</sup> AND A. FORCHEL<sup>(c)</sup>

<sup>(a)</sup> *Istituto Nazionale di Fisica della Materia, Dipartimento di Fisica, Università degli Studi di Firenze, via Sansone 1, I-50019 Sesto Fiorentino, Italy*

<sup>(b)</sup> *Istituto Nazionale di Fisica della Materia, Dipartimento di Fisica, Università degli Studi di Roma "La Sapienza", Piazzale A. Moro 2, I-00185 Roma, Italy*

<sup>(c)</sup> *Universität Würzburg, Technische Physik, Am Hubland 97074 Würzburg, Germany*

The search for highly efficient light emitters in the (1.3-1.55)  $\mu\text{m}$  range compatible with the GaAs technology has led to a renewed interest in the physical properties of  $\text{In}_x\text{Ga}_{1-x}\text{As}_{1-y}\text{N}_y/\text{GaAs}$  heterostructures.[1] Indeed, the incorporation of small amounts of N ( $y \sim 0.01$ ) results in a giant band gap bowing of the  $\text{In}_x\text{Ga}_{1-x}\text{As}$  host lattice for increasing  $y$ . [1]. However the alloy disorder present in the  $\text{In}_x\text{Ga}_{1-x}\text{As}_{1-y}\text{N}_y$  layers affects strongly the carrier motion [2] and leads to a radiative recombination at low temperature ( $T < 150$  K) generally dominated by localized excitons [3]. Therefore a study of the carrier recombination dynamics in these materials is necessary for a full exploitation of III-N-V alloys in optoelectronic devices. In this paper we present a detailed experimental investigation on the exciton dynamics in InGaAsN/GaAs quantum wells by means of both CW and picosecond time-resolved photoluminescence measurements. Several samples have been investigated for different indium and nitrogen content and for various well thicknesses. In particular samples have been compared with the very same growth parameters except the nitrogen content. CW and time integrated data show a significant shift of the emission to lower energy when nitrogen is introduced and as the excitation density is increased a blue shift of the PL line is observed indicating a saturation of localized states which is more important for samples with nitrogen. Time-resolved experiments have been performed by means of a picosecond Ti:Sapphire laser for the excitation and for detection a S1 streak camera has been used allowing for a time-resolution of 2 picosecond. Time-resolved PL spectra show an evolution of the band to low energy when the time-delay respect to the excitation pulse increases. Such effect becomes more significant for samples with nitrogen, indicating again the dominance of localized states in the dynamics. The time-decay of the PL band is roughly exponential with a time constant of the order of a few hundreds of picoseconds, depending on the well thickness, and gets longer when a nitrogen content is present.

An analysis of the whole set of data is presented and the role of nitrogen is discussed in order to determine the nature of radiative and non-radiative channels.

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[2] S R. KURTZ, A. A. ALLERMAN, C. H. SEAGER, R. M. SIEG, AND E. D. JONES, *APL* **77**, 400 (2000).

[3] A. POLIMENI, M. CAPIZZI, M. GEDDO, M. FISCHER, M. REINHARDT, AND A. FORCHEL *Phys. Rev. B* **63**, 195320 (2001).

T-4 10h10

**Molecular beam epitaxy growth of group III-nitrides microcavities : optical and structural properties**

F. NATALI<sup>(a)</sup>, N. ANTOINE-VINCENT<sup>(b)</sup>, D. BYRNE<sup>(a)</sup>, F. SEMOND<sup>(a)</sup>, M. LEROUX<sup>(a)</sup>, N. GRANDJEAN<sup>(a)</sup>, J. MASSIES<sup>(a)</sup> AND J. LEYMARIE<sup>(b)</sup>

<sup>(a)</sup> *CRHEA-CNRS, rue Bernard Grégory, Sophia Antipolis, F-06560 Valbonne, France*

<sup>(b)</sup> *LASMEA, Université Blaise Pascal-Clermont Ferrand II, F-63177 Aubière Cedex, France*

Due to the large exciton binding energy associated with the large oscillator strength in wide-bandgap materials, the observation of a giant Rabi splitting is anticipated in Nitride-based microcavities [1]. Previous work highlighted that GaN-based microcavities are an excellent candidate for studying the physics of light-matter coupling and the strong coupling regime in wide-bandgap materials [2]. The main difficulty in realising such structures lies in the epitaxial growth of high quality Nitride-based Distributed Bragg Reflectors (DBRs) upon which an active layer of comparable quality must be subsequently grown.

To investigate further this problem, a number of AlGaIn / AlGaIn DBR mirrors with different compositions were grown by molecular beam epitaxy (MBE) on silicon substrates and the results of reflectivity, X-ray diffraction and transmission electron microscopy will be presented. The results and insights gained from the optical and structural characterisation of the subsequent growth of GaN microcavity structures will also be summarised.

[1] A. KAVOKIN ET AL., *Appl. Phys. Lett.* **72**, 2880 (1998)

[2] N. ANTOINE-VINCENT, F. NATALI, P. DISSEIX, M. MIHAILOVIC, A. VASSON, J. LEYMARIE, F. SEMOND, M. LEROUX AND J. MASSIES, *Phys. Stat. Sol. (a)* **190**, 187 (2002).

10h30

**Coffee Break**

T-5 11h00

**Stimulated Spin Scattering in Semiconductor Microcavities**

P. LAGOUDAKIS<sup>(a)</sup>, P. G. SAVVIDIS<sup>(a)</sup>, D.M. WHITTAKER<sup>(a)</sup>, J. J. BAUMBERG<sup>(a)</sup>, R. M. STEVENSON<sup>(b)</sup>, M. S. SKOLNICK<sup>(b)</sup> AND J. S. ROBERTS<sup>(c)</sup>

<sup>(a)</sup> *Dept. of Physics & Astronomy, University of Southampton, Southampton SO17 1BJ, UK*

<sup>(b)</sup> *Department of Physics, University of Sheffield, Sheffield S3 7RH, UK*

<sup>(c)</sup> *Department of Electronic and Electrical Engineering, Sheffield S1 3JD, UK*

Parametric gains in a semiconductor microcavity are shown to be maximized for pump polarizations, which excite both polariton spins. Stimulated spin-flip scattering is also observed, of use in optical switching, despite its being forbidden theoretically.

Combining photonic and electronic heterostructures within a single device provides a new opportunity to engineer the dispersion of the optically-coupled electronic excitations. Semiconductor microcavities in the strong coupling regime have mixed light-matter quasiparticles called exciton-polaritons, which dominate the optical response. Recently their distorted dispersion relation and their extremely light mass have been shown to give rise to extraordinarily large nonlinear optical properties [1-3].

Here we show that the nonlinear response which arises from the 'parametric' scattering of pairs of polaritons, possesses a strong and unusual dependence on the spin of the polaritons [4]. Previously we showed that the polariton spin (up or down) is well defined and uniquely accessed by the particular circular polarisation (right or left respectively) of the excitation lasers. By developing time-resolved spectroscopies that measure the gain of a probe pulse along three independent polarisation axes (horizontal or vertical linear, diagonal crossed linear, and right or left circular), we completely specify the polarisation of the microcavity emission for the first time. This polarisation varies enormously as the ratio of excess spins excited by the pump pulse is varied, while keeping the total excitation density constant. For instance, if equal polariton spin populations are excited by a horizontal linear pump pulse, the amplified emission is linear but at 45 degrees to the vertical, in complete disagreement with simple theoretical models. The orientation of the emitted linear polarisation rotates several times as

the relative pump spin populations are changed by only 10%. Even more significantly, if all the incident energy creates polaritons with solely a single spin, the gain is only half that of the case where the same energy is divided into equally pumping spin-up and spin-down polaritons. This implies that the dominant parametric scattering is not driven by two polaritons of the same spin orientation. Our experiments imply polaritons with oppositely oriented spins scatter more than twice as efficiently as co-aligned spins. Disturbingly, current theories insist that the scattering between oppositely spinning polaritons should be virtually zero.

Our results have significant implications for nonlinear devices based on parametric scattering. Indeed, we show it is even possible to stimulate the spin-flip of polaritons, enabling high-efficiency all-optical spin switches.

[1] P.G. SAVVIDIS *ET AL.*, *Phys. Rev. Lett.* **84**, 1547 (2000).

[2] C. CIUTI *ET AL.*, *Phys. Rev. B* **62**, R4825 (2000).

[3] R.M. STEVENSON *ET AL.*, *Phys. Rev. Lett.* **85**, 3680 (2000).

[4] P.G. LAGOUDAKIS *ET AL.*, submitted to *Phys. Rev. Lett.* (2001)

T-6 11h20

### **Polarisation rotation in resonant emission of semiconductor microcavities**

A. KAVOKIN <sup>(a)</sup>, G. MALPUECH <sup>(a)</sup>, J. J. BAUMBERG <sup>(b)</sup>, P. LAGOUDAKIS <sup>(b)</sup>,  
K. KAVOKIN <sup>(c)</sup>

<sup>(a)</sup> *LASMEA, UMR-6602, Université Blaise Pascal, 24 av. des Landais, 63177, Aubiere, France*

<sup>(b)</sup> *Department of Physics and Astronomy, University of Southampton, SO17 1BJ Southampton, United Kingdom*

<sup>(c)</sup> *School of physics, University of Exeter, Stocker Road, Exeter, EX4 4QL, UK*

We present the semi-classical theory of the non linear propagation of polarised light in semiconductor microcavities. This formalism explains the mysterious rotation of the polarisation plane of light emitted by a microcavity in the regime of stimulated scattering observed recently [1]. The model describes the stimulated four-wave mixing in microcavities in the framework of a tensor formalism. We show that the exciton spin-splitting induced by the polarized pumping is responsible for giant resonant Faraday rotation of the polarisation plane of light emitted by the cavity.

[1] P. LAGOUDAKIS *ET AL.*, *Phys. Rev. B* **65**, 161310 (2002).

T-7 11h40

### **The Transition from Strong to Weak Coupling and the Polariton Laser in Semiconductor Microcavities**

R. BUTTÉ,<sup>1</sup> G. DELALLEAU,<sup>1</sup> A.I. TARTAKOVSKII,<sup>1</sup> M.S. SKOLNICK,<sup>1</sup> V.N. ASTRATOV,<sup>1</sup> J.J. BAUMBERG,<sup>2</sup> G. MALPUECH,<sup>3,4</sup> A. DI CARLO,<sup>4</sup> A.V. KAVOKIN,<sup>3</sup> J.S. ROBERTS<sup>5</sup>

<sup>1</sup> *Department of Physics and Astronomy, University of Sheffield, Sheffield, S3 7RH, UK*

<sup>2</sup> *Department of Physics and Astronomy, University of Southampton, Southampton, SO17 1BJ, UK*

<sup>3</sup> *LASMEA, Université Blaise Pascal Clermont-II, 63177 Aubière Cedex, France*

<sup>4</sup> *INFN-Department of Electrical Engineering, University of Rome Tor Vergata, I-00133 Roma, Italy*

<sup>5</sup> *Department of Electronic and Electrical Engineering, University of Sheffield, Sheffield S1 3JD, UK*

Angular dependent emission spectra are investigated in a strongly coupled InGaAs-GaAs-AlAs microcavity as a function of excitation intensity and of detuning between the uncoupled exciton and photon modes. Under conditions of non-resonant excitation, it is shown that the onset of stimulated emission always occurs in the weak coupling regime, in strong contrast to the case of resonant

excitation. Angular dependent studies show that the transition to weak coupling occurs when the linewidth of high  $k$  excitons becomes of the order of the normal mode splitting of the exciton-polariton coupled modes.

The polariton relaxation dynamics were modelled by means of Boltzmann kinetic equations for the polariton population. The main features of the experimental spectra are reproduced very well by the theory, namely (i) the suppression of the bottleneck with increasing excitation intensity at small negative detuning, (ii) the trend of weaker suppression of the bottleneck with increasing negative detuning as the exciton fraction of the low  $k$  states decreases, (iii) the shift of the maximum of the distribution to lower  $k$  with power at large negative detuning. The good overall agreement between theory and experiment confirms the dominant role of exciton-exciton scattering processes, one of the key ingredients of the theory, in controlling the dynamics of the cavity polaritons under conditions of non-resonant excitation for intensities greater than  $\sim 5 \text{ W/cm}^2$  (phonon scattering being dominant at lower powers).

Further information into the mechanisms underlying the loss of the strong coupling is given by the comparison of the calculated polariton population over a large range of  $k$  deduced from kinetic equations for a power close to the transition from strong to weak coupling with the equilibrium distribution function expected for a Bose gas of polaritons with zero chemical potential ( $\mu$ ). The critical density for condensation (and hence  $\mu = 0$ ) is calculated to be much smaller than the density deduced from Boltzmann kinetic equations. The major differences between the calculated “kinetic” distribution and the thermal equilibrium one are (i) the strong deviation observed at small  $k$ , a direct consequence of the bottleneck effect, (ii) the shift of the kinetic distribution at higher  $k$  with respect to the equilibrium distribution demonstrating the extra population of the reservoir, due to the inefficient relaxation, this large reservoir population being a key factor in the loss of strong coupling before stimulation is achieved.

We conclude that, under non-resonant excitation, “polariton lasing”, where stimulated polariton scattering followed by photon emission occurs in the strong coupling regime, is likely to be achieved in systems with larger exciton binding energy than in GaAs-based structures or in GaAs microcavities containing excess concentrations of free electrons, the additional exciton-electron scattering channel being expected to lead to very effective population of the low  $k$  states at relatively low exciton densities.

T-8 12h00

**Polariton Bose condensation in microcavities, thermodynamic and kinetic aspects.**

G. MALPUECH<sup>(a)</sup>, A. KAVOKIN<sup>(a)</sup>, F. P. LAUSSY<sup>(a)</sup>, A. DI CARLO<sup>(b)</sup> AND J. J. BAUMBERG<sup>(c)</sup>

<sup>(a)</sup> *LASMEA, Université Blaise Pascal Clermont-II/CNRS*

<sup>(b)</sup> *INFM-Department of Electrical Engineering, University of Rome Tor Vergata, I-00133 Roma, Italy*

<sup>(c)</sup> *Department of Physics and Astronomy, University of Southampton, Southampton, SO17 1BJ, UK*

Critical conditions for the Bose condensation of exciton-polaritons in conventional microcavities containing quantum wells are derived and analysed from the thermodynamic and kinetic point of view.

From the thermodynamic point of view, we calculate the critical temperature of the condensation of interacting polaritons in an infinite 2-dimensional cavity, in the frame of the Bogoliubov formalism [1]. We then show that in real finite systems, the critical temperature is governed not only by the shape of the polariton in-plane dispersion curve but also on either the lateral size of the system or even on the size of the light-spot that excites the system. The regime of

condensation is strongly dependent on the spatial scale of the in-plane potential disorder in the quantum well. Optimistically, we estimate the critical temperature of the polariton Bose condensation as up to 100 K in GaAs-based microcavities, 150 K in CdTe-based microcavities, and more than 300 K in hypothetical GaN- or ZnO-based microcavities. We conclude that the most serious obstacle for the experimental observation of the polariton Bose condensation is the kinetic blocking of the polariton relaxation down to its ground state in a microcavity [2]. Resolving numerically the classical Boltzmann equations for the exciton-polaritons in the cavity, we observe the strong kinetic blocking (“bottleneck”) effect. We show that the polariton relaxation becomes much more efficient in n-doped microcavities due to the electron-polariton scattering [3].

[1] V.A. ZAGREBNOV AND J. B. BRU, *Phys. Rep.* **350**, (2001) and ref. therein.

[2] R. BUTTÉ ET AL, *Phys Rev. B* **65**, 205310 (2002).

[3] G. MALPUECH ET AL, *Phys. Rev. B* **65** 153310 (2002).

T-9 12h20

### Electron-polariton scattering in Semiconductor Microcavities

P. G. LAGOUDAKIS<sup>(a)</sup>, M. D. MARTIN<sup>(a)</sup>, G. MALPUECH<sup>(a)</sup>, J. J. BAUMBERG<sup>(a)</sup>, E. COHEN<sup>(b)</sup>, L.N. PFEIFFER<sup>(c)</sup>, R. ANDRE<sup>(d)</sup>

<sup>(a)</sup> *Dept. of Physics & Astronomy, University of Southampton, SO17 1BJ, UK*

<sup>(b)</sup> *Solid State Institute, Technion-Israel Institute of Technology, Haifa 32000, Israel*

<sup>(c)</sup> *Bell Laboratories, Lucent Technologies, Murray Hill, New Jersey 07974*

<sup>(d)</sup> *Lab. de spectrometrie Physique, Universite Joseph Fourier, CNRS, Grenoble 1, France*

Exciton-polaritons, the elementary optical excitations of planar semiconductor microcavities may be understood as a superposition of excitons and cavity photons. The first evidence of the bosonic behavior of polaritons came recently with the observation of a strong stimulated polariton-polariton scattering process [1]. However, Bose-Einstein condensation of polaritons has not yet been observed from an initial incoherent population of excitons. The reason is the presence of the relaxation bottleneck in the dispersion relation of the semiconductor microcavity [2].

Recently, an innovative idea of introducing an electron gas into such structures theoretically solved the problem of the relaxation bottleneck [3]. Electron-polariton scattering was proposed as an efficient process that could drive polaritons from the bottleneck region to the ground state achieving Bose amplification of the emission. Due to the small effective mass of electrons confined to the same quantum wells within the structure, more energy can be removed from excitons for each scattering process. Here we present the first experimental observations of enhanced photoluminescence (PL) due to electron-polariton scattering in such heterostructures. In order to separate the favorable and detrimental effects of electrons interacting with the excitons in the quantum wells, we use samples in which the carrier densities can be varied. In our studies we also study both n-doped and p-doped planar semiconductor microcavities to explore the dependence on effective mass. The n-doped sample is a GaAs  $\lambda$  microcavity in which the central wider quantum well, which couples to the photon cavity mode, is surrounded by narrower quantum wells, which can supply electrons when optically pumped. We excite non-resonantly with a cw Ti-Sa laser at a temperature of 10K in order to create a reservoir population of incoherent excitons. The carrier density is produced using a defocused 635nm laser diode and the light emitted from the samples is angle resolved for various doping densities, exciton-cavity detuning and excitation densities. We see the clear signature of enhanced photoluminescence from the lower polariton branch around an optimal electron density of  $3 \cdot 10^9 \text{ cm}^{-3}$ . At higher intensities however,

the photoluminescence line broadens considerably as the electron scattering from the excitons increases. At even higher powers, the exciton oscillator strength reduces and thus the Rabi splitting reduces enough to enter into the weak-coupling regime. These thresholds are extremely dependent on the detuning, and show that there is a fine balance between the help provided by electron doping and the destruction of the strong coupling microcavity regime.

[1] P.G. SAVVIDIS ET AL., *Phys. Rev. Lett.* **84**, 1547 (2000).

[2] F. TASSONE ET AL., *Phys. Rev. B.* **56**, 7554 (1999).

[3] G. MALPUECH ET AL., to appear in *Phys. Rev. B* (2002).

T-10 12h40

**Elastic scattering of microcavity polaritons**

M. LITINSKAIA<sup>1)</sup>, G.C. LA ROCCA<sup>2)</sup>, V.M. AGRANOVICH<sup>1)</sup>

<sup>1)</sup> *Institute of Spectroscopy, Russian Academy of Sciences, Troitsk, Moscow Reg., 142190, Russia*

<sup>2)</sup> *Scuola Normale Superiore, Piazza dei Cavalieri 7, 56126, Pisa, Italy*

We study theoretically the elastic scattering of two-dimensional exciton-polaritons in semiconductor microcavities on structural imperfections. Besides of the experimentally observable inhomogeneous broadening, the disorder influences the character of propagation of the cavity polaritons. It will be shown analytically that in state of the art samples the scattering is dominated by the resonant contribution occurring when the cavity polariton has the same energy as a bare exciton localized in a disorder potential minimum. The suggested analysis (i) explains the microscopic mechanism responsible for the inhomogeneous broadening of lower polariton and (ii) allows one to discuss the possible kinetic regimes of lower polariton propagation in very simple terms of the corresponding length scales. In particular, the conditions under which weak localization of cavity polaritons is possible will be summarized.

13h00

**LUNCH**

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T-11 14h30 Invited **Atomic Force Microscopy and Electrostatic Force Microscopy observations on Gallium Nitride**

PAUL GIRARD

*Laboratoire d'Analyse des Interfaces et de Nanophysique (UMR CNRS 5011)  
CC 082, Université de Montpellier II, Place E. Bataillon 34095  
MONTPELLIER CEDEX, France*

Atomic Force Microscopy (AFM) and Electrostatic Force Microscopy (EFM) are modern methods allowing observations and measurements of morphological and electrical properties, respectively, down to the scale of some tens of nanometers. They are based on Scanning Probe Microscopy (SPM), and these observations can be carried out simultaneously<sup>[1]</sup>, which appears particularly interesting at such scales.

To achieve EFM experiments, a voltage  $V$  is applied between the sensor and the material to be examined, it carries a dc and an ac term (pulsation  $W$ ), i.e.  $V = (V_{dc \text{ applied}} + V_{\text{surface}}) + V_{ac} \sin Wt$ . The resulting electrical force is attractive and shows two interesting properties: i) it bends the sensor, ii) it changes the effective return force of the sensor. First of all, the Electrical Force Microscopy results of the detection of such sensor bendings. Secondly, since the resonance frequency of the sensor writes:  $w_0 = (k - \text{Grad}F_z)/m)^{1/2}$  and the force gradient  $\text{Grad}F_z$  - in the direction of vibration - is changed by the existence of voltages or charges, the detection of frequency changes corresponds to Electrostatic Force Gradient Microscopy (EFGM)<sup>[2]</sup>.

Since the electrical force writes:  $F = \frac{1}{2} dC/dz V^2$ ,  $C$  being the tip to sample capacitance, due to the time dependence of the voltage  $V$ , it results terms at different frequencies that can be detected experimentally.

First of all,  $F_{2W} = -1/4 dC/dz V_{ac}^2$  is only related to  $dC/dz$ . Since  $C$  is composed of two capacitors in series, i.e. the air gap and the surface to bulk, it is sensitive to morphology and to the presence of surface depletion. So, in principle differently doped regions can be visualised. Secondly,  $F_W = dC/dz (V_{dc \text{ applied}} + V_{\text{surface}}) V_{ac} \sin Wt$  is depending on both the capacitive coupling  $dC/dz$  and the surface potential  $V_{\text{surface}}$ . If a counter voltage is applied in order to keep  $F_W = 0$ , the surface voltage variations become achievable,  $V_{\text{surface}} = -V_{dc \text{ applied}}$ , this is the nano-Kelvin operation. Finally, the dc item, i.e.  $F_{dc} = \frac{1}{2} dC/dz [(V_{dc \text{ applied}} + V_{\text{surface}})^2 + V_{ac}^2/2]$  is only available via its derivative  $\text{Grad}F_{z,dc}$ , when scanning the sample at constant distance of some tens of nanometers, using the "lift" operation in EFGM.

Since accidents in morphology are often related with local electrical changes, the interpretation of electrical observations becomes more complex<sup>[3]</sup>, so the ability to correlate different observations is particularly helpful. In fact, GaN films show electrical defects often associated with topography<sup>[4,5]</sup>. On samples with various dopings, it has been shown that EFM (i.e.  $F_i$ ) observations can be related to Hall mobility and fractal behaviour too<sup>[6,7]</sup>. In addition, on GaN films with different dopings too, we show how to correlate different AFM, EFM and EFGM observations to explain the electrical effects, for example on the domains of different size. It results that SPM methods give powerful capabilities to explore a complex material such as Gallium Nitride.

It is a pleasure to acknowledge colleagues from Ioffe Institute and particularly Dr N. Shmidt, Dr A.S. Usikov, Dr W.V. Lundin, Pr A. N. Titkov for their demonstrative samples and helpful discussions and Dr M. Ramonda from Laboratoire de Microscopie à Champ Proche (Montpellier) for his expertise in SPM experiments.

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<sup>2</sup>- P. GIRARD AND M. RAMONDA, *SPM'01 Conference Proceedings*, Vancouver July 2001, **338**.

<sup>3</sup>- P. GIRARD, A.N. TITKOV, M. RAMONDA, V.P. EVTIKHIEV AND V.P. ULIN, to be

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<sup>7</sup> N. SHMIDT, V.V. EMTSEV, A. G. KOLMAKOV, A.S. KRYZHANOVSKY, W.V. LUNDIN, D.S. POLOSIN, V.V. RATNIKOV, A.N. TITKOV, A.S. USIKOV AND E.E. ZAVARIN, *Nanotechnology* **12**, 471 (2001).

T-12 15h00 Invited **High-pressure studies of internal electric fields in nitride quantum structures**

P. PERLIN

*High Pressure Research Center "Unipress", ul. Sokołowska 29/37, 01-142 Warszawa, Poland*

Binary nitrides: GaN, AlN, InN and their solid solutions represent a family of semiconductors of crucial importance for modern optoelectronics. Strained quantum wells, like GaN/AlGaIn and specially InGaIn/GaN, form active layers of the light emitters working in green-UV part of the spectrum. The emission spectra of the considered quantum structures are greatly influenced by the presence of built-in electric fields which affects the device performance. The electric field acting via Quantum Confined Stark Effect determines both the light emission energies and radiative recombination efficiencies. High-pressure investigations of the light emission in the nitride quantum structures revealed an unexpected anomaly of pressure dependence of the piezoelectric polarization. This observation forced the researchers to modify the standard method of calculation of piezoelectric polarization by including nonlinear terms in its strain dependence. In this presentation I will review the current status and understanding of high-pressure (and lower symmetries deformation) induced modification of the light emitting phenomena in wurtzite nitrides including recent pressure studies of cubic InGaIn structures.

T-13 15h30

**Wishful physics: some common misconceptions about InGaIn**

K.P.O'DONNELL, R.W. MARTIN, P.R. EDWARDS, S. PEREIRA AND M.E. WHITE  
*Department of Physics and Applied Physics, University of Strathclyde, John Anderson Building, 107 Rottenrow East, Glasgow G4 0NG, Scotland UK*  
[k.p.odonnell@strath.ac.uk](mailto:k.p.odonnell@strath.ac.uk)

In the development of new areas of technology, misconceptions demarcate a boundary between two contrasting realms of activity. While scientists seek insight and understanding by finding problems, technologists look for solutions that offer new functionality and marketing opportunities. A dividing line is set between what we want to know and what we need to know: along this line, misconceptions take root.

All III-N visible light emitters contain ultrathin active layers of InGaIn. Although the material has been widely and deeply studied during the last ten years or so, opinion is divided as to its nature. Most would agree with the proposition that nitrides are a mess, when we consider the crystalline perfection and structural regularity that is routinely obtained in III-As growth. It may then be argued that the quality of InGaIn samples is too variable to allow general statements about the nature of the material. This is misconception number one. The similarities between luminescent InGaIn samples from different laboratories outweigh the differences. Any differences that occur can be confidently accounted for, in terms of growth parameters. We conclude that InGaIn is not

messy because the growth is messy: it is just messy.

The second misconception is that InGaN can be described theoretically as an alloy. We have recently completed an in-depth study of the relationship between the luminescence spectrum and composition for InGaN epilayers, with unprecedented statistical rigour (>100 samples with InN fraction in the range [0,0.25]). These data show a complete absence of the alloy bowing which is predicted theoretically.

Thirdly, we consider the assertion that InGaN is a phase-segregated mixture of InN and GaN. This misconception is currently rife. Through a careful multidisciplinary study, double peaks in X-ray diffraction and photoluminescence are shown *not* to provide evidence for such segregation.

The fourth common misconception involves the comparison of studies of ultrathin layers, as used in devices, and the thick layers that provide sufficient material for accurate compositional and structural analysis. This matter will be discussed in relation to several recent contributions to the InGaN literature.

T-14 15h50

### The Anomalous Band Bowing in GaAsN

U. TISCH, E. FINKMAN, AND J. SALZMAN

*Department of Electrical Engineering, Technion, Haifa 32000, Israel*

The fundamental band gap of GaAsN has an anomalous composition dependence, because of the large difference of the As and N atoms in size and atomic orbital energies. The underlying physical cause, whether two level anti-crossing, N impurity band formation within the band gap, or intra-band mixing within the conduction band and interaction with N-cluster-states, is still controversial. To complicate matters, there is still a lack of reliable experimental data, despite many previous studies, because:

- a) Only dilute alloys, either As or N-rich, can be realized, due to a large miscibility gap;
- b) Most previous studies contain few samples and the reported experimental data scatters considerably, due to varying material quality and inconsistent experimental methods. In this work we study the composition dependence of the fundamental band gap of thin, pseudomorphic GaAs<sub>1-x</sub>N<sub>x</sub> layers (0<x<5%) on GaAs substrates. We use the most extensive set of samples presented so far, of 36 GaAsN layers, produced and analyzed under comparable conditions. Composition and strain of the layers are determined by high-resolution x-ray diffraction (both symmetric (004) and asymmetric (115) rocking curves). E<sub>g</sub> is determined by optical transmission. The measured band gaps versus N molar fraction are shown in fig. 1(a). As we have obtained a large number of experimental values with little scatter, it is clear that E<sub>g</sub> decreases with increasing N molar fraction in a non-linear fashion. E<sub>g</sub> of a conventional ternary III-V alloy is well represented by:

$$E_g(A_xB_{1-x}) = xE_g^A + (1-x)E_g^B - bx(1-x) \quad (1)$$

The bowing parameter, *b*, is typically a small constant. In GaAsN, however, we found that *b* is very large for dilute alloys (where the values of *b* reach 40 eV) and that it decreases strongly with increasing N molar fraction (Fig. 1(b)). We obtained an empirical double exponential composition dependence of the bowing parameter that fits the experimental results well. For N molar fractions above 8%, the bowing parameter is extrapolated to a constant value of 7.5 eV. This indicates that three different physical mechanisms control the gap behavior. The first dominates in the dilute range, below 0.6%, the second in an intermediate range, which seems to extend up to ~ 8%, and alloy behavior is expected at larger compositions. The present work seems to confirm the presence of three N regimes: Impurity region, where cluster states form within the band gap,

intermediate amalgamation region, where the cluster states are within the conduction band and strongly interact with the conduction band states, and the alloy region, where the cluster states are far above the conduction band minimum [P. R. C. Kent and A. Zunger, PRB 64, 115208 (2001)].

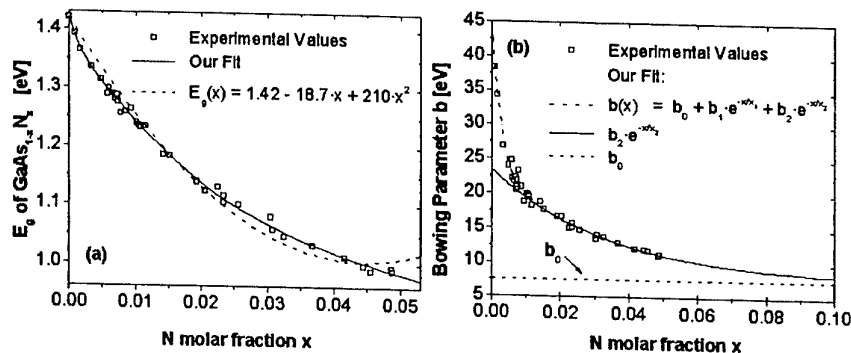


Fig. 1: (a)  $E_g$  of  $\text{GaAs}_{1-x}\text{N}_x$  ( $0 < x < 5\%$ ) on GaAs substrates: Our experimental results (symbols), and interpolation (full line) and for comparison a less accurate quadratic interpolation (dashed line). (b) Bowing parameter, determined from the measured band gaps (symbols), and the exponential interpolation (line).

T-15 16h10 Invited **Energy Gap and Optical Properties of  $\text{In}_x\text{Ga}_{1-x}\text{N}$**

F. BECHSTEDT

Friedrich-Schiller-Universität Jena, Institut für Festkörpertheorie und Theoretische Optik, Max-Wien-Platz 1, 07743 Jena, Germany, email: [bechstedt@ifto.physik.uni-jena.de](mailto:bechstedt@ifto.physik.uni-jena.de)

The recent developments in blue-green optoelectronics are essentially due to the high efficiency of luminescence from  $\text{In}_x\text{Ga}_{1-x}\text{N}/\text{GaN}$  heterostructures with  $x < 0.2$ . Despite of its importance several properties of  $\text{In}_x\text{Ga}_{1-x}\text{N}$  alloys are not fully understood, in particular for more In-rich systems with  $x > 0.2$ . Among them are the optical transition energies, their composition dependence, and the strain influence on this composition dependence. The presented study of alloy properties is based on first-principles calculations within the density functional theory (DFT) and the local density approximation (LDA). They are combined with quasiparticle shifts to account for the excitation aspect or a cluster-expansion method to describe the alloy character. The results are compared with recent photoluminescence, absorption and X-ray diffraction measurements.

A key quantity is the fundamental band gap of InN. We calculate quasiparticle gaps of 0.52 (1.31) eV for zinc-blende InN and 0.74 (1.50) eV for the wurtzite structure in dependence of the treatment of the In4d electrons. The value, where the  $pd$  repulsion is overestimated, is smaller by 0.8 eV than the value (in parenthesis) for which the  $pd$  repulsion is neglected. The values 0.8 and 1.0 eV with a reasonable amount of the  $pd$  repulsion are much smaller than the 1.9 eV-gap value accepted commonly for nanocrystalline hexagonal InN. Our calculations are however in agreement with recent photoluminescence measurements on high-quality MBE samples [1]. The calculated absorption coefficient shows an exceptional step-like behaviour above the absorption edge. This and the shape of the critical-point structures agree well with spectra obtained by ellipsometry [2].

We derive an unusual S-like-shape behaviour of the average gap of  $\text{In}_x\text{Ga}_{1-x}\text{N}$  versus composition. The bowing parameter depends strongly on the composition. It decreases with increasing In molar fraction from 2.4 to 1.2 eV [3]. A discussion of the three contributions indicates that the dominant contribution to the gap bowing is due to the composition-induced disorder in the bond length.

The seeming disagreement with experimental results for the bowing is discussed. We also discuss the gap variations due to composition fluctuations. Together with gap variations due to phase-separation effects they may explain the observed huge Stokes shifts.

The spinodal decomposition of the alloy can lead to the formation of quantum dots and, hence, modify its optical properties. The tendency for phase separation is remarkably influenced by the strain stage of the  $\text{In}_x\text{Ga}_{1-x}\text{N}$  layers. Allowing a complete adaption of average lattice constant parallel to the growth axis, we show for pseudomorphically grown layers that the phase separation is not complete. This is contrast to the generally accepted suppression of phase separation by strain [4].

[1] V.Y. DAVYDOV ET AL., *phys. stat. sol. (b)* **229**, R1 (2002).

[2] R. GOLDHAHN ET AL., unpublished.

[3] M. FERHAT, F. BECHSTEDT, *Phys. Rev. B* **65**, 075213 (2002).

[4] A. TABATA ET AL., *Appl. Phys. Lett.* **80**, 769 (2002).

16h40

*Coffee Break*

T-16 17h10 Invited **GaN-based Schottky Barrier Photodetectors from near Ultraviolet to Vacuum Ultraviolet (360 - 50nm)**

K. HIRAMATSU AND A. MOTOGAITO

*Department of Electrical and Electronic Engineering, Mie University, 1515 Kamihama, Tsu, Mie 514-8507, Japan*

*e-mail: [hiramatu@elec.mie-u.ac.jp](mailto:hiramatu@elec.mie-u.ac.jp)*

Characterization of Schottky type ultraviolet (UV) photodetectors with transparent electrode from near ultraviolet to vacuum ultraviolet (VUV) using synchrotron radiation is described. The responsivity of the detectors is about 0.15 A/W at 360 nm and is about 0.01 A/W in the VUV region. These detectors are effective to detect UV light from near UV to VUV without any photoemission.

Ultraviolet (UV) detectors are one of the most attractive devices in the group III-nitride semiconductors. Recently, Si-based photodetectors are mainly used for the measurement of UV light. However, light sensitivity often deteriorates due to radiation damage in the vacuum ultraviolet (VUV) region (50 - 200 nm). Several groups have reported on GaN or AlGaN based UV detectors [1]. They have responsivity from 200 to 360 nm and clear cut-off characteristics at a cut-off wavelength (360 nm). We had already reported on the responsivity spectra of Schottky type UV detectors with a comb-shaped electrode in the VUV region, however photoemission of GaN causes at shorter than 130 nm [2].

Characterization of the responsivity spectra of Schottky type UV detectors with transparent electrode was carried out at UVSOR Beam Line 7B (BL7B) in Institute of Molecular Science, Japan. The transparent electrode was fabricated on i-GaN with a composed of 10-nm-thick-Au and 1-nm-thick-Ni. The diameter of the detector was 6.5 mm. The transmittance of the electrode was approximately 0.4.

The responsivity spectra of the detectors with zero bias were obtained in the wide range between 563 nm and 50 nm. No responsivity was observed in visible region (360<math>\lambda</math>563 nm). Furthermore, the photoemission current from Au electrode could be canceled by improving the measuring circuit, and thus we succeeded in operating the detectors without any photoemission current from Au and GaN.

[1] E. MUNOZ ET AL.: *J. Phys.: Condens. Matter*, **13**, pp.7115-7137 (2001).

[2] A. MOTOGAITO ET AL.: *Japan. J. Appl*

T-17 17h40 Invited **Microstructure and the Optical Properties of  $\text{In}_x\text{Ga}_{1-x}\text{N}$  and  $\text{Al}_x\text{Ga}_{1-x}\text{N}$  Alloys**

F. A. PONCE

*Department of Physics and Astronomy, Arizona State University, Tempe, Arizona, USA*

The ternary nitride semiconductors are currently an important challenge from the point of view of crystal growth, physics, and engineering. High quality GaN epitaxial layers are currently achieved using a variety of growth techniques. While large densities of dislocations are typically observed, several techniques for minimizing their effect have been engineered, such as the various lateral epitaxial overgrowth methods. The growth of alloys is highly desirable for device fabrication.  $\text{In}_x\text{Ga}_{1-x}\text{N}$  alloys are typically used in the active region of light-emitting devices and laser diodes, while  $\text{Al}_x\text{Ga}_{1-x}\text{N}$  alloys are used as cladding layers for optical confinement in laser diode structures. The growth of these alloys has been challenging, and the difficulty in producing uniform films is currently a significant barrier in the development of blue, green and UV laser diodes, and highly monochromatic, high efficiency light emitting devices. This talk will review the issues related to the role microstructure plays in determining the microscopic properties of these alloys.

T-18 18h10

**Disorder-induced modification of the transmission of light in two dimensional photonic crystal**

M. A. KALITSEVSKI, J. MANZANARES MARTINEZ, D. CASSAGNE, J.P. ALBERT

*Groupe d'Etude des Semiconducteurs, Université Montpellier II, Place Bataillon, 34095, France*

Photonic crystals (PCs) have attracted considerable interest for their ability to confine, manipulate or guide light and also for their potential to inhibit spontaneous emission. One of the main technological problems which prevent the use of photonic crystals is the occurrence of *disorder*. The presence of defects in the crystalline photonic lattice can then damage the photonic band gap (PBG), by filling it with localized photonic states and decrease an attenuation of light in the frequency region corresponding to the PBG. For the one-dimensional case, it is known that a certain critical threshold "amount of disorder" is required for the damaging of the dip [1]. A natural question is: will the same behavior be observed in the case of 2D systems? In the 2D case, the properties of the PC along the different directions of light propagation can differ substantially. The subject of our study is the case of a PBG that exists only for certain particular directions, so-called incomplete PBG.

In experimental studies, there are two main schemes which analyze either *ballistic* transmission (when the transmitted wave has the same direction of propagation as incident light) or total transmission (all the waves, emerging from the rear side of the sample, which include *ballistic* and *scattered* waves, for which direction of the propagation differs from the direction of the incident light).

We have calculated the light transmission through the supercell of 323 cylinders for , for various "amount of the disorder", described by a deviation  $\delta$  in the cylinder radius, which is uniformly distributed in the interval from  $r_0(1-\delta)$  to  $r_0(1+\delta)$ . The insertion of the disorder into the PC leads to substantial modifications of the transmission spectra. In the case of a single configuration of disorder small peaks disrupt the transmission dip of the *ballistic* light. These spikes are associated to photonic states localized in the direction of the light propagation. Further more, in contrast to the case of the ideal structure, scattered light appears, and the transmission dip for the scattered light has an asymmetric shape, with the minimum shifted towards the high frequency edge of the PBG. It is worth noting that the scattered transmission is more than 10 times as large as than the ballistic one, so its effect will be largely dominant in the total

transmission. The spectra, averaged over different configuration of disorder shows quite different behaviour for the *ballistic* and *scattered* light. For the latter, the spectra have triangle dip with the minimum shifted towards edge of PBG. This effect can be described in simple physical terms of scattering of light from evanescent mode into passing mode. Hence, the minimum of the total transmission does not necessary correspond to the center of the PBG. This effect can lead to an error in the positioning of incomplete PBGs when assigning the gap center to the minimum of transmission as is usually done in transmission studies.

For the scattered light, attenuation decreases dramatically with insertion of the even very small disorder. On the contrary, increase of the ballistic transmission is more tolerant to disorder since it has a threshold like behavior as a function of disorder and then sustains a certain amount of disorder before changing (note that for the ballistic transmission, in the case of  $\delta = 0.05$  transmission spectra for the disordered and ideal structures almost coincide). This indicates that certain small degree of disorder does not damage the PBG in the 2D PC.

[1] YU. A. VLASOV, M.A. KALITEEVSKI, AND V.V. NIKOLAEV, *Phys. Rev. B*. **60**, 1555 (1999)

20h00

**DINNER**

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- W-1 9h00 Invited **High-Performance AlGaIn/GaN Solar-Blind Detectors grown by Metalorganic Chemical Vapor Deposition**  
R. D. DUPUIS<sup>1</sup>; U. CHOWDHURY<sup>1</sup>; C. J. COLLINS<sup>1</sup>, M. M. WONG<sup>1</sup>; B. YANG, J. C. DENYSZYN<sup>1</sup>; AND J. C. CAMPBELL<sup>1</sup>

<sup>1</sup>The University of Texas at Austin, Microelectronics Research Center, 10100 Burnet Road, Building 160, Austin, TX 78758 USA

Phone: +1-512-471-0537, e-mail: [dupuis@mail.utexas.edu](mailto:dupuis@mail.utexas.edu)

Photodetectors having a photoresponse only in the wavelength range between 250 and 300 nm, referred to as the solar-blind regime, can be used for applications such as missile detection and tracking and for biological agent and chemical detection. We report the growth, fabrication and characterization of high-quality AlGaIn/GaN solar-blind PIN photodetectors by low-pressure metalorganic chemical vapor deposition (MOCVD) with trimethylgallium (TMGa), trimethylaluminum (TMAI), bis (cyclopentadienyl) magnesium (Cp<sub>2</sub>Mg), silane (SiH<sub>4</sub>), and ammonia (NH<sub>3</sub>) precursors. The epitaxial films were studied using X-ray diffraction, secondary ion mass spectroscopy, atomic force microscopy, and cathodoluminescence at both room temperature and 4K. We studied the correlation of the symmetric and asymmetric X-ray diffraction linewidths, surface morphology, and the thickness of the absorption layer and of the window layer on the dark current, white light photoresponse and ultraviolet photoresponse. The epitaxial layers were grown on double-polished c-plane (0001) sapphire substrates to allow for back-side illumination. The PIN photodiode structures typically consist of a 0.8 μm-thick Al<sub>0.60</sub>Ga<sub>0.40</sub>N "window" layer, graded to a 0.2 μm-thick Al<sub>0.45</sub>Ga<sub>0.55</sub>N N layer, a 0.15 μm-thick Al<sub>0.30</sub>Ga<sub>0.70</sub>N I layer, a 0.2 μm-thick Al<sub>0.45</sub>Ga<sub>0.55</sub>N P layer, and capped with a 25 nm GaN:Mg contact layer. At a 0V bias, the processed PIN devices exhibit a solar-blind photoresponse having a maximum responsivity of 0.1 A/W at 270 nm, corresponding to an external quantum efficiency of  $\eta_{ext} \sim 58\%$ , uncorrected for reflections, etc. This is the highest quantum efficiency yet reported for solar-blind photodetectors. The noise characteristics and speed of response for these devices are also excellent. These devices exhibit high values of detectivity ( $D^* \sim 3.5 \times 10^{14} \text{ cm-Hz}^{1/2} \text{ W}^{-1}$ ) and are suitable for the fabrication of back-illuminated solar-blind imaging photodetector arrays.

- W-2 9h30 Invited  
L. HIRSCH

- W-3 10h00 Invited **GaN-based electronics and opto-electronics in production scale MOCVD systems**

M. HEUKEN

AIXTRON AG, Kackertstr. 15-17, D-52072 Aachen, Germany

e-mail: [m.heuken@aixtron.com](mailto:m.heuken@aixtron.com), phone: +49-241-8909-154

The recent years have seen a continuous transfer of exciting new technologies from basic research institutions to high yield mass production into our everyday lives. Devices made from novel GaN-based semiconductor compounds will be found in products ranging from consumer electronics to high speed backbone communication networks and wireless telecom base stations as well as high temperature and high power applications in the automotive and aerospace industry. Optoelectronic devices include high brightness UV, blue and green light emitting diodes for display and lighting applications.

We investigated the growth of electronic and optoelectronic GaN-based structures in AIXTRON MOCVD reactors ranging from small scale AIX 200 RF systems to large production scale planetary reactors such as the AIX 2600 G3 HT in the 8 x 4 and 24 x 2 inch configurations. In addition to standard sapphire substrates the growth on alternative substrates such as Si was investigated using

novel strain reducing concepts like the double nucleation method.

All types of structures were characterized with respect to room-temperature electro- and photoluminescence (RT-EL, PL) intensity, wavelength and luminescence halfwidth under low levels of continuous wave (CW) HeCd laser and high levels of pulsed N<sub>2</sub> laser excitation. Optically pumped laser samples were created and investigated at room temperature (RT). RT optically pumped lasing was achieved with a relatively low threshold of about 50 kW/cm<sup>2</sup> (λ = 470 nm, T<sub>0</sub> = 530 K). The lasing mechanism at λ = 470 nm will be discussed.

The RT-PL peak at low excitation intensity with a wavelength of 468.7 nm exhibits an extremely narrow full width at half maximum of only 11.5 nm, indicating little alloy broadening in the InGaN QWs. This data can be reproduced on all wafers of a fully loaded 24x2 inch run. At a mean wavelength of λ = 471.7 nm for all wafers of the run a wavelength standard deviation of only σ<sub>w2w</sub> = 1.5 nm and a maximum-minimum spread of Δ<sub>w2w</sub> = 4.9 nm was found. The reproducibility of these results could be confirmed over a sequence of up to 10 consecutive runs with the same growth recipe.

In addition, transistor structures were processed into devices with gate lengths of 0.7 and 0.5 μm, respectively. A unity gain frequency of 20 and 32 GHz and a maximum frequency of oscillation of 22 and 27 GHz were obtained, respectively. In a mass production environment the uniformity and reproducibility of the growth process is directly related to the yield of the device fabrication. Hence, the stability of the growth process and the growth system must be proven. Doping levels of up to 6.5x10<sup>18</sup> cm<sup>-3</sup> and electron mobilities of around 200 cm<sup>2</sup>/Vs were achieved. The uniformity of the doping exhibited a standard deviation of the sheet resistance as low as 0.67% over the whole 2 inch wafer without edge exclusion.

Add-ons like in-situ monitoring of the growth process by reflectometry (Filmetrics<sup>®</sup>) help in a considerable reduction of the development time and costs, hence improving innovation cycles and the time-to-market of novel devices since the growth of the material can be monitored in real time.

10h30

### Coffee Break

W-4 11h00

### Photoluminescence of n-doped InGaN/GaN and AlGaIn/GaN Multiple Quantum Well structures, role of depletion fields and polarization fields

B. MONEMAR<sup>(a)</sup>, P P PASKOV<sup>(a)</sup>, G POZINA<sup>(a)</sup>, J P BERGMAN<sup>(a)</sup>, S KAMIYAMA<sup>(b)</sup>, M IWAYA<sup>(b)</sup>, H AMANO<sup>(b)</sup>, I AKASAKI<sup>(b)</sup>

<sup>(a)</sup> Dpt. of Physics and Measurement Technology, Linköping University S-581 83 Linköping, Sweden

<sup>(b)</sup> Dpt. of Electrical Engineering and Electronics and High-Tech Research Center, Meijo University, 1-501 Shiogamaguchi, Tempaku-ku, Nagoya 468, Japan

Tel: +46-13-281765, e-mail: [bom@ifm.liu.se](mailto:bom@ifm.liu.se)

We report on a detailed study of low temperature photoluminescence (PL) in In<sub>x</sub>Ga<sub>1-x</sub>N multiple quantum wells (MQWs) with x in the range 0.1, and with highly Si doped barriers of In<sub>0.01</sub>Ga<sub>0.99</sub>N. The entire MQW structure was grown at 800 C. One sample with 3 QWs of width 3.5 nm and barriers of width 10.5 nm had the MQW placed in the depletion region related to the outer surface. Two PL peaks were observed at 2 K, one at higher energy (Q1) explained as a QW exciton from the QW closest to the GaN buffer, one lower energy peak (Q2) related to a 2DEG at the interface to the GaN buffer layer. The electron pocket carrying the 2DEG may be largely induced by the optical excitation. The linewidth of the Q1 peak is about 40 meV, as expected for a single QW in this materials system. The two QWs closer to the surface are not active in PL,

presumably due to a strong depletion field at the position of these QWs. In a second similar sample 5 QWs of width 3 nm and with 6 nm highly Si doped  $\text{In}_{0.01}\text{Ga}_{0.99}\text{N}$  barriers the MQW was placed in the n-side depletion region of a pn-junction, i.e. a complete LED structure with semitransparent top metallisation. Two PL peaks are observed also in this case at low temperatures (2 K), of similar origin as described above. A third peak is discovered in the temperature dependent spectra. This means that not more than two QWs appear to be active at no forward bias. A reverse bias only moderately decreases the intensity of these PL emissions. With increasing forward bias this structure gradually develops lower energy PL emission peaks, indicating the activation of the other QWs closer to the pn-junction as the depletion fields becomes smaller. The difference in photon energy between the QW closest to the buffer layer (about 3.1 eV) and the one closest to the pn-junction (about 2.95 eV) is about 0.15 eV at low temperature. This difference is mainly attributed to different screening of the piezoelectric field in the different QWs under conditions when the depletion field has been decreased under forward bias, a conclusion supported by the transient PL data. At high forward bias the low energy part of the PL spectrum becomes similar to the electroluminescence (EL) spectrum. At room temperature the PL and EL spectra are quite similar.

Preliminary results from similar work on AlGaN/GaN MQWs with 5 QWs will also be presented. These samples are also highly Si doped, in most cases in the barriers. Both near surface structures and pn-junction structures are studied. Clearly effects of the depletion field are strong in these cases as well.

W-5 11h20

A. HOFFMAN

11h40

**CLOSING SESSION**

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12h00

**LUNCH AND EXCURSION TO HERAKLION**

20h00

**BANQUET DINNER**

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