Novel Gain Materials and Devices Based on III-V-N/Bi Compounds

24-26 SEPTEMBER 2013

ISTANBUL, TURKEY

ABSTRACT BOOK

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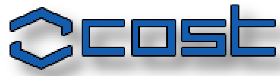

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Helene Carrere
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Eli Kapon
EPFL Lausanne

Janne Konttinen
EpiCrystals, Inc., Finland

Peter Ludewig
Philipps-Universität, Germany

Eoin O'Reilly
Tyndall National Institute, Ireland

Stefano Sanguinetti
University of Milano-Bicocca, Italy

PROGRAM

24 SEPTEMBER 2013 TUESDAY	
09:00 - 10:15	Registration
10:15 -10:30	Welcome remarks **A. Erol**
SESSION I -DILUTE NITRIDES I 10:30-12:20 **CHAIR: N. BALKAN**	
10:30 - 11:00	*Low-Dimensional Dilute Nitride InGaAsN/GaAs Heterostructures* **E. Kapon**, R. Carron, A. Surrente, P. Gallo, B. Dwir and A. Rudra
11:00 - 11:20	*Strain engineering of dilute nitrides via spatially selective hydrogenation* **M. Felici** , S. Birindelli, R. Trotta, A. Notargiacomo, A. Gerardino, S. Rubini, F. Martelli, A. Polimeni, M. Capizzi
11:20- 11:40	*Single photon emission from site-controlled Ga(AsN) quantum dots* **S. Birindelli** , M. Felici, R. Trotta, J. Wildmann, A. Gerardino, S. Rubini, F. Martelli, A. Polimeni, M. Capizzi
11:40- 12:00	*Carrier dynamics in dilute nitrides: Experimental study versus Monte-Carlo simulations* **R. Kudrawiec**, M. Baranowski, M. Latkowska, M. Syperek, and J. Misiewicz
12:00-12:20	*Self -Consistent Green's Function Method for Band Structure, Scattering and Carrier Mobility in Dilute Nitride Alloys* **M. Seifikar** , S. Fahy , E. P. O'Reilly
12:20- 14:30	**LUNCH BREAK**
SESSION II -DILUTE NITRIDES II 14:30-16:40 **CHAIR: C. FONTAINE**	
14:30 - 15:00	*Frequency-converted dilute nitride laser diodes for mobile display applications* **J. Konttinen**
15:00 - 15:20	*Room temperature luminescence beyond 1.3 µm from GaAsSbN-capped InAs quantum dots* **A.D. Utrilla** , J.M. Ulloa, L. Domínguez, D.F. Reyes, D. González, A. Guzman, A. Hierro
15:20 - 15:40	*Hydrogen irradiation of In(AsN)* S. Birindelli, L. Qi, M. Kesaria, Q.D. Zhuang, A. Krier, A. Patanè, A. Polimeni, **M. Capizzi**
15:40 - 16:00	$Ga_{0.35}In_{0.65}N_{0.02}As_{0.08}$ */GaAs Bi-directional Light Emitting and Absorbing Heterojunction operating at 1.3 µm* **F. A. I. Chaqmaqchee** , Naci Balkan
16:00 – 16:20	*GaInNAsSb Solar Cells Grown by MBE* **A. Aho** , A. Tukiainen, V. Polojärvi, W. Zhang, J. Salmi, M. Guina
16:20 – 16:40	*Strain-engineered InAs/Ga(In)NAs/GaAs quantum dot solar cells* **E. Pavelescu**, V. Polojärvi, A. Aho, A. Tukiainen, A. Schramm, W. Zhang, J. Salmi, M. Guina
16:40 – 17:00	**BREAK**

SESSION III - InGaN & GaN 17:00-18:00 **CHAIR: E. TIRAS**	
17:00 – 17:20	*Molecular Beam Epitaxy of Single Phase InGaN Films in the Entire Alloy Composition Range for Photovoltaic Applications* E. Papadomanolaki, M. Androulidaki, K. Tsagaraki, C. Bazioti, Th. Kehagias, G. Dimitrakopulos, **E. Iliopoulos**
17:20 – 17:40	*InGaN MQW photoluminescence enhancement by localized surface plasmons in isolated Ag nanoparticles* **G. Tamulaitis** , D. Dobrovolskas, J. Mickevicius, C.-W. Huang, C.-Y. Chen, C.-H. Liao, C. Hsieh, Y.-L. Jung, and C.C. Yang
17:40 – 18:00	*Chemical Synthesis and Characterization of GaN Quantum Dots Incorporated in Simple Photonic Devices* **M. Vasileiadis** , I. Koutselas, D. Alexandropoulos, N. Kehagias, K. Dimos, M. Karakassides, L'uboš Jankovic, R. Zboril, Peter Komadel, N. Vainos
POSTER PRESENTATIONS 18:00-20:00 *Beverages and Snacks will be served during the session*	

25 SEPTEMBER 2013 WEDNESDAY

SESSION IV - III-V on Silicon & Bismide alloys I 09:00-10:20 **CHAIR: M. HOPKINSON**	
09:00 - 09:30	*3D heteroepitaxy of Ge and GaAs on patterned Si substrates: a new monolithic integration strategy* **S. Sanguinetti,** R. Bergamaschini, S. Bietti, F. Isa, G. Isella, A. Marzegalli, F. Montalenti, F. Pezzoli, A. Scaccabarozzi, C. V. Falub, H. von Känel, L. Miglio
09:30 - 09:50	*Bi-assisted nucleation of GaAs grown on silicon by molecular beam epitaxy* P. Boonpeng, H. Makhloufi, G. Lacoste, A.Arnoult, **C.Fontaine**
09:50 - 10:20	*Valence band structure of dilute bismide alloys for optoelectronic device applications* **Eoin P. O'Reilly**, C. Broderick, P. Harnedy, M. Usman
10:20 - 11:00	**BREAK**
SESSION V- BISMIDE ALLOYS II 11:00-12:30 **CHAIR: C. ARIKAN**	
11:00- 11:30	*Optical and spin properties of GaAsBi epilayers* S. Mazzucato, H. Lehec, **H. Carrere**, T. T. Zhang, D. Lagarde, P. Boonpeng, A. Arnoult, G. Lacoste, A. Balocchi, T. Amand, C. Fontaine, and X. Marie
11:30 -11:50	*Morphological instabilities in GaAs1-xBix layers grown by molecular beam epitaxy* **E. Luna** , M. Wu, J. Puustinen and M. Guina
11:50 -12:10	*Formation and phase transformation of Bi-containing clusters in annealed GaAs1-xBix epilayers* **M. Wu**, E. Luna, J. Puustinen, M. Guina and A. Trampert
12:10 -12:30	*Analysis of bismuth distribution in GaAsBi/GaAs layers: segregation and CuPtB atomic ordering* **D.F. Reyes,** F. Bastiman, A.R. Mohmad, D.L. Sales, R. Beanland, A.M. Sanchez, J.P.R David, D. González
12:30-14:30	**LUNCH BREAK**

SESSION VI -BISMIDE ALLOYS III 14:30-16:20 CHAIR: A. POLIMENI	
14:30 -14:50	*Optical characterization of bulk GaBixAs1-x and GaAs/GaBixAs1-x quantum well structures* **O. Donmez** , A. Erol, E. Akalin, M. C. Arikan, C. Fontaine
14:50 - 15:10	*Structural an optical properties of GaAs1–xBix quantum wells grown by molecular beam epitaxy – Effect of rapid thermal annealing* **H.Makhloufi** , P. Boonpeng, S. Mazzucato, H. Carrère, J. Nicolai, G. Lacoste, A. Arnoult, X. Marie, A. Ponchet and C. Fontaine
15:10 - 15:30	*Effect of hydrogen on the electronic properties of Ga(AsBi) alloys* **G. Pettinari** , A. Patanè, A. Polimeni, M. Capizzi, Xianfeng Lu, T. Tiedje
15:30 - 15:50	*Structural and optical characterizations of InPBi thin films grown by molecular beam epitaxy* Y. Gu, K. Wang, H. F. Zhou, Y. Y. Li, C. F. Cao, L. Y. Zhang, Y. G. Zhang, Q. Gong, **S.M. Wang**
15:50 - 16:20	*MOVPE growth of Ga(AsBi)/(AlGa)As heterostructures and laser diodes* **P. Ludewig**, N. Knaub, Z. Bushell, L. Nattermann, S. Chatterjee, W. Stolz, and K. Volz
16:30 – 18:15	**FREE TIME** (Beyazıt Tower and Botanical Garden are availabel to visit for the participants)
19:30 - 23:00	**DINNER & BOSPHORUS BOAT TOUR**

26 SEPTEMBER 2013 THURSDAY

MP0805 ACTION FINAL ASSESMENT 08:30-12:30

08:30-09:00 *1. COST Presentation*
M. Moragues

09:00-09:15 *2. Overview of Action's MoU and the main results*
M. Guina

- Summary of training events
- Summary of STSMs and Publications
- Gender Issues

09:15-10:15 *Presentations of WG Leaders – Results of the actions*

M. Hopkinson (WG1),
R. Kudrawiec (WG2),
D. Alexandropoulos (WG3),
X. Marie (WG4)

(10 minutes overview + 5 minutes questions for each WG)

10:15-10:30 *4. Other Presentations*
M. Guina

MP0805 results – path to commercialization success stories

10:30 - 11:00 BREAK

11:00 -12:30 *Discussion between evaluation panel*

(DC Rapporteur, External Expert 1, External Expert 2 and So) and the Chair of the Action and Grant Holder Scientific Representative)

Attended by the MC members, the external Evaluators and the COST Office representatives. Financial report from the COST Office, comments and questions from the DC Rapporteur and the external Evaluators, general discussion, future plans including final reporting requirements and deadlines.

12:30 *End of the meeting*

POSTER PRESENTATIONS

P1	*Effect of Gamma Irradiation on deep levels detected by DLTS in GaAsxN1-x with different Nitrogen concentration* **N. Al Saqri** , M. Aziz , J. F. Felix, D. L. da Cunha , R. H. Mari , D. Jameel , W. M. de Azevedo, E.F. da Silva jr, D. Taylor , M. Henini
P2	*Trapping and escape time in p-i-n GaInNAs/GaAs multiple quantum wells structures* **H. M. Khalil**, S. Mazzucato, N. Balkan
P3	*Effect of Post Growth Thermal Annealing on Deep Level Defects in MBE Grown Dilute Nitride Ga1-xInxNyAs1-y p-i-n Structures* **D.A. Jameel**, M. Aziz, R. H. Mar, J. Francisco Felix, N. Al saqri, S. Tan, D. Taylor, M. Henini
P4	*Optical and Magneto-Optical Properties of GaAsBi Layers Grown by Molecular Beam Epitaxy* H.V.A. Galeti, Y. Galvão Gobato, V. Orsi Gordo, M.P.F. de Godoy, R. Kudraviec, O.M. Lemine, A.Alkaoud, **M. Henini**
P5	*Spin Effects in InGaAsN/GaAs Quantum Wells Grown by Molecular Beam Epitaxy* H.V.A. Galeti, Y. Galvão Gobato, M.P.F. de Godoy, V. Orsi Gordo, L. Kiyoshi Sato de Herval, A. Khatab, **M. Henini**, O.M. Lemine, M. Sadeghi, S. Wang
P6	*Determination of the electron effective mass in AlInN/AlN/GaN heterostructures by using the quantum Hall effect measurements* **E. Tiras**, , S. Ardali , E. Arslan , E. Ozbay
P7	*Impact of the temperature on the performances of GaInNAs-based PBG waveguide modulators* ***G. Calò**, D. Alexandropoulos, V. Petruzzelli*
P8	*Experimental investigation and numerical modelling of photocurrent oscillations in GaInNAs/GaAs p-i-n photodiodes* B. Royall, **S. Mazzucato**, H. Khalil, A. Erol, Y. Ergun, M. Hugues, M. Guina, N. Balkan
P9	*Spectral Photoconductivity Studies on GaAs1-xBi x Epilayers* **M. Aslan**, V. Bahrami, T. Tiedje
P10	*Thermal annealing- and Nitrogen-induced effects on electronic transport in n-and p-type modulation doped GaInNAs/GaAs quantum well structures* O. Donmez, F. Sarcan, A. Erol, M. Gunes, **M. C. Arikan**, J. Puusitinen, M. Guina
P11	*Optical properties of GaBiAs ternary alloys* **F. Sarcan**, A. Erol, M. C. Arıkan, C. Fontaine
P12	*GaAsPN alloys for optoelectronics on Silicon* H. Carrere, A. Balocchi, **D. Lagarde**, T. Amand and X. Marie
P13	*High Field Hot Electron Energy Relaxation in InGaN/GaN Samples* **S. Mutlu** , S. Ardali , E. Tiras , N. Balkan
P14	*Identification of four-hydrogen complexes in In-rich InGaN alloys using Photoluminescence, x-ray absorption, and density functional theory* **M. De Luca**, G. Pettinari, G. Ciatto, L. Amidani, F. Filippone, A. Polimeni, F. Boscherini , A . Amore Bonapasta, M. Capizzi
P15	*Hot Electron Energy Relaxation in Al 0.83 In 0.17 N/AlN/GaN heterostructure* **S. Ardali**, S. Mutlu, E. Tiras , E. Arslan , E. Ozbay
P16	*Photoreflectance and photoluminescence studies of GaAsBi layers and quantum wells* **J. Kopaczek** , R. Kudrawiec , J. Misiewicz, F. Bastiman
P17	*Gain in electrically-driven 1.3 um dilute nitride VCSOAs* **S. B. Lisesivdin**, N. A. Khan , S. Mazzucato , N. Balkan, M. J. Adams

P18	*GaInNAsSb/GaAs semiconductor optical amplifiers and laser diodes* **V.M. Korpijärvi**, D. Fitsios, G. Giannoulis, J. Viheriälä, J. Mäkelä, A. Laakso, N. Iliadis, M. Spyropoulou, G.T. Kanellos, N. Pleros, M. Guina
P19	*Time-resolved photoluminescence study on GaNAsSb solar cells* **A. Gubanov**, V. Polojärvi, A. Aho, A. Tukiainen, W. Zhang, A. Schramm, M. Guina
P20	*Morphology and electronic properties of site-controlled InAs quantum dots* **T.V. Hakkarainen**, E. Luna, A. Schramm, J. Tommila, M. Guina
P21	*A study on negative differantial resistance in n- and p-type GaInNAs/GaAs QWs* **L.B. Buklu**, A. Erol, M.C. Arıkan, J. Puustinen, M. Guina
P22	*Performance Prediction of Quantum Dots Based Highly Resonant Optical Amplifiers* **M. Vasileiadis**, D. Alexandropoulos , C.(T) Politi, N. Vaino
P23	*Investigation of GaBiAs alloy using Raman spectroscopy* **E.Akalın**, A. Erol, F. Sarcan, M.C.Arıkan, C. Fontaine
P24	*Photoluminescence Redshift Relative to Photoabsorption in III-V-Nitride Structures* **R. Brazis**

ABSTRACTS

ORAL PRESENTATIONS

SESSION I -DILUTE NITRIDES I

24 SEPTEMBER 2013 TUESDAY

10:30-12:20

Low-Dimensional Dilute Nitride InGaAsN/GaAs Heterostructures

E. Kapon, R. Carron, A. Surrente, P. Gallo, B. Dwir and A. Rudra

Laboratory of Physics of Nanostructures
Ecole Polytechnique Fédérale de Lausanne
Switzerland

Low-dimensional dilute nitride systems such as InGaAsN/GaAs quantum wells (QWs), wires (QWRs) and dots (QDs) bring about an interesting regime in which quantum confinements by heterostructures and by atomic levels interplay. We investigated such low-dimensional, dilute alloy structures made by organometallic vapor phase epitaxy on patterned (100) and (111)B GaAs substrates. Dilute-nitride vicinal QWs, V-groove QWRs and pyramidal QDs show clear quantum confinement effects in photoluminescence (PL) spectra. However, whereas in the higher-dimensionality systems heterostructure confinement prevails, the dilute-nitride QDs are dominated by confinement around individual N atoms or clusters. Structural analysis of the 3D shape evolution of the pyramidal QD, based on atomic force microscopy and kinetic Monte Carlo simulations, reveals hexagonal dot symmetry for the base InGaAs/GaAs pyramidal QDs. Polarization-resolved PL spectroscopy permits the evaluation of the fine structure splitting and polarization state of the QD emission. Implications of the observed properties of the site-controlled QDs on their possible applications are discussed.

Strain engineering of dilute nitrides via spatially selective hydrogenation

M. Felici[1], S. Birindelli[1], R. Trotta[2], A. Notargiacomo[3],
A. Gerardino[3], S. Rubini[4], F. Martelli[4,5], A. Polimeni[1], M. Capizzi[1]

[1] *Physics Department, Sapienza University of Rome, Italy*
[2] *Institute of Semiconductor and Solid State Physics, Johannes Kepler University Linz, Austria*
[3] *Institute for Photonics and Nanotechnologies, IFN-CNR, Rome, Italy*
[4] *TASC-IOM-CNR, Area Science Park, Trieste, Italy*
[5] *IMM-CNR, Rome, Italy*

Defect engineering via spatially selective hydrogenation of dilute nitrides allows for modulating the electronic and structural properties of the host material *in the growth plane* [1]. In the present work, the surface of a $GaAs_{1-x}N_x$ (x=0.8%) epilayer (thickness=300 nm) was lithographically patterned with H-opaque Ti wires (width w=500nm), oriented at different angles (0°, 22°, 45°, 67°, and 90°) with respect to the [110] crystallographic direction. Following H irradiation, the creation of an *anisotropic strain field* in the plane of the epilayer —due to the lattice expansion of the fully hydrogenated barriers surrounding the GaAsN wires— results in a high degree of polarization of the light emitted by single wires. Polarization-resolved micro-photoluminescence measurements reveal *a non-trivial dependence* of the polarization degree and of the polarization angle on the wire orientation, as theoretically calculated. By allowing for a careful tailoring of the strain fields present in the material, this technique could be useful for the realization of *X-ray optics applications* based on the enhanced translation experienced by X-ray beams when propagating through a deformed crystal (*Berry-phase effect*; see [2]).

[1] R. Trotta *et al*., Adv. Funct. Mater. **22**, 1782 (2012)
[2] Y. Kohmura *et al*., Phys. Rev. Lett. **110**, 057402 (2013)

Single photon emission from site-controlled Ga(AsN) quantum dots

S. Birindelli[1], M. Felici[1], R. Trotta[2], J. Wildmann[2], A. Gerardino[3], S. Rubini[4], F. Martelli[4], A. Polimeni[1], M. Capizzi[1]

[1]*Dipartimento di Fisica, Sapienza Università di Roma, Piazzale Aldo Moro 5, 00185 Roma, Italy*
[2]*Institute of Semiconductors and Solid State Physics, Johannes Kepler University, Altenbergerstr.69, A-4040 Linz, Austria*
[3] *Istituto di Fotonica e Nanotecnologie, IFN-CNR, Via Cineto Romano 42, 00156 Roma, Italy*
[4] *Laboratorio Nazionale TASC, INFM-CNR, S.S 14 Km 163.5, 34149 Trieste, Italy*

Hydrogen irradiation of dilute nitrides, such as Ga(AsN), allows tuning all electronic, optical, and structural properties of these materials in a fully controllable and reversible way, due to the formation of stable N-2H complexes [1]. Deposition of H-opaque Ti masks by electron beam lithography and subsequent hydrogenation offers the opportunity to modulate the physical properties of these materials in the growth plane. Given the extremely sharp H diffusion profile in dilute nitrides (a few nm/decade), spatially controlled hydrogenation can be achieved with nanometer resolution and site-controlled nanostructures with arbitrary shape and size can be realized.
Here we report the fabrication of ordered arrays of Ga(AsN) quantum dots, whose optical properties have been extensively investigated by means of micro-photoluminescence (PL) and photon correlation spectroscopy. Single dot spectra are fully characterized by power dependent micro-PL and emission lines originating from the recombination of excitons, biexcitons, and charged excitons are identified. Also, photon correlation measurements reveal a clear antibunching from the excitonic emission of a single quantum dot.

[1] R. Trotta *et al.*, Adv. Funct. Mater. **22**, 1782 (2012)

Carrier dynamics in dilute nitrides: Experimental study versus Monte-Carlo simulations

R. Kudrawiec, M. Baranowski, M. Latkowska, M. Syperek, and J. Misiewicz

Institute of Physics, Wroclaw University of Technology, Wybrzeze Wyspianskiego, 2750-370 Wroclaw, Poland

Incorporation of a small amount (a few percentage) of nitrogen atoms into Ga(In)As host strongly affects its band structure and optical properties including the optical quality. Usually nitrogen atoms deteriorate optical properties of Ga(In)As host and some characteristic features are observed for this material in photoluminescence (PL) and time resolved PL (TRPL) spectra at low temperatures. PL spectra are very broad, asymmetric, and the temperature dependence of PL peak energy exhibits a deviation from Varshni's formula, i.e., so called S-shape. In TRPL spectra a strong dependence of PL decay time on the emission energy is observed, i.e., the decay times are longer at low energies than at high energies. All these observations are related to carrier localization which is typical for disordered semiconductors such as dilute nitrides. To date the theoretical description of the PL decay dynamics in disordered semiconductor compounds was a subject of a few papers where analytic and numerical approaches to explain experimental data were presented and discussed. However these analysis narrow to low temperature regime (<10K) and assume that the population of photogenerated excitons is so low that states in the band tail of density of states can be treated as unoccupied. Such conditions are difficult to achieve in a typical time resolved PL experiment since the sample is excited by a pulse laser. In this work we show that the model of hopping excitons proposed by Baranovskii at al. [1] and modified by us [2] can be applied to simulate the dynamics of PL spectra for GaInNAs/GaAs QWs [3]. The introduced modifications enable us to take into account the impact of excitation power, temperature, and nonradiative recombination on the dynamic of PL spectra. Using this model we are able to explain all characteristic features observed in TRPL experiment for GaInNAs/GaAs QWs: the shape of PL decay

curve, the dispersion of PL decay times, and its changes with the temperature increase. The results of TRPL experiment can be easily simulated basing only on a few parameters taken from the time integrated PL spectra. In this work we will show a comparison of our simulations with experimental results as well as theoretical study of the impact of different parameters related to localizing states (i.e., their distribution, average energy, and density) on the carrier dynamics in GaInNAs QWs. It will be shown that the Monte-Carlo simulations can be very helpful in the interpretation of TRPL data and evaluation of the optical quality of investigated materials.

[1] S. D. Baranovskii, *et al.,* Phys. Rev. B **58**, 13081 (1998)
[2] M. Baranowski, *et al.,* J. Phys.: Condens. Matter **23** 205804 (2011).
[3] M. Baranowski, *et al.,* Gupta, Appl. Phys. Lett. **100**, 202105 (2012).

Self-Consistent Green's Function Method for Band Structure, Scattering and Carrier Mobility in Dilute Nitride Alloys

M. Seifikar, S. Fahy , E. P. O'Reilly

Tyndall National Institute, Lee Maltings, Dyke Parade, Cork, Ireland Department of Physics, University College Cork, Cork, Ireland

We have used a self-consistent Green's function (SCGF) approach for the Anderson many-impurity model to calculate the band dispersion and density of states near the conduction band edge in GaN_xAs_{1-x} dilute nitride alloys. Two different models of the localised nitrogen induced N-states have been studied to investigate the band structure of these materials: (1) the two-band model, which assumes all N-states have the same energy, E_N; (2) a model which includes a distribution of N-state energies obtained by allowing for direct interaction between N sites [2]. The density of states, calculated by the two-band model, are in excellent agreement with those previously obtained in supercell calculations [1] and reveal a gap in the density of states just above E_N, in contrast with the results of previous non-self-consistent Green's function calculations [3]. However, including the full distribution of N states destroys this gap, in agreement with experiment. We also investigate the band structure, scattering and mobility of carriers by finding the poles of the Green's function. This method leads to a lower calculated carrier mobility for GaN_xAs_{1-x} compared to previous approaches [4,5], in better agreement with experiments.

References:

[1] M. Seifikar, et al., Phys. Status Solidi B 248, 1176 (2011).
[2] A. Lindsay and E. P. O'Reilly, Phys. Rev. Lett. 93, 196402 (2004).
[3] M.P. Vaughan and B. K. Ridley, Phy. Rev. B 75(15), 195205, (2007).
[4] S. Fahy, et al., Phys. Rev. B 74, 035203 (2006).
[5] M. Seifikar, et al., Phys. Rev. B 84, 165216 (2011).

SESSION II -DILUTE NITRIDES II

24 SEPTEMBER 2013 TUESDAY

14:30-16:40

Frequency-converted Dilute Nitride Laser Giodes for Mobile Display Applications

J. Konttinen

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Red laser light sources in the wavelength range of ~620 nm are particularly interesting for mobile display applications due to increased luminous efficacy and higher achievable brightness within eye-safety regulations [1]. Unfortunately, this wavelength range is difficult to achieve by using traditional GaInP/AlGaInP red laser diodes [2]. Another, well-known drawback of GaInP/AlGaInP diodes is the reduction of characteristic temperature of threshold current (T0) with wavelength. High T0 values have been demonstrated with red laser diodes emitting at >650 nm wavelength [3] while shorter wavelength diodes suffer from poor temperature characteristics [4], being an undesired feature for a light source in embedded projection displays where large operating temperature range is typically required.

Frequency conversion of infrared laser emission is an attractive solution for short wavelength red light generation [5]. While GaInAs quantum well (QW) emission wavelength is practically limited to ~1200 nm [6], by using dilute nitride GaIn(N)As QWs with tiny fraction of nitrogen added to the highly strained GaInAs, the emission wavelength can be extended to 1220-1240 nm for high luminosity red light generation at 610-620 nm by frequency conversion [5]. In addition, excellent temperature characteristics and high power operation have been demonstrated with GaInNAs laser diodes in this wavelength range [7].

[1] E. Buckley, *J. Display Technol.*, vol. 8, no. 3, March 2012.
[2] R. Bohdan et al. *J. Appl. Phys.*, vol. 104, 063105 (2008).
[3] T. Onishi et al. *IEEE J Quantum Electron.*, vol. 40, no. 12, December 2004.
[4] B. Qiu et al. *Opt. Quant. Electron.*, vol. 40, pp. 1149–1154 (2008).
[5] A. Härkönen et al. *Opt Express.*, vol. 15, issue 6, pp. 3224-3229 (2007).
[6] K. Nakahara et al. *IEEE 20th ISLC Conference Digest*, pp. 161 – 162 (2006).
[7] D. Bisping et al. I*EEE Photon. Technol. Lett.*, vol. 20, no. 21,2008

Room temperature luminescence beyond 1.3 µm from GaAsSbN-capped InAs quantum dots

A.D. Utrilla,[1] J. M. Ulloa,[1] L. Domínguez,[2] D. F. Reyes,[2] D. González,[2] A. Guzman[1] and A. Hierro[1]

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The use of the quaternary GaAsSbN as a capping layer (CL) on InAs/GaAs quantum dots has been proposed as a strategy to tune independently the electron and hole confinement potentials and to lengthen the peak emission wavelengths while keeping a type-I band alignment. However, to date, no room temperature emission has been reported in such a system. Aiming this target, an extensive study has been carried out in MBE grown samples in order to find the optimum growth conditions for the CL. After optimization, intense room temperature photoluminescence around 1.3 µm is obtained. Using high growth rates, the GaAsSbN CL provides an enhanced integrated intensity and longer peak wavelengths than the ternary GaAsSb or GaAsN CLs, revealing a significant improvement by the simultaneous presence of Sb and N in the CL. Moreover, the best luminescence properties are obtained by using a GaAsSb/GaAsN superlattice-like structure as a CL, which also allows extending the peak wavelength beyond 1.4 µm. The influence of the growth conditions on the structural properties of the samples was investigated by transmission electron microscopy.

Hydrogen irradiation of In(AsN)

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Small amounts of nitrogen atoms into III-V semiconductors ─such as GaAs and InAs─ greatly affect the physical properties of these materials, whose bandgap energy decreases because of a large optical bowing. Recently, a bright photoluminescence (PL) emission ─up to 4.5 µm─ reported in In(AsN) alloys has raised a considerable interest because of its potential for the realization of optical devices operating in the mid infrared range [1].

Here, we report the effects that low energy (≈ 100 eV) hydrogen irradiation has on the optical properties of In(AsN) epilayers ([N] up to ≈2%) grown by nitrogen plasma source molecular beam epitaxy. PL emission intensity may increase by more than one order of magnitude upon low temperature (250 °C) hydrogenation. A passivation of surface defects for hydrogen doses decreasing with increasing N content is inferred. Measurements of the In(AsN) energy gap have been performed easily up to room temperature. Preliminary results of hydrogenation at 300 °C show, instead, increasing band-filling effects, which supports the formation of bulk donors upon deep hydrogenation we previously demonstrated by transport measurements in these sample samples.

[1] M. de la Mare *et al*., J. Phys. D: Appl. Phys. **45,** 395103 (2012) and references therein

$Ga_{0.35}In_{0.65}N_{0.02}As_{0.08}$/GaAs Bi-directional Light Emitting and Absorbing Heterojunction operating at 1.3 µm

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Top-Hat Hot Electron Light Emission and Lasing in Semiconductor Heterostructure Vertical Cavity Semiconductor Optical Amplifier (THH-VCSOA) is a bi-directional light emitting and absorbing heterojunction device.

The device contains 11 $Ga_{0.35}In_{0.65}N_{0.02}As_{0.08}$/GaAs MQWs in its intrinsic active region which is enclosed between 6-pairs of AlAs/GaAs top DBR and 20.5-pairs of AlAs/GaAs bottom DBR mirrors. The THH-VCSOA is fabricated using a four-contact-configuration. The wavelength conversion with amplification is achieved by the appropriate biasing of the absorption and emission regions within the device. Absorption and emission regions may be reversed by changing the polarity of the applied voltage. Emission wavelength is about 1300 nm and a maximum gain at this wavelength is around 5 dB at T=300K.

GaInNAsSb Solar Cells Grown by MBE

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Multijunction solar cells (MJSC) are excellent devices for concentrated and space photovoltaics. The driving force for the material and technological development of these multilayer structures is the high efficiency, which is further improved under highly concentrated solar illumination. Currently up to 44% efficiency triple junction solar cell has been demonstrated and efficiencies of more than 50% are predicted when using more junctions [1, 2] .We studied the molecular beam epitaxy growth of GaInNAsSb solar cells with N and Sb contents ranging from 0 to 6% and 0 to 4%, respectively. Without Sb, the short circuit current densities of solar cells were improved up to 4% N. [3] N contents higher than 4% lead to phase separation during growth. The best solar cells without Sb showed short circuit current density of 39 mA/cm^2 (real sun illumination, 1000 W/m^2), which is among the highest reported values. [4] With addition of Sb the current density improves 7.5%. [5] Also the band gap of GaInNAsSb lattice matched to GaAs can be pushed down below 0.85 eV which helps absorption of long wavelength photons. This however comes with a cost of bandgap open circuit voltage offset, which is lower for solar cells without Sb. Finally, we present the performance of GaInP/GaAs/GaInNAs(Sb) triple junction solar cells.

[1] M. A. Green *et al.* Progress in Photovoltaics: Research and Applications, **21**, pp 1–11, (2013)
[2] R. R. King *et al.*, Advances in OptoElectronics, **2007**, 2007
[3] A. Aho *et al.*, 26th EU PVSEC 58-61 (2011), doi:10.4229/26thEUPVSEC2011-1AO.8.3
[4] A. Aho *et al.*, Proc. SPIE 8620, (2013); doi:10.1117/12.2002972
[5] A. Aho *et al.*, AIP Conf. Proc. **1477**, pp. 49-52; (2012) doi:http://dx.doi.org/10.1063/1.4753831

Strain-Engineered InAs/Ga(In)NAs/GaAs Quantum Dot Solar Cells

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III-V quantum dots (QD) are interesting candidates for intermediate band in semiconductor solar cells. In order to form an efficient intermediate band and increase its absorbtion several layers of, for example, InAs QDs, need to be stacked and ordered in all three dimensions. Also, the shape, size and composition of the QDs should be uniform. It is known, that stacks with more than ~ 10 layers of InAs/GaAs QDs with lattice mismatch of ~7% easily generate defects due to accumulated strain. Therefore, strain compensation layers, such as GaNAs with about 1% of N, have been previously proposed to compensate the induced strain in QD solar cell structures. Here we present a study of Ga(In)NAs strain compensation and mediation layers inserted into InAs QD solar cells. The effect of strain-engineering dilute nitride layers on QD photoluminescence (PL) emission, dots morphology as well as spectral response at near-infrared part of the spectrum was investigated. It was found that the insertion of the GaInNAs strain-mediating into the close vicinity of the strain-compesated InAs/GaNAs QDs improves the optical quality and significantly red shifts the absorption edge of the solar cells structures.

SESSION III - InGaN & GaN

24 SEPTEMBER 2013 TUESDAY

17:00-18:00

Molecular Beam Epitaxy of Single Phase InGaN Films in the Entire Alloy Composition Range for Photovoltaic Applications

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Indium gallium nitride (InGaN) alloys is a family of wurtzite compound semiconductors ideally suited for photovoltaic (PV) applications[1]. Their direct bandgaps almost spans the entire solar spectrum, ranging from 3.4 eV (GaN) to 0.65 eV (InN). Furthermore, their internal polarization fields enhance electron-hole separation. However, for successful application of these alloys, in PV devices, two major problems need to be effectively addressed: (a) alloy phase separation phenomena[2,3], present due to the large miscibility gap in the corresponding quasi-binary alloy phase diagram, which are highly detrimental for PV devices since they promote carrier recombination and (b) extended structural defects in epitaxial layers, caused by the large difference in alloy endpoints lattice constants, which may detriment material optoelectronic properties. In this work, plasma assisted molecular beam epitaxy (RF-MBE) on GaN(0001) substrates was employed, to develop thick (300-600 nm) single phase epitaxial $In_xGa_{1-x}N$ layers, in the entire composition range (x=0 to 1) and their structural and optoelectronic properties were studied by high-resolution x-ray diffraction (HR-XRD), high resolution transmission electron microscopy (HR-TEM), scanning electron microscopy (SEM), atomic force microscopy (AFM), variable angle spectroscopic ellipsometry (VASE), photoluminescence (PL) and Hall effect measurements.

The kinetic mechanisms involved in the RF-MBE growth of metal-polar InGaN alloys have been studied as a function of substrate temperature, ratio of group-III atoms to active nitrogen species arrival rate (III/V flux ratio) and nominal alloy composition. In lower substrate temperatures, indium incorporation is dictated solely by the available N^* arrival flux, similarly to the case of AlGaN RF-MBE growth. In higher substrate temperatures, indium incorporation is dictated by the interplay of indium adatoms desorption and InGaN decomposition. In the latter case, an arrival III/V flux ration independent growth mode is established, and the layer composition is controlled solely by the substrate temperature.

Phase separation was not observed in as-grown InGaN(0001) films, neither by x-ray diffraction or transmission electron microscopy studies. The absence of phase separation, despite growth temperatures well within the miscibility gap of the alloy phase diagram, is attributed to the far-from-equilibrium character of the RF-MBE growth. Rarely, under specific growth conditions, secondary compositions peaks are observed in the XRD spectra, as would be expected for phase separated alloy films. However, in those cases, these peaks are attributed to unstable growth conditions driven, rather than thermodynamics-driven, composition modulations.

Structural studies by TEM and HR-TEM confirm that the principal threading dislocations (TDs) were of a-type. Introduction of misfit dislocations at the InGaN/GaN(0001) interface was attributed to in-plane sources. Depending on the growth conditions, discontinuous or continuous strain relaxation was observed. The former comprised a strained InGaN interfacial layer followed by introduction of TDs from an extended stacking fault (SF). In the case of continuous relaxation, TDs were gradually introduced with increasing thickness. The optoelectronic properties of the InGaN epitaxial layers have been studied in details and correlated to growth conditions and structural defects.

[1] E. Trybus *et al.*, J. Crys. Growth 288, 218 (2006)
[2] R. Singh *et al.*, Appl. Phys. Lett. 70, 1089 (1997)
[3] I. Ho *et al.*, Appl. Phys. Lett. 69, 2701 (1998)
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Acknowledgement This research has been co-financed by the European Union (European Social Fund – ESF) and Greek national funds through the Operational Program "Education and Lifelong Learning" of the National Strategic Reference Framework (NSRF) - Research Funding Program: THALES.

InGaN MQW photoluminescence enhancement by localized surface plasmons in isolated Ag nanoparticles

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InGaN-based light emitting diodes (LEDs) efficiency can be enhanced by increasing radiative recombination rate by coupling emitted photons with plasmons in metal layers or nanoparticles in close proximity of the active layer of an LED.

In this work we report on spatially resolved photoluminescence (PL) study of InGaN multiple quantum wells (MQW) with silver nanoparticles (NPs) deposited on top. The localized surface plasmon resonance (LSP) wavelength was tuned to match PL emission by controlling the size of the silver NPs. Near-field scanning microscopy and confocal spectroscopy were employed to study the spatial distribution of PL. Atomic force microscopy was used to match the location of the nanoparticles with the image of PL spatial distribution in confocal experiments. A reference sample without NPs was also studied.

PL intensity mapping images of sample covered with Ag NPs reveal areas, where PL intensity exceeds the average value by a factor up to 4. The effect is especially strong in the areas close to assemblies of several metal NPs. It was found that the enhancement was stronger in the microscopic sample areas emitting at wavelengths better matched with LSP resonance.

Chemical Synthesis and Characterization of GaN Quantum Dots

Incorporated in Simple Photonic Devices

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In this paper we discuss a novel route for low-temperature (650oC) synthesis of gallium nitride (GaN) quantum dots (QDs) and there implementation in photonic devices. Simple solid state reaction is shown to produce GaN QDs, exhibiting blue shifted photoluminescence in the UV region compared to bulk GaN. For the synthesis no organogallium precursor was used. The growth of the QDs was assisted and controlled by a host matrix of an ordered mesoporous silica MCM-41. The QDs were successfully extracted by destruction of the host matrix and transferred via solvent exchange methods to polypropylene glycol methyl ether acetate (PGMEA) in order to facilitate the mix with polymers for the fabrication of photonic structures. The fabrication of our final photonic devices was performed by means of soft nanolithography and excimer laser micro fabrication techniques.

Research co-financed by the European Union and Greece through the Operational Program "Heracleitus II".

SESSION IV - III-V on Silicon & Bismide alloys I

25 SEPTEMBER 2013 WEDNESDAY

09:00-10:20

3D heteroepitaxy of Ge and GaAs on patterned Si substrates: a new monolithic integration strategy

S. Sanguinetti[1], R. Bergamaschini[1], S. Bietti[1], F. Isa[2], G. Isella[2], A. Marzegalli[1], F. Montalenti[1], F. Pezzoli[1], A. Scaccabarozzi[1], C. V. Falub[3], H. von Känel[3] and L. Miglio[1]

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We have recently shown that crystal defects and internal stresses commonly hampering Ge heteroepitaxy on Si can be greatly reduced by promoting the nucleation of micro-crystals at the top of Si pillars deeply patterned on the substrate [1]. Ge-on-Si epitaxy by low-energy plasma-enhanced CVD (LEPECVD), allows for controlling the microcrystal faceting, in turn affecting the evolution of threading dislocations and providing complete expulsion of threading arms to the microcrystal sidewalls [2]. In addition, the microcrystals are self-assembled in dense arrays, with a spacing ranging from tens to one hundred nanometers. The growth mechanism of the micro-crystals is an intriguing “nano” effect, which has been interpreted in terms of independent facet growth. This effect is not a unique feature of Ge deposition by LEPECVD, but a more general growth mode, which can be extended to other materials systems and deposition techniques. GaAs microcrystals deposited by MBE on patterned Si substrates show as well the complete tessellation of the surface by closely separated microcrystals. The complete elimination of thermal strain and reduction of threading dislocations is confirmed by the high PL yield.

[1] C.V. Falub *et al.*, Science, **335**, 1330-1334, 2012;
[2] A. Marzegalli *et al.,* Advanced Materials, 2013

Bi-assisted nucleation of GaAs grown on silicon by molecular beam epitaxy

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GaAs Nucleation on (001) silicon is known to lead to a high density of defects: stacking faults, microtwins, dislocations and antiphase defects. One of the origin of these defects is related to 3D islanding occurring upon GaAs/Si nucleation. We have investigated on the surfactant effect of Bi to improve this situation. The results that we have obtained for molecular beam growth in a 32P RIBER system of thin (<100nm) GaAs layers on 5°off (011) silicon substrates will be presented. The substrates were ex situ treated in a diluted HF2 : H2O solution and then were annealed in the growth chamber. We will discuss how the Si surface evolves by means of reflection high energy diffraction (RHEED). We will then present our study of the early stage of GaAs(Bi) growth on these silicon surfaces by using different analyses during GaAs(Bi)/Si nucleation: RHEED iffraction during growth and, ex-situ, atomic force analyses, X-Ray diffraction.

We will discuss the low temperature emission properties of GaInAs quantum wells grown at different distances from the GaAs/Si interface. Finally, rapid thermal annealing has been applied to these heteroepitaxial structures. Its influence on the quantum well mission will be shown.

Valence band structure of dilute bismide alloys for optoelectronic device applications

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$GaBi_xAs_{1-x}$ has several novel electronic properties, including a rapid reduction in energy gap and a strong increase in spin-orbit-splitting energy with increasing Bi composition, x. This makes dilute bismide alloys a strong candidate system for the realisation of highly efficient and temperature stable GaAs-based photonic devices operating at telecom and longer wavelengths.

We present tight-binding calculations which confirm that the observed variation of the band gap and spin-orbit-splitting energy are well described by a band-anticrossing interaction between the GaAs valence band edge states and localized Bi impurity states in the valence band. We then derive an accurate 12-band **k.p** model for GaBiAs heterostructures, which we use to analyse the electronic structure and gain characteristics of $GaBi_xAs_{1-x}$ lasers grown at Marburg (x~2-4%). Photovoltage measurements support a weak type-I conduction band offset for a $GaBi_{0.02}As_{0.98}$/GaAs quantum well (QW) structure. We show that this weak confinement can be overcome by using AlGaAs barriers, and report self-consistent gain calculations to identify an Al barrier composition which delivers the maximum modal gain. We then consider higher Bi composition GaBiAs/GaAs and GaBiNAs/GaAs QW structures, and present calculations to illustrate the wide flexibility which such alloys offer for the design and implementation of high efficiency photonic devices.

SESSION V- BISMIDE ALLOYS II

25 SEPTEMBER 2013 WEDNESDAY

11:00-12:30

Optical and spin properties of GaAsBi epilayers

S. Mazzucato[1], H. Lehec[1], **H. Carrere**[1], T. T. Zhang[1], D. Lagarde[1], P. Boonpeng[2,3], A. Arnoult[2,3], G. Lacoste[2,3], A. Balocchi[1], T. Amand[1], C. Fontaine[2,3], and X. Marie[1]

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In recent years, dilute bismides have attracted much attention for their potential use in optoelectronic and spintronic applications. Adding even a small amount of bismuth to arsenides strongly affects the material band structure and induces a significant lowering of their bandgap energy, as well as an increase of the spin-orbit (SO) split-off energy. On the one hand, this opens up opportunities for optoelectronics. Grown on GaAs substrates, GaAsBiN quaternaries can be both strained or lattice-matched, and could reach the 1.3-1.55 µm range of telecommunication applications while reducing Auger and Inter-valence band absorption loss mechanisms [1]. Compressively strained GaInAsBi quantum wells have also proven emission near 1.3µm [2]. Grown on InP, GaInAsBi has been proposed for thermoelectric and mid-IR optoelectronic applications [3]. On the other hand, the conduction band electron spin properties, which depend critically on the SO interaction, could be tuned by adding Bismuth to GaAs. Indeed, the large increase of the SO splitting energy is expected to result in a reduction of the conduction electron spin lifetime [4]. In this talk, we present the singular optical and spin properties of GaAsBi epilayers. Samples are grown by molecular beam epitaxy and elastically strained on GaAs substrates. The optical properties of ternary alloys are investigated by CW and time resolved photoluminescence from cryogenic to room temperature, evidencing strong carrier localization. The effect of rapid thermal annealing upon material quality is also discussed. We observe only a low improvement of PL intensity but a strong reduction of bismuth-related localized state density associated to changes in photoluminescence lifetime [5]. The measurement of photoluminescence polarization dynamics after circular excitation leads to the determination of electron spin lifetime. When applying an external transverse magnetic field (Voigt configuration), the measurement of the photoluminescence polarization oscillations resulting from the Larmor precession of electron spins yields an accurate determination of the Landé g-factor. We observe a large increase in g factor as compared to its value in GaAs, in agreement with the larger spin-orbit interaction in GaAsBi [6]. Hence, only a small fraction of Bi introduced in GaAs can lead to major changes of the electron spin properties.

Morphological instabilities in $GaAs_{1-x}Bi_x$ layers grown by molecular beam epitaxy

E. Luna[1], M. Wu[1], J. Puustinen[2] and M. Guina[2]

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$GaAs_{1-x}Bi_x$ is a highly-mismatched alloy which is formed by the substitution of elements with very different size and/or electronegativity. Consequently, the alloy has a strong tendency for clustering, phase separation and atomic ordering. Despite these features can influence the optical and electronic properties, little is known about the microstructure of $GaAs_{1-x}Bi_x$ layers. We investigate the microstructure of $GaAs_{1-x}Bi_x$ epilayers by transmission electron microscopy. The layers are grown by molecular beam epitaxy on GaAs(001) substrates at temperatures T_s between 220-315°C. The Bi content ranges between 1.4 - 5%. In as-grown structures, no clustering is detected but we find that the samples exhibit a complex microstructure which is strongly dependent on the growth conditions, in particular on T_s and on the As/Ga flux ratio. We find that while the layers grown at the higher T_s = 315°C show a homogeneous Bi incorporation, the layers grown at T_s = 220°C exhibit quasi-periodic lateral composition modulations (LCM) with Bi-rich and As-rich areas spontaneously formed. Furthermore, depending on the growth conditions, atomic ordering is also detected, thus some layers present simultaneous LCM and ordering. Unlike other works reporting CuPt-ordering in $GaAs_{1-x}Bi_x$, our findings evidence a new class of triple-period ordering on {111} planes.

Formation and phase transformation of Bi-containing clusters in annealed $GaAs_{1-x}Bi_x$ epilayers

M. Wu[1], E. Luna[1], J. Puustinen[2], M. Guina[2] and A. Trampert[1]

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We investigate the formation and phase transformation of Bi-containing clusters in $GaAs_{1-x}Bi_x$ epilayers upon annealing by transmission electron microscopy. The $GaAs_{1-x}Bi_x$ epilayers were grown by molecular beam epitaxy under low (220˚C) and high (315˚C) temperatures and subsequently annealed in a rapid thermal annealing furnace at various temperatures (600–800˚C) and periods (60–120 s). Bi-containing clusters are identified only in the annealed samples that were grown at low temperature, revealing a relatively homogeneous size distribution. Depending on the annealing temperature and period, the clusters show different sizes ranging from 5 to 20 nm; and the phase of either coherently strained zinc-blend $GaAs_{1-x}Bi_x$ (zb Bi-rich) or rhombohedral pure Bi (rh-Bi). We find that: (1) the formation of the zb Bi-rich clusters is driven by the intrinsic tendency of the alloy to phase separate and is mediated by the native point defects present in the low temperature grown epilayers; (2) the phase transformation from zb Bi-rich to rh-Bi is determined by the accumulation of local strain in the clusters. With strain energy criteria, we predict a Bi content in the zb Bi-rich clusters higher than 20%.

Analysis of bismuth distribution in GaAsBi/GaAs layers: segregation and $CuPt_B$ atomic ordering

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III-V-Bismuthides have recently aroused great interest. Among other benefits, GaAsBi exhibits a band gap reduction, a strong enhancement of spin-orbit splitting and a temperature insensitive band gap.[1-3] These are attractive properties for infrared lasers, photodetectors and terahertz optoelectronic devices applications. However, the growth of high bismuth content III-V alloys has been hindered by the extremely large miscibility and a very small equilibrium solid solubility. As a consequence, the Bi in GaAs has a tendency for alloy clustering, phase separation and atomic ordering to occur during growth.[4] zThe present work analyses by photoluminescence (PL) and transmission electron microscopy (TEM) techniques the structure and compositional distribution of Bi in GaAsBi molecular beam epitaxy layers. Bi-content undergoes a strong and irregular decrease in the first 25nm, which then remains almost constant till the end of the layer and does not follow a planar segregation front. Additionally, high resolution TEM images and diffraction patterns evidence the formation of $CuPt_B$-type atomic ordering. Finally, the ordering distribution along the GaAsBi layer is determined by reconstruction of the phase maps extracted from HRTEM images. The PL behavior is justified by the formation of $CuPt_B$ ordering and the bimodal Bi content.

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[2]S. Francoeur et al. APL **82** (22), 3874 (2003).
[3]B. Fluegel, et al. Physical Review Letters **97** (6) (2006).
[4]A.G. Norman et al., J. Vac. Scien.&Technol. B: Microelectron. Nanometer Struc. **29**, 03C121 (2011).

SESSION VI -BISMIDE ALLOYS III

25 SEPTEMBER 2013 WEDNESDAY

14:30-16:20

Optical characterization of bulk $GaBi_xAs_{1-x}$ and GaAs/ $GaAs_{1-x}Bi_x$ quantum well structures

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We present optical characterization of bulk $GaAs_{1-x}Bi_x$ and $GaAs/GaAs_{1-x}Bi_x$ single quantum well (QW) structures with various Bi concentrations using room temperature photomodulated reflectance (PR) spectroscopy. The modulation spectrum is analyzed using Lorentzian line-shape of third derivative functional form. As Bi content increases, the line-broadening is determined to increase in bulk structures, in contrary, a reduction is observed in QW structures. It is observed that the Bi dependence of bandgap and split-off band energy are 74meV/% Bi and 48meV/%Bi, respectively. The FWHM of bandgap related PR spectrum is about 3 times larger than that of split-off band. In addition, we also observed PR signal at 0.7eV which may correspond to transition between Bi anti-site defect level and conduction band edge. Raman spectroscopy is used to analyze Bi-related vibrations in the bulk structures. Moreover, effect of thermal annealing on the sample structure is investigated using Atomic Force Microscopy (AFM).

Structural an optical properties of $GaAs_{1-x}Bi_x$ quantum wells grown by molecular beam epitaxy – Effect of rapid thermal annealing

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Dilute bismide GaAsBi alloys exhibit peculiar electronic properties. The valence band of the GaAs matrix is affected, leading to promising properties for optoelectronics. Here, we present results on GaAsBi-GaAs quantum wells grown by molecular beam epitaxy. We will describe how we have achieve thick layers and quantum wells containing up to respectively 4 and 7% Bi and elastically strained. Then we will focus on quantum well properties. Results of X-ray diffraction and transmission electron microscopy will be presented.

We will also discuss the effect of rapid thermal annealing on these quantum wells. The X-ray diffraction was used to estimate the structural changes of the quantum well structures.

Stationary and time-resolved photoluminescence spectroscopy measurements were performed. An emission wavelength of 1.25 µm is obtained at room temperature. We will show that rapid thermal annealing lead to strongly blue-shifting the quantum well emission. Localized states accounted for by alloy disorder and formation of aggregates are present in these quantum wells and are not completely suppressed by annealing as shown by carrier life-time measurements.

Finally, we will discuss the surfactant role of the bismuth for growth of GaInAs quantum wells. Finally, we will discuss the surfactant role of the bismuth for growth of GaInAs quantum wells.

Effect of hydrogen on the electronic properties of Ga(AsBi) alloys

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The electronic properties of Ga(AsBi) alloys, as-grown and hydrogen irradiated, are investigated in a wide range of Bi-concentration ($0.6\% \leq x \leq 10.6\%$) by performing Hall effect measurements at high magnetic fields (B up to 14 T) and photoluminescence spectroscopy. In untreated, nominally undoped samples, we report a native *p*-type conductivity that increases with increasing the Bi-concentration, free hole density increasing by more than three orders of magnitude in the investigated Bi-concentration range. Free holes result to be thermally excited from *shallow* Bi-induced acceptor levels lying at ~26 meV above the valence band edge of Ga(AsBi). Upon hydrogen incorporation, these *shallow* acceptor levels are passivated and the hole mobility increases by a factor of ten, for all the investigated Bi-concentrations. The emission energy, instead, is negligibly affected by hydrogenation. This indicates that the narrowing of the band-gap energy with increasing Bi concentration and the native *p*-type conductivity are two uncorrelated effects, which arise from different Bi defect centres. Finally, passivation by hydrogen of the *shallow* Bi-acceptor levels permits to indentify *deep* Bi-acceptor states.

Structural and optical characterizations of InPBi thin films grown by molecular beam epitaxy

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Novel semiconductor alloy $InP_{1-x}Bi_x$ samples have been grown on InP substrates by gas source molecular beam epitaxy. By X-ray diffraction measurements, the layer peaks corresponding to InPBi layers are observed, and the Bi composition is calculated to be around 2% by using Vegard's law. InBi-like phonon signals are observed in Raman measurements, confirming the In-Bi bonding in the epi-layers. In the absorption spectra, the band-gap corresponding to the absorption edge of InPBi samples is smaller than that of InP, indicating the band-gap reduction of the InPBi alloys. Photoluminescence (PL) measurements reveal broad PL signals with a wavelength span of 900 nm around the centre wavelength of 2 μm at room temperature. Our results show that InPBi alloy has a great potential in IR optoelectronics applications.

MOVPE growth of Ga(AsBi)/(AlGa)As hetero structures and laser diodes

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Dilute bismide Ga(AsBi) based lasers diodes are promising candidates for high efficiency infrared light sources since, for Bi > 10 %, hot-hole generating Auger recombination and inter-valence band absorption (IVBA) processes could be suppressed. In this work we present recent results of the MOVPE growth of Ga(AsBi)/GaAs MQW and bulk structures on GaAs (001) substrates and the successful deposition of electrical pumped Ga(AsBi)/(AlGa)As QW laser diodes. Ga(AsBi) layers with Bi fractions up to 6% in good quality were realized without any formation of metallic droplets. The incorporation of Bi into GaAs is limited depending on the applied growth temperature and growth rate as well as the V/V and V/III ratios. Surplus Bi segregates to the surface and can incorporate into subsequent layers if it is not evaporated by a growth interruption at higher temperatures. Mixing Al into the GaAs barriers improve the electronic confinement of the Ga(AsBi) QW and therefore enables the growth of laser diodes. Electrically pumped laser devices with up to 4% Bi were realized, providing the proof of principle of bismide containing laser diodes.

POSTER PRESENTATIONS

24 SEPTEMBER 2013 TUESDAY

18:00-20:00

P1

Effect of Gamma Irradiation on deep levels detected by DLTS in GaAsxN1-x with different Nitrogen concentration

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The addition of nitrogen atoms into gallium-arsenide (GaAs) leads to a remarkable band-gap reduction, which originates predominantly from a downward of the conduction band edge. Due to this circumstance, GaNAs as well as other III-V-N alloys are strong candidates for various applications in semiconductor electronics, such as solar cells and GaAs-based telecommunication laser diodes [1]. The scientific literature suggests that the Irradiation of GaAs samples with high-energy radiation can leads to production of lattice defects in the form of vacancies, defect clusters and dislocations. Thus in this work it was investigated the effect of gamma radiation (γ-ray) on GaAs samples prepared with different Nitrogen concentrations of 0.2%, 0.4%, 0.8% and 1.2% [2]. The effects of γ-ray were studied by deep level transient spectroscopy (DLTS) and Laplace DLTS [3]. The DLTS measurements on gamma irradiated sample found that with small Nitrogen contents (0.2% and 0.8%) most of defects are compensated. However irradiation did not compensate defects with higher Nitrogen concentration. If the defects induced by γ-ray can be monitored by electrical / electronic measurements techniques this system could be used as a semiconductor sensor device for gamma radiation.

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P2

Trapping and escape time in p-i-n GaInNAs/GaAs multiple quantum wells structures

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We used a semi-classical quantum model to describe the hole capture, crossing and thermionic escape time into and from GaInNAs/GaAs quantum wells, together with the electron escape time. The results have been used to explain the observed oscillations in the photocurrent of a p-i-n GaInNAs/GaAs multiple quantum well (MQW) structure, in terms of different hole and electron escape time, resulting in induced charge accumulation and field domain effects.

P3

Effect of Post Growth Thermal Annealing on Deep Level Defects in MBE Grown Dilute Nitride $Ga_{1-x}In_xN_yAs_{1-y}$ p-i-n Structures

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To study the electronic behavior of Ga1−xInxNyAs1−y p-i-n, deep level transient spectroscopy (DLTS) studies are performed on MBE grown structures. The as-grown effect of post-growth thermal annealing on deep levels is investigated. Rapid thermal annealing generates some extra electron and hole traps and a decrease in the net acceptor concentration is observed. This suggest that annealing reduces the extent of free carrier trapping. Furthermore, the leakage current of the InGaAsN/GaAs p-i-n devices decreases by 2 orders after annealing. The relationship between non-radiative centres and their effect on Electroluminance (EL) is established. After rapid thermal annealing, the EL blue shifts and enhanced EL intensities are observed.The main electron traps and single hole trap detected by DLTS in as-grown samples are due to split interstitials and arsenic vacancy, respectively. Similarly, relationship between low reverse currents and defects densities upon annealing is established.

P4

Optical and Magneto-Optical Properties of GaAsBi Layers Grown by MBE

H.V.A. Galeti [1], Y. Galvão Gobato [2], V. Orsi Gordo[2], M.P.F. de Godoy [2] , R. Kudraview[3], O.M. Lemine [4], A.Alkaoud[4], **M. Henini** [5]

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In this work, we have studied photoluminescence (PL) and polarized resolved photoluminescence on GaBiAs samples as function of temperature and magnetic fields up to 14T. The effects of thermal annealing on the optical properties were also investigated. The GaBiAs layers were grown by molecular beam epitaxy on (001) GaAs substrates at a growth temperature of 350 ^{0}C with different As flux ratios. In this abstract, we focus on a 1μm GaBiAs layer with 3% of Bi. The samples were annealed at 200 ^{0}C for 3 hours in nitrogen ambient. Both samples present a red shift of PL peak as we decrease the laser power which is consistent with localization effects. The shift is slightly higher for the annealed sample. The annealed sample showed an improvement of about 2.5 times in the photoluminescence intensity while the PL peak energy show a blue shift of about 6meV at 2K. In general, our PL results show clear evidence of carrier localization for both samples. We have also observed that the annealing treatment decreases the diamagnetic shift which indicates that the annealing process at low temperatures results in an increase of localization of carriers in this alloy. Therefore, the observed improvement of PL intensity seems not to be related to the reduction of defects but to another effect. In addition, we have also observed an increase of circular polarization degree for the annealed sample with values up to 41% at 14T and 2K. In addition, at lower temperatures the polarization degree increases with the decrease of laser power. In conclusion, low thermal annealing process improves the optical quality and spin polarization degree of GaBiAs samples and important localization effects are observed.

P5

Spin Effects in InGaAsN/GaAs Quantum Wells Grown by Molecular Beam Epitaxy

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In the last years, the spin manipulation was successfully realized in non-magnetic semiconductors nanostructures. However, with increasing temperatures up to room temperature (RT), free carriers get delocalized and their spin relaxation time drastically decreases. This limits the electron spin polarization under continuous-wave (CW) photoexcitation to a few per cent. More recently, it was reported that spin-dependent recombination (SDR) processes via spin-filtering Ga_i self-interstitial defects can transform a nonmagnetic (In)GaAsN into an efficient spin filter operating at RT without applying a magnetic field. These processes provide conditions that are desirable for device applications. In this work, we have investigated spin effects in $In_xGa_{1-x}As_{1-y}N_y$ / GaAs quantum wells (QWs) for linearly and circularly laser excitation at different temperatures, magnetic fields, and laser intensities. Our samples consist of double $In_xGa_{1-x}As_{1-y}N_y$ /GaAs QWs with 4 and 7 nm , x=36%, and y=1.2% or y=0 (control sample) grown by molecular beam epitaxy on (100) GaAs substrates. We have observed that the spin polarization degree becomes stronger in the wider QWs, probably due to an increase in the sheet concentrations of the spin-filtering defects. In addition, when the temperature is increased, the polarization degree for N-free QWs decreases monotonically as a function of temperature while for N-containing samples the polarization degree increases up to 220 K. We have also measured the polarization degree under high magnetic fields up to 14T for as-grown and annealed samples as function of temperature and magnetic field. Our results show that the polarization degree presents higher values for as-grown samples than for annealed samples at higher temperatures probably due to the presence of higher concentration of defects in as-grown samples. However, the interpretation of these results and the effect of defects on spin properties of InGaAsN QWs are still under investigation.

P6

Determination of the electron effective mass in AlInN/AlN/GaN heterostructures by using the quantum hall effect measurements

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We have performed quantum Hall effect measurements in AlInN/AlN/GaN heterostructures at low temperature and magnetic field up to 11 T. The integer quantum Hall effect is observed in two-dimensional electron gas at the AlN/GaN interface. The quantum oscillations in Hall resistance have been used to determine the carrier density, effective mass and Fermi energy of two-dimensional electrons in the AlInN/AlN/GaN heterostructures. The results are in good agreement with those determined from the Shubnikov-de Haas effect in magnetoresistance in the same structure.

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P7

Impact of the temperature on the performances of GaInNAs- based PBG waveguide modulators

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Dilute nitride semiconductor devices exhibit better temperature performance compared with InP-based structures. This attribute makes GaInNAs-based semiconductor devices viable candidates for next generation communication networks and photonic integrated circuits. In recent papers the authors studied the performance of GaInNAs-GaInAs Multi Quantum Wells (MQW) active ridge waveguides, patterned with a periodic one-dimensional grating and a defective region placed in the central layer, for efficient optical active switches and modulators. The switching mechanism was obtained around the Bragg wavelength $\lambda \cong 1.289$ µm at the room temperature T=298 K by properly designing the periodic grating and changing the injected density current from $J_{OFF}=0$ $J_{ON}=0.8$ mA/mm^2. With reference to the two ON/OFF states, the proposed device exhibits high performances in terms of crosstalk, contrast ratio, modulation depth and bandwidth. In this paper, we will evaluate the influence of the temperature changes on the switching performances of the proposed ON/OFF modulator. In particular, we will explore the temperature range values for which the performances of the designed device do not appreciably change. As an example, in the ON state we have verified that at $\lambda \cong 1.289$ µm the normalized output power P_T assume an almost constant value (ranging from $P_T=2.9$ to $P_T=3.1$) for temperature values ranging from T=298 K to T=330 K, whereas P_T reduces to about 1.8 by increasing the temperature to T=390 K. Moreover, the full width at half maximum increases from FWHM≅0.95 nm for T=298 K to FWHM≅1.17 nm for T=390 K.

P8

Experimental investigation and numerical modelling of photocurrent oscillations in GaInNAs/GaAs p-i-n photodiodes

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Photocurrent oscillations observed at low temperatures in GaInNAs/GaAs multiple quantum well (MQW) p-i-n samples are investigated as a function of temperature, applied bias and the excitation wavelength. These oscillations appear only at low temperatures (below 200K) and have the highest amplitude when the optical excitation energy corresponds to the GaInNas bandgaps. Therefore, they are associated with photoconductivity in the GaInNAs QWs and explained in terms of charge accumulation and the formation of high field domains because of the disparity between the photo excited electron and hole lifetimes in the wells. In this paper we describe and model our experimental results. It is shown that due to the low valence band offsets in GaInNAs/GaAs, non-equilibrium hole escape rates from the wells are much higher than those for the electrons. This results in the accumulation of negative charge in the wells and the formation of high filed domains. Increasing the applied electric field results in the motion of the high field domain towards the anode where the excess charge dissipates from the well adjacent to anode. Therefore the number of oscillations corresponds to the total number of QWs in the sample.

P9

Spectral Photoconductivity Studies on $GaAs_{1-x}Bi_x$ Epilayers

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We studied different temperature (20K-300K) spectral photoconductivity (PC) measurements on GaAsBi epilayer in order to understand its photovoltaic properties for solar cell applications. Various Bi concentration and different thickness of undoped GaAsBi epilayer samples which grown by molecular beam epitaxy (MBE) were studied. It was found that the shape of the photoconductive signal spectral distribution is dependent on the layer thickness. In this study we found different broaden peak places which is dependent of Bi concentration. From the peak energy versus temperature fit, we analyzed the S shape behavior at low temperature and we have achieved the Varshni parameters of the alloys. Additionally, we also realized from our measurement that, there is strong defect level which is active in wide temperature range.

P10

Thermal annealing- and Nitrogen-induced effects on electronic transport in n-and p-type modulation doped GaInNAs/GaAs quantum well structures

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We report an investigation of the annealing- and Nitrogen-induced effects on in-plane carrier mass, carrier mobility, and carrier lifetime in n- and p- type modulation doped $Ga_{0.68}In_{0.32}N_yAs_{1-y}$ (y=0, 0.9, 1.2 and 1.7) quantum well (QW) structures. The in-plane effective mass and quantum lifetime of 2D carriers have have been obtained from the temperature and magnetic field dependence of the amplitude of Shubnikov de Haas (SdH) oscillations. The carrier density and the Fermi energy have been determined from the period of the SdH oscillations. Carrier mobility are obtained from Hall effect and magnetotransport measurements. The effective electron mass are observed to enhance with increasing nitrogen and rapid thermal annealing. With increasing nitrogen, effective hole mass tends to decrease. We do not observe significant change in effective hole mass upon thermal annealing. Both electron and hole mobility are improved after thermal annealing. As nitrogen increases, the carrier lifetime decreases and after thermal annealing it tends to decrease for n-type and decrease for p type QW structures.

P11

Optical propertes of GaAsBi ternary alloys

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We investigated optical properties of GaAsBi ternary alloys with different Bi concentration grown by moleculer beam epitaxy using temperature dependent (40-300K) photoluminenesce (PL) measurements. The PL result show that PL peak energy red-shifts with increasing Bi concentration in GaAsBi alloys. Moreover, PL peak enegy of all samples strongly dependends on excitation laser power intensity. Temperature dependence of PL peak energy exhibits an S-shape behaviour was observed at low temperatures. We explain this anomalous temperature dehaviour by strong carrier localization in localized states at low temperatures. On the outher hand, while the excitation laser power incereases we observed a decrease in localized energy value due to the filling of localized states.

P12

GaAsPN alloys for optoelectronics on Silicon

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The monolithic integration of III-V semiconductors on Silicon substrates has attracted much attention due to the potential all-integrated optoelectronics as well as cost reductions. Epitaxial growth of III-V alloys on Si remains challenging, however major improvements have been done in recent years, leading to the fabrication of Ga(As)PN materials for both photovoltaic and laser applications [1,2]. Indeed both GaPN ternary and GaAsPN quaternary alloys can be lattice-matched to Si, allowing growth of bulk layers suitable for multi-junction solar cells. Increasing the As content, GaAsPN quantum wells grown under compressive strain are good candidates for laser applications at 850 nm and above.
GaP is an indirect bandgap semiconductor, however, the introduction of a small fraction of Nitrogen drastically modifies its band structure, resulting in a direct type semiconductor. The effect of Nitrogen upon the electronic properties of the alloy has been nicely described by the conduction band anticrossing model (BAC), considering a strong interaction between the highly localized N states and the extended states of the matrix conduction band [3-5]. We use the BAC model in a 6 band k.p hamiltonian in order to describe the band structure of GaAsPN/GaPN/Si quantum wells. The BAC parameters used are $E_N^{GaP} = 2.18\ eV$ and $C_{NM}^{GaP} = 3.05\ eV$ and $E_N^{GaAs} = 1.65\ eV$ and $C_{NM}^{GaAs} = 2.7\ eV$ [3,5]. In the GaPN barrier, the N level lies about 60 meV below the Γ minimum of the conduction band. The interaction between these two levels leads to the formation of a Γ-like band and a direct bandgap transition but the resulting conduction states are strongly localized [6]. In GaAsPN, depending on the As fraction, the N level may lie either below or above the conduction band minimum. Both As and N fractions are varied in order to investigate the more suitable alloy composition for reaching emission in the NIR range. The calculated values are compared to experimental data available in the literature. The material gain is then calculated as a function of carrier injection density.

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P13

High Field Hot Electron Energy Relaxation in InGaN/GaN Samples

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Molecular Beam Epitaxy (MBE) growth $In_xGa_{1-x}N/GaN$ samples with indium fractions ranging between x=0.44 and 1.00 have been studied by the pulsed current voltage (I-V) measurements at 1.7 K. The drift velocity, electron mobility and electric-field dependent power loss per electron were determined from the analysis of the data. The drift velocity increased linearly and electron mobility was also remained constant with increasing electric field. The power balance equations were used to obtain power loss per electron as a function of applied electric-field. The results showed that the drift velocity, electron mobility and power loss per electron increased in the range x=0.44-0.66, and then slowly decreased in the range x=0.66-1.00.

P14

Identification of four-hydrogen complexes in In-rich InGaN alloys using photoluminescence, x-ray absorption, and density functional theory

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InGaN alloys have enormous potential for solar energy harvesting and efficient lighting, thanks to their direct band gaps spanning the spectrum from near-infrared to near-ultraviolet. While the Ga-rich region has been widely investigated and exploited in technology, the same is not true for the In-rich region.
Here we investigate the effects of post-growth H-irradiation at low energy (10-100 eV) on the optical and structural properties of In-rich $In_xGa_{1-x}N$ alloys [1]. As long as In concentration exceeds 50%, H-irradiation gives rise to a remarkable blue-shift of light emission and absorption edge energies.

To unveil the microscopic origin of the changes in the optical properties, we combined x-ray absorption measurements at In and N edges with first-principle calculations. H complexes suggested by *ab initio* density-functional-theory simulations were tested with spectral simulations to find the best matches to the experimental evidences.

A novel four-hydrogen defect accounts for all the observed effects: Four H atoms bind to as many N atoms, all nearest neighbors of a same In atom. Complex stability arises from a strong reduction of local strain due to cooperative effects between H, In, and N atoms.

[1] M. De Luca *et al.*, Phys. Rev. B **86**, 201202(R) (2012)

P15

Hot Electron Energy Relaxation in $Al_{0.83}In_{0.17}N/AlN/GaN$ heterostructure

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The temperature depended power loss per electron were determined using the mobility comparison method in $Al_{0.83}In_{0.17}N/AlN/GaN$ heterostructure sample grown by Metalorganic Chemical Vapor Deposition (MOCVD) technique. In order to find electron temperature, the electric-field dependent mobility at fixed temperature was compared with the lattice temperature dependent mobility at a fixed low electric field. The hall mobility measurements were performed in the temperature range between 1.8 and 300 K. It was found that the hall mobility in $Al_{0.83}In_{0.17}N/AlN/GaN$ heterostructure was associated with optical phonon emission above 100 K. The experimental evaluated electron energy loss rate was also compared with theoretical power balance equations derived in the literature. The electron-phonon scattering rates obtained from the analysis of the data was determined as 0.65 ps.

P16

Photoreflectance and photoluminescence studies of GaAsBi layers and quantum wells

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Dilute bismuthides, i.e., III-V alloys with a few percent of Bi atoms, have attracted attention because of their interesting properties [1-3], including a large bandgap reduction and a strong increase in the spin-orbit splitting due to the partial replacement of As with much larger and more metallic Bi atoms. It has been shown that the electronic band structure of such highly mismatched alloys (HMAs) can be described in terms of an anticrossing interaction between the localized states of Bi and the extended valence band states of the host semiconductor [2]. In addition, it has been claimed that the temperature dependence of the energy gap in dilute bismuthides is strongly reduced upon Bi incorporation [1], but this conclusion was gained from PL measurements which can be inappropriate to study the temperature dependence of the energy gap at low temperature because of the strong carrier localization effects in HMAs. The temperature dependence of energy gap for such alloys can be studied by an absorption-like technique which is insensitive to localized states. In this paper, we applied photoreflectance (PR) spectroscopy to study the temperature dependence of the fundamental transition (E_0) for bulk $GaAs_{1-x}Bi_x$ alloys with $0<x\leq0.06$ and $GaAs_{1-x}Bi_x/GaAs$ multi quantum wells. PR spectroscopy, due to its differential and absorption-like character, is an excellent tool to study optical transitions between delocalized states in III-V semiconductors. Samples studied in this work (GaAsBi layer and GaAsBi/GaAs QWs) were grown by molecular beam epitaxy [4]. Strong spectral features related to E_0 and $E_0+\Delta_{SO}$ transitions were observed in PR spectra at low temperatures for all samples studied in this paper. It has been observed that the E_0 transition shifts to longer wavelengths with the increase in Bi concentration (~50meV per % of Bi). The temperature induced shift of E_0 transition in GaAsBi bulk and GaAsBi/GaAs quantum wells in the temperature range of 15-295K has been found to be ~70-80meV and ~60-90meV, respectively, that is very close to the energy shift in GaAs host material in the same temperature range. Due to strong alloy inhomogeneities in this material the temperature-related increase in broadening of optical transitions is smaller than the broadening associated with alloying effects. Energies and broadenings of optical transitions have been determined using the proper analysis of PR data and fitted by the Varshni and Bose-Einstein formulas. The Varshni and Bose-Einstein parameters have been found to be close to the parameters of narrow bandgap III-V semiconductors.

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Gain in electrically-driven 1.3 µm dilute nitride VCSOAs

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We reported an optical amplification of electrically driven dilute nitride 1.3 µm vertical cavity semiconductor optical amplifier (VCSOAs) with 5 µm aperture at room temperature. With the help of amplified spontaneous emission and amplified optical signal, gain is calculated with respect to injected light's wavelength and power for two types of samples, which are with and without a confinement layer located at the top of bottom Distributed Bragg Reflector (DBR). At lower injected laser powers, nearly 10 dB gains are observed for both samples. At power injections over 1nW, gain is observed to drop to a value of 0 dB, drastically. For nearly all power values, sample with confinement layer represents slightly higher gain.

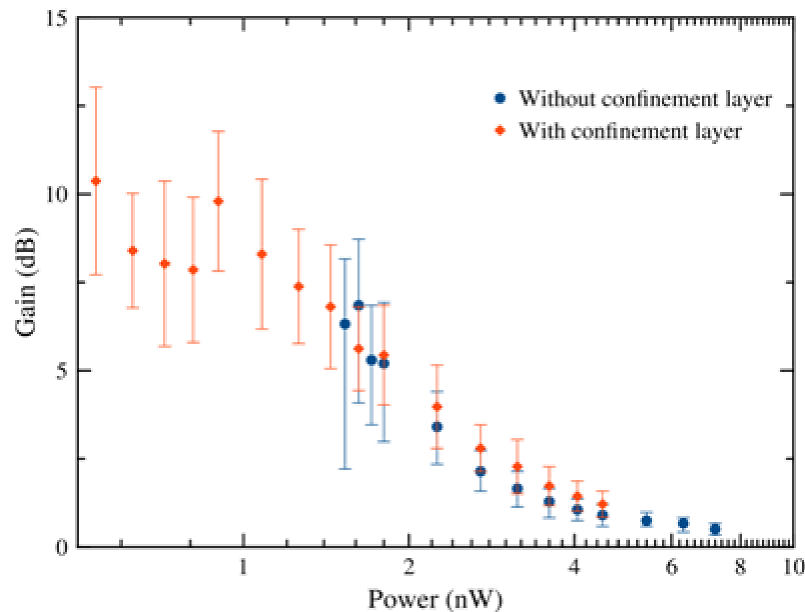

Fig. Power dependent gain of the electrically driven 1.3 µm VCSOAs with or without oxide confinement layer

P18

GaInNAsSb/GaAs semiconductor optical amplifiers and laser diodes

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Numerous applications would benefit from fast and energy-efficient semiconductor optical amplifiers (SOAs) operating without external cooling. In particular, these SOAs are required for integrated optical circuits with advanced functionality that involve a high density of devices, such as SOA-based optical random access memories (RAM) [1]. Such optical RAMs are envisaged to be a key part of next generation optical computing architectures. One of the main advances of GaInNAs(Sb)/GaAs technology over the traditional InP-technology is the large conduction band offset between GaInNAs(Sb)/GaAs quantum well and GaAs barrier, which is manifested as less temperature sensitive operation characteristics. Here, we present our recent developments of 1.3 and 1.55 µm GaInNAs(Sb)/GaAs SOAs and related laser diodes. The GaInNAs(Sb)/GaAs heterostructures were grown by plasma-assisted molecular beam epitaxy. The QWs for devices operating at 1.3 µm consisted of GaInNAs whereas small amount of Sb was added to improve the optical quality of 1.55 µm QWs. After the epitaxy and characterization, GaInNAs(Sb) wafers were processed into ridge-waveguide (RWG) laser diodes and SOAs. The laser process was run parallel to SOA process for process monitoring and for relating the laser characteristics to SOA characteristics. The laser facets were as- cleaved whereas the SOAs had angled and anti-reflection coated facets for minimized reflections. 1.3 µm SOA with two QWs showed good characteristics with a measured maximum gain of 18 dB. Real maximum gain is estimated to be about 28 dB, because the measured value includes the coupling losses of the fiber-optic measurement setup. The gain recovery of the same device was measured to be about 200 ps using a pump-probe measurement setup. On the other hand, the 1.55 µm GaInNAsSb/GaAs SOAs suffer from low gain. Still, good performance was measured for the related 1.55 µm RWG lasers: for example 2x1000 μm^2 RWG laser had threshold current of Ith=50 mA and reached the roll-over limited maximum output power of Pout,max=48 mW in continuous wave operation at room temperature.

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P19

Time-resolved photoluminescence study on GaNAsSb solar cells

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Dilute nitride and antimonide materials are very relevant for the development of high-efficiency III-V multijunction solar cells. Lattice constant as well as band gap of these materials can be varied by tuning their composition. This allows growing films which are lattice matched to GaAs or Ge substrates and having a band gap of 1 eV, which is ideal for absorbing infrared radiation in three-junction solar cell. Recently, conversion efficiency as high as of 44 % has been demonstrated under high concentration radiation for molecular beam epitaxy (MBE) grown three junction solar cell incorporating a 1 eV GaInNAsSb bottom junction.[1] Yet, there is still room for improving the conversion efficiencies by improving the material quality and developing devices with more junctions. Incorporation of nitrogen requires use of RF plasma sources to generate N atoms and growth at relatively low temperatures. This

causes unwanted defects which reduce the material performance ultimately decreasing the carrier lifetimes and the diffusion lengths. Therefore, thermal annealing is typically needed to improve the crystal quality and, for example, increase the lifetime and diffusion length of the electrons and holes. We investigated MBE grown GaNAsSb solar cell material with ~1 eV band gap by time-resolved photoluminescence. We observed a clear wavelength dependency on the decay constants, showing increase when moving closer to the band edge. We also performed thermal annealing on GaNAsSb material. Four to five times longer lifetimes were recorded from the annealed samples, which can be related to the reduction of the defects in dilute nitride material. Also photoluminescence intensity was found to increase with thermal annealing. Material diffusion / reordering related blue shift was also observed due to thermal annealing.

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P20

Morphology and electronic properties of site-controlled InAs quantum dots

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The ability to deterministically position InAs quantum dots (QDs) at the moment of nucleation is instrumental for practical approaches to implement future quantum optical devices, such as single- and entangled-photon sources. The deterministic positioning of InAs QDs can be achieved by so-called site-controlled Stranski-Krastanov growth, where the QDs nucleate in pits or grooves defined by various lithography methods, such as nanoimprint lithography [1-7], E-beam lithography, focused ion beam implantation, or interference lithography. However, the impact of prepatterned growth surface on the properties of QDs is still largely unknown. Here, we present an extensive study of the influence of groove patterned surface on the structural and optical properties of InAs QDs. The structure of the QDs is investigated by means of transmission electron microscopy (TEM), lattice distortion analysis (LADIA), and finite element method based strain model. The emission properties of QD are studied by cleaved-edge photoluminescence (PL) combined with a quantum mechanical model for electron and hole wavefunctions and transition energies. The QDs grown on the groove pattern are compared with reference QDs that were grown on planar surface under identical conditions. We show that the prepatterned surface influences the reduction of the height of the QDs during capping as well as the magnitude and distribution of strain within them. These structural changes influence the localization of electrons and holes in the QDs, which is reflected to the polarization of the PL emission.

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P21

Investigation of GaBiAs alloy using Raman spectroscopy

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The excitation source-dependent nature of Raman scattering spectrum, vibration, electronic or both, have been studied using different excitation sources on as-grown and annealed $GaBi_xAs_{1-x}$ epilayers. The samples were grown by molecular beam technique (MBE) with different Bi concentrations (x = 0.012, 0.018, 0.023, 0.030, 0.038, 0.050). Micro-Raman measurements have been carried out using 532 nm and 785 nm line of diode lasers, whereas 1064 nm line of Nd-YAG laser has been used for FT-Raman scattering measurements. Raman scattering measurements with different excitation sources have revealed that the excitation energy is decisive mechanism on the nature of the Raman scattering spectrum. We observed that when the excitation energy is close to the electronic band gap energy of the constituent semiconductor material in the sample, electronic transition dominates on the line-shape characteristics, resulting in a very broad peak. The vibration modes related to the Bi was only observed with 532nm excitation source. Upon annealing, Bi-induced vibration modes have been observed to be more prominent for all samples.

P22

Performance Prediction of Quantum Dots Based Highly Resonant Optical Amplifiers

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The benefits of combing quantum dots (QDs) as the gain material in highly resonant optical amplifiers are explored theoretically. The structures under study, micro-ring resonators (MR) and vertical cavity semiconductor optical amplifiers (VCSOAs) have a wide range of applications ranging from all optical processing to optical switching and optical gates. Temperature insensitive operation and high differential gain are some of the advantages of quantum dots (QD) allowed by the atomic like nature of the density of states. Indeed the limited carrier capacity of the energy states of the QDs allows for the design of highly resonant devices that never reach lasing threshold thus overcoming a major drawback of amplifying devices, i.e. the need to limit the pumping current to avoid lasing. By being able to drive the device at high current high speed operation is possible by exploiting more efficiently the fast dynamics of the QDs. Using a rate equation model design guidelines are provided while high speed operation is theoretically predicted.

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P23

A study on negative differantial resistance in n- and p-type GaInNAs/GaAs QWs

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We have investigated the transport characteristic of as-grown and annealed n- and p-type modulation doped GaInNAs/GaAs quantum well (QW) structures with different N concentrations, using Hall measurements and high speed I-V measurements. Under the light of experimental findings, influence of the effect of N amount and annealing on carrier velocity and I-V characteristic has been analyzed.

P24

Photoluminescence red shift relative to photoabsorptıon ın III-V-Nitride Structures

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In 1954, W. van Roosbroeck and W. Shockley formulated the theory of recombination radiation of the optically excited solids stating the radiation spectral density $I(h\nu)$ to be directly related to the absorption index $\kappa(h\nu)$ weighted by the Planck function for photons at an effective temperature T_0 of the emitters/absorbers. Essentially the same relation (differing by the replacements of Planck by Boltzmann function, and $h\nu \rightarrow h\nu - \mu$ where c is certain characteristic energy: chemical potential, forbidden gap, etc.), is referred to Stepanov, Kennard-Stepanov, or Kubo-Martin-Schwinger. Based on the Kirchhoff's law of radiation and conventionally used in PL line analysis, the theory by W. Van Roosbroeck and W. Shockley fails to describe the red shift of PL relative to OA.This report is aiming to present the new model of PL/OA spectral shift relating it to the normal/inverted states of the sub-wavelength-size emitters/absorbers [1]. In the framework of COST Action MP0805, the model is applied to existing experimental data on PL and OA in GaN and other N-containing III-V compounds.

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