Wrocław University of Technology
Institute of Physics
Centre for Advanced Materials and Nanotechnology

NRC·CNRC Canada

NanoQuine
QUantum INformation Electronics

Canada – Poland – Japan

International Symposium on Nanoscience

Semiconductor, carbon, magnetic and photonic nanostructures for information and communication technologies, energy, health and environment

5 - 7 October, 2009

Institute of Physics
Wrocław University of Technology

Book of Abstracts

SUPPORT

Lower Silesian Voivodship Marshal's Office

QuantumWorks
RÉSEAU DE L'INFORMATION QUANTIQUE CANADA
QUANTUM INFORMATION NETWORK CANADA

Government of Canada
Embassy of Canada

http://cpj.pwr.wroc.pl

Organizers

Wrocław University of Technology

Institute of Physics

Centre for Advanced Materials and Nanotechnology

Institute for Microstructural Sciences,

National Research Center, Ottawa, Canada

Institute of Physics, Polish Academy of Science, Warsaw

NanoQuine

QUantum INformation Electronics

University of Tokyo, Japan

Sponsors

Wrocław University of Technology

Rector of Wrocław University of Technology
Department of Fundamental Problems of Technology
Institute of Physics
Centre for Advanced Materials and Nanotechnology

Lower Silesian Voivodship
Marshal's Office

QuantumWorks

RÉSEAU DE L'INFORMATION QUANTIQUE CANADA

QUANTUM INFORMATION NETWORK CANADA

Government of Canada
Embassy of Canada

Coordinating Committee

Paweł Hawrylak

Institute for Microstructural Sciences, National Research Council of Canada, Ottawa, Canada

Yasuhiko Arakawa

Institute for Nano Quantum Information Electronics, University of Tokyo, Japan

Jacek Kossut

Institute of Physics, Polish Academy of Science, Warsaw, Poland

Jan Misiewicz

Institute of Physics, Wrocław University of Technology, Wrocław, Poland

Abstracts

Nanocomposite Semiconductor Ferromagnetic Systems

Tomasz Dietl

Institute of Physics, Polish Academy of Sciences, Warsaw, Poland
University of Warsaw, Poland

There is growing amount of evidences that owing to a significant contribution of *d* orbitals to bonding, semiconductors alloyed with transition metals may allow to fabricate in a self-organized fashion nanocomposite semiconductor/ferromagnetic metal systems with the controllable size, shape, and motive of buried ferromagnetic regions. Recent theoretical and experimental studies indicated that such modulated semiconductors may exhibit novel and hitherto unexplored functionalities in spintronics, but also in photonics and thermoelectrics [1,2].

In the talk we will review extensive studies of MBE grown (Zn,Cr)Te [3], either undoped or co-doped with N or I, and MOVPE-grown (Ga,Fe)N [4,5], either undoped or co-doped with Si or Mg. These materials have been thoroughly characterized by element specific microscopy and synchrotron radiation probes. The finding demonstrate that the transition metal (TM) cations can be distributed in the semiconductor matrix in a way giving rise either to a diluted random alloy or to ferromagnetic condensed semiconductor nanocrystals that aggregate by precipitation or by spinodal decomposition into regions more or less rich in the magnetic component. Since this aggregation correlates with the ferromagnetic response and no spontaneous magnetization is observed in the films without magnetic doping, we take our results as a strong support of the notion that the high-T_C ferromagnetism discovered in a number of magnetically doped oxides and semiconductors results from a non-uniform distribution of the magnetic component.

Interestingly, we find that the aggregation of TM cations exhibits a strong dependence on the growth flow rate and growth temperature, allowing – when appropriately mastered – a control of the solubility limit of the transition metal ions in the semiconductor matrix. Moreover, the formation of the TM-rich nanocrystals and, hence, the ferromagnetic response of the studied systems can be affected by co-doping with donors and acceptors. Our findings guide us to the far-reaching conclusion that the attractive force between magnetic cations can be adjusted through varying their charge state [3-6].

[1] H. Katayama-Yoshida, K. Sato, T. Fukushima, M. Toyoda, H. Kizaki, V. A. Dinh, P.H. Dederichs, *phys. stat. solidi* (a) **204** 15 (2007).
[2] T. Dietl, *J. Appl. Phys*. **103** 07D111 (2008).
[3] S. Kuroda, N. Nishizawa, K. Takita, M. Mitome, Y. Bando, K. Osuch, T. Dietl, *Nature Mat.* **6** 440 (2007).
[4] A. Bonanni, A. Navarro-Quezada, Tian Li, M. Wegscheider, Z. Matej,V. Holy, R.T. Lechner, G.Bauer, M. Rovezzi, F.D'Acapito, M.Kiecana, M. Sawicki, T. Dietl, *Phys. Rev. Lett.* **101** 135502 (2008).
[5] M. Rovezzi, F, D'Acapito, A. Navarro-Quezada, B. Faina, T. Li, A. Bonanni, F. Filippone, A. Amore Bonapasta, T. Dietl, *Phys. Rev*. B **79** 195209 (2009).
[6] T. Dietl, *Nature Mater*. **5** 673 (2006).

First Principles Modeling of Magnetic Tunnel Junctions

Hong Guo

Centre for the Physics of Materials and Department of Physics, McGill University, Montreal, QC H3A 2T8 Canada

I will discuss an aspect of nanoelectronic device theory, namely modeling nanoelectronics from atomic first principles. Some important issues of quantum transport theory in the atomic limit will be reviewed. I will then report a recent theoretical development for treating atomistic disorder in nonlinear and non-equilibrium quantum transport modeling. The theory uses non-equilibrium vertex corrections to handle the configurational average of random disorder at the density matrix level. Using this technique, we have analyzed spin injection in magnetic tunnel junctions with interface roughness as well as with oxygen vacancies in the tunnel barrier. Disorder effect is found to significantly alter spin polarized tunneling.

Nuclear Magnetic Resonance in Semiconductor Quantum Structures

Yoshiro Hirayama

Graduate School of Science, Tohoku University
ERATO Nuclear Spin Electronics Project
e-mail: hirayama@m.tains.tohoku.ac.jp

Nuclear magnetic resonance (NMR) is widely used in the physical, chemical, and biological sciences. However, conventional NMR based on induction-detection has drawbacks of low-sensitivity and the need of a large volume of sample. It is not suitable to investigate semiconductor quantum structures, whose characteristics are controlled by gates. To overcome these drawbacks, we have developed a resistively-detected technique relying on enhanced interactions between electron and nuclear spins at the $\nu = 2/3$ fractional quantum Hall state. It should be stressed that the special states of $\nu = 2/3$ are needed for dynamic nuclear-spin polarization and M_z detection, but we can apply NMR spectrum and nuclear-spin relaxation (T_1 time) measurements for any state we want to estimate [1].

These NMR and relaxation measurements have been successfully applied to semiconductor nanostructures as well as heterostructures. We clearly observed NMR spectra of ^{69}Ga, ^{71}Ga and ^{75}As in GaAs point contact region. The quadrupolar splitting found for the point contact devices was highly sensitive to a tiny strain in the structure. The nuclear-spin-based measurements are also successful to observe electron spin features, which are difficult to detect in conventional transport and optical measurements. For example, the spin texture called Skyrmion was detected as a strong enhancement of nuclear spin relaxation on either side of $\nu = 1$. Such relaxation measurement has been extended to quantum wires and the obtained results suggest mutually correlated Skyrmions in the wide 2DEG and its melting in the narrow wire structure [3].

As a novel manipulation of nuclear spins, we have demonstrated nuclear spin resonance using RF electric field instead of magnetic field [4]. The experiments were carried out at the $\nu = 2/3$ transition point. After dynamic polarization of nuclear spins, an RF electric field was applied to the gate. When the RF frequency is set at the resonance frequency of nuclear spins, the R_{xx} enhancement is suppressed, indicating that nuclear spins are depolarized. This nuclear electric resonance (NER) is induced by a temporal oscillation of the hyperfine field due to domain-wall spatial oscillations, which are excited by the RF electric field. The RF power and duration dependence of the NER spectrum provides insights into the interplay between nuclear spins and the oscillating domain walls [4]. Since RF electric field can be generated by exciting a gate, this technique has an advantage of spatial selectivity.

The experiments discussed here were carried out in collaboration with K. Muraki, G. Yusa, K. Hashimoto, N. Kumada, T. Kobayashi, S. Watanabe, G. Igarashi, and F. M. Hamzah.

[1] Y. Hirayama *et al.*, Semicond. Sci. and Technol. 24, 023001 (2009) (Topical Review).
[2] G. Yusa *et al.*, Nature, **434**, 1001 (2005).
[3] T. Kobayashi *et al.*, ICPS (2008).
[4] N. Kumada *et al.*, Phys. Rev. Lett. 101, 137602 (2008); S. Watanabe *et al.*, EP2DS (2009).

Optically Controlled Quantum Dot Nanomagnets

Sebastian Maćkowski

Institute of Physics, Nicolaus Copernicus University, Toruń, Poland

We report on several spectacular experimental observations obtained for self-assembled CdTe quantum dots doped with magnetic impuritie.

First of all, we find that for such structures resonant excitation of spin polarized excitons leads to robust ferromagnetic alignment of magnetic impurities within CdMnTe quantum dots. Due to strong spatial confinement this optically induced zero-field magnetization is very stable and persists up to 150K. This remarkable effect has been observed on both ensemble and single quantum dot levels.

Secondly, subwavelength optical microscopy imaging of CdMnTe quantum dots reveals that at B = 0T for continuous laser illumination each dot exhibits strong and unique circular polarization despite completely unpolarized ensemble emission. This implies that after an exciton recombines, the spontaneous ferromagnetic alignment of magnetic impurities persists for over 100 microseconds, which is a million times longer than in CdMnTe quantum wells. The spin memory effect points toward a qualitatively different picture of magnetization dynamics in the zero-dimensional limit.

We also propose and demonstrate a way to directly probe the magnetization of magnetic quantum dots by measuring the exciton Zeeman splitting of nonmagnetic CdTe quantum dots placed in the vicinity of ferromagnetically aligned CdMnTe quantum dots. From the dependence of the Zeeman splitting on the polarization of the excitation we estimate the internal magnetic field of spin polarized Mn ions to be of the order of 0.2T. Possible mechanisms responsible for the observed effects will be discussed. Importantly, as the exciton spin relaxation in nonmagnetic CdTe quantum dots depends on the energy level degeneracy (which can be lifted by external magnetic field), this approach can be successfully used to tune the spin dynamics of the excitons confined in semiconductor quantum dots.

S. Mackowski, T. A. Nguyen, H. E. Jackson, L. M. Smith, J. Kossut, G. Karczewski,*Applied Physics Letters* **83**, 5524 (2003).

S. Mackowski, T. Gurung, T.A. Nguyen, H.E. Jackson, L.M. Smith, G. Karczewski, J. Kossut, *Applied Physics Letters* **84**, 3337 (2004).

S. Mackowski, T.A. Nguyen, T. Gurung, K.P. Hewaparakrama, H.E. Jackson, L.M. Smith, J. Wróbel, K. Fronc, J. Kossut, G. Karczewski, *Physical Review* **B 70**, 245312/1-9 (2004).

S. Mackowski, T. Gurung, H.E. Jackson, L.M. Smith, J. Kossut, G. Karczewski, *Applied Physics Letters* **87**, 072502/1-3 (2005).

T. Gurung, S. Mackowski, G. Karczewski, H.E. Jackson, L.M. Smith, *Applied Physics Letters*, **93**, 153114/1-3 (2008).

Physics of Graphene and its Multilayers: From Zero-Mode Anomalies to Band-Gap Opening

Tsuneya Ando

Department of Physics, Tokyo Institute of Technology, 2-12-1 Ookayama, Meguro-ku, Tokyo 152-8551, Japan

URL: http://www.stat.phys.titech.ac.jp/ando/

The purpose of this paper is to give a brief review on characteristic features of electronic states in graphene and its multi-layers mainly from a theoretical point of view, together with topics on roles of electron-phonon interactions studied recently.

The electron motion in graphene is governed by Weyl's equation for a neutrino or the Diracequation with vanishing rest mass characterized by a velocity which is about 1/300 of the light velocity. The pseudo-spin wave function exhibits a sign change due to Berry's phase when the wave vector $\boldsymbol{k}$ is rotated around the origin and therefore has a topological singularity at $\boldsymbol{k} = 0$. This singularity is the origin of the peculiar behavior in the transport properties of graphene, such as the minimum conductivity in the absence of a magnetic field, the quantum Hall effect, and the dynamical conductivity [1], as well as the absence of backscattering in metallic carbon nanotubes [2–4]. The neutrino equation is invariant under special time-reversal operation S corresponding to the system with strong spin-orbit interaction. Because S is not the real time-reversal symmetry, it can be destroyed by various perturbations, leading to interesting symmetry crossover characteristic to the graphene system [5–8].

There are three different kinds of phonons contributing to electron-phonon interaction. They are long-wavelength acoustic phonons, zone-center optical phonons, and zone-boundary phonons [9]. In particular, optical phonons can be strongly modified by the Fermi-level tuning due to the interaction [10,11]. Inter-layer interaction in bilayer graphene destroys the linear dispersion into an approximate parabolic dispersion [12,13]. In this system, strong asymmetry in the potential of two layers can be introduced by external fields, leading to band-gap opening and strong mixing of symmetric and antisymmetric optical phonons [14,15].

[1] T. Ando, *Physica* E **40** (2007) 213 and references cited therein.
[2] T. Ando and T. Nakanishi, *J. Phys. Soc. Jpn*. **67** (1998) 1704.
[3] T. Ando, T. Nakanishi, and R. Saito, *J. Phys. Soc. Jpn*. **67** (1998) 2857.
[4] T. Ando and H. Suzuura, *J. Phys. Soc. Jpn*. **71** (2002) 2753.
[5] H. Suzuura and T. Ando, *Phys. Rev. Lett.* **89** (2002) 266603.
[6] T. Ando and K. Akimoto, *J. Phys. Soc. Jpn*. **73** (2004) 1895.
[7] T. Ando, *J. Phys. Soc. Jpn*. **75** (2006) 054701.
[8] E. McCann, K. Kechedzhi, V. I. Falko, H. Suzuura, T. Ando, and B. L. Altshuler, *Phys. Rev. Lett.* **97** (2006) 146805.
[9] H. Suzuura and T. Ando, *J. Phys. Soc. Jpn*. **77** (2008) 044703.
[10] T. Ando, *J. Phys. Soc. Jpn*. **75** (2006) 124701.
[11] T. Ando, *J. Phys. Soc. Jpn*. **76** (2007) 024712.
[12] E. McCann and V. I. Falko, *Phys. Rev. Lett*. **96** (2006) 086805.
[13] M. Koshino and T. Ando, *Phys. Rev*. B **73** (2006) 245403.
[14] T. Ando, *J. Phys. Soc. Jpn*. **76** (2007) 104711.
[15] T. Ando and M. Koshino, *J. Phys. Soc. Jpn*. **78** (2009) 034709.

Dirac-like Electrons and Phonons in Graphene-based Systems

Marek Potemski

Grenoble High Magnetic Field Laboratory, CNRS, Grenoble, France

The results of magneto-spectroscopy (absorption and Raman scattering) studies of graphene, of multilayer-graphene on SiC and of graphite will be reported. Properties of these relativistic-like electronic systems will be discussed and their quality evaluated. The effects of resonant magneto-phonon will be also reported.

Optical and TEM Investigations of Epitaxial Graphene on SiC

A. Drabińska[1], K. Grodecki[1,2], J.Borysiuk[1] , R. Bożek[1], A. Wysmołek[1], K. Korona[1], W. Strupiński[2], R. Stępniewski[1], J.M. Baranowski[1,2]

[1] *Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Poland*
[2] *Institute of Electronic Materials Technology, Warsaw, Poland*

Production of graphene by annealing of silicon carbide (SiC) substrates has recently attracted a lot of interest. Opposite to the micromechanical cleavage the annealing of SiC substrates this method is more compatible with nowadays industrial processing techniques. However, reaching large area coverage with controlled number of deposited graphene layers still is a big challenge.

In this communication optical absorption and Raman scattering as well as Transmission Electron Microscopy (TEM) studies of epitaxial graphene structures obtained on 4H-SiC on-axis substrates are presented. The graphene layers were grown using Epigres V508 hot wall chemical vapour deposition (CVD) reactor with a SiC and TiC coated graphite susceptors, heated by RF generator. Before the growth of graphene the SiC substrates were etched at 1600^0C in atmosphere of hydrogen and propane. After etching, process of graphitisation (annealing) was done at 1600^0C in argon atmosphere. Series of samples with different argon pressure in the reactor and different annealing times were studied.

Optical absorption and Raman scattering were used to determine the thickness and furthermore the numbers of graphene layers. Both techniques showed to be consistent. The observed dependence of the number of graphene layers on time and argon pressure, strongly suggests that growth mechanism of graphene deposited on the on carbon face of 4H-SiC(000-1) substrates is limited by evaporation and two-dimensional diffusion of Si.

The High Resolution TEM (HRTEM) revealed a distinctive distance differences between the first carbon layer and SiC surface for graphene grown on carbon and silicon terminated faces of the substrate. The first graphene layer grown on silicon terminated surface is separated about 2Å from SiC surface. This short distance indicates that a strong covalent bonds between carbon layer and silicon atoms on the SiC surface exist. In contrary to this result the HRTEM of carbon terminated substrate does not show such close distance of the first carbon layer in respect to SiC surface. The distance between first carbon layer and SiC surface for carbon polarity is above 3Å, what indicates lack of strong covalent bonds. In this case graphene is loosely bound with the SiC surface, and it can be easily removed from the SiC crystal. The prolonged growth on on-axis 4H-SiC substrate with carbon polarity, in addition to increase of number of graphene layers, leads to observed splitting between stack of graphene layers and the SiC surface.

Magnetism and Correlations of Fractionally Filled Zero-energy States in Graphene Quantum Dots

A.D. Güçlü[1], P. Potasz[1,2], O. Voznyy[1], M. Korkusiński[1] and P. Hawrylak[1]

[1]*Institute for Microstructural Sciences, National Research Council of Canada, Ottawa, Canada*
[2]*Institute of Physics, Wroclaw University of Technology, Wrocław, Poland*

Graphene quantum dots are atomically thick nanometer-scale islands etched out of a single graphene sheet. In this work, we focus on electronic and magnetic properties of triangular dots with zig-zag edges. Strikingly, such structures were suggested [1,2] to lead to a band of degenerate zero-energy states at the Fermi level (Dirac point). Therefore, electrons in the zero energy band (shell) can be expected to form a strongly correlated electronic system, in analogy with the fractional quantum Hall effect. The degeneracy is proportional to the edge size and can be made macroscopic. This opens up a possibility of designing strongly correlated systems as a function of the fractional filling of the shell at the zero energy, in analogy with the quasi-two-dimensional electrons exhibiting the fractional quantum Hall effect, but without the need for magnetic field. Furthermore, it was shown [1,2] that within Hubbard approximation the edges of the dot are spin polarized and the ground state can be treated as a solid ferromagnet.

In this work, we present new results demonstrating the important role of electronic correlations, beyond the Hubbard and mean-field models [1,2]. The interactions are treated by a combination of density functional theory (DFT), tight-binding, Hartree-Fock and configuration interaction methods (tb-HF-CI). In addition to the on-site interaction term, all scattering and exchange terms within second nearest neighbors, and all direct interaction terms are included in the calculations. Our model also includes the effect of next nearest neighbor hopping term, positive background charge, and charge induced on the gate. We show that the magnetic properties of the ground and excited states of triangular graphene quantum dots are strongly dependent on the filling fraction of the band of zero-energy states and on the dot size, in contrast with the Hubbard model that favorizes fully magnetized zero-energy states.

[1] J. Fernandez-Rossier and J.J. Palacios, *Phys. Rev. Lett*. **99** 177204 (2007).
[2] M. Ezawa, *Phys. Rev.* **B 77**, 155411 (2008).

Directed Self-Assembly of Single Quantum Dot Optical Devices

Dan Dalacu

Institute for Microstructural Sciences, National Research Council of Canada, Ottawa, Canada

Progess on controlling the nucleation site of a single InAs/InP quantum dot is discussed. The deterministic approach, with its a priori knowledge of the quantum dot position, leads to straight forward fabrication of gated single dot structures and coupled dot-cavity systems using standard alignment techniques. Examples are given of deterministically nucleated single dots in vertical and lateral electric fields and in high finesse optical microcavities. Such devices form the basis of efficient sources of single photons and entangled photon pairs and their implementation using deterministically nucleated quantum dots is described.

Multiexcitonic Emission from Quantum Dots Grown by "Indium-Flush" Method

A. Babiński[1], A. Golnik[1], T. Tite[1], P. Kossacki[1], J.A. Gaj[1], S. Raymond[2], P. Płochocka[3], M. Potemski[3] and Z. Wasilewski[2]

[1]*Institute of Experimental Physics, University of Warsaw, Warsaw, Poland*
[2]*Institute for Microstructural Sciences, National Research Council, Ottawa, Canada*
[3]*Laboratoire National des Champs Magnétiques Intense , CNRS, Grenoble, France*

Quantum dots (QDs) are often referred to as "artificial atoms". Their electronic and optical properties are influenced by symmetry properties of the confining potential, atomic crystal structure and the geometric shape of the dots. In the case of "lens-shaped" QDs, while the energies and envelope wave functions of electronic states are well described by the *s*, *p*, and *d* energy shells of a two-dimensional harmonic oscillator, the hole energy levels cannot be grouped into such quasidegenerate shells. This is in contrast to the structure of QDs grown by the indium-flush method, in which both electronic and hole states can be described by the *s*, *p*, and *d* energy shells of a two-dimensional harmonic oscillator.

Properties of the QD grown by the indium-flush method will be reviewed in this presentation. The characteristic electronic structure of the "indium-flushed" dots is reflected in the pattern of the magnetic field evolution of the multiexcitonic emission, which resembles a single-particle Fock-Darwin diagram. Effects of interaction between the multiexcitonic configurations are clearly visible when single-particle states become nearly degenerate: at $B = 0$ and at a level crossing induced by the magnetic field.

Photonic Band Gap Materials: Light Trapping Crystals

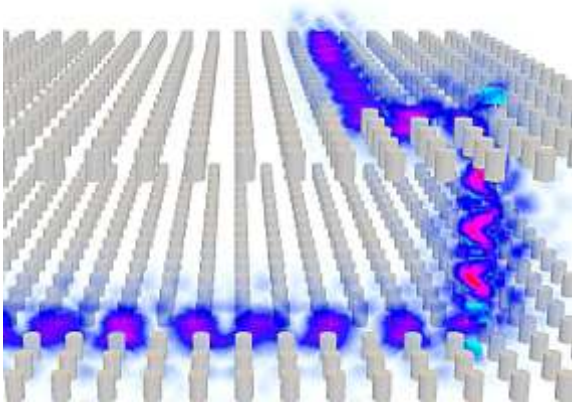
Sajeev John

Department of Physics, University of Toronto, Canada

Photonic Band Gap (PBG) materials are artificial, periodic, dielectrics that enable engineering of the most fundamental properties of electromagnetic waves. These include the laws of refraction, diffraction, and spontaneous emission of light. Unlike traditional semiconductors that rely on the propagation of electrons through an atomic lattice, PBG materials execute their novel functions through selective trapping or “localization of light”. This is a fundamentally new and largely unexplored property of Maxwell’s equations. This is also of practical importance for alloptical communications, information processing, efficient lighting, and solar energy trapping.

Three dimensional (3D) PBG materials offer a unique opportunity to simultaneously (i) synthesize micron-scale 3D circuits of light that do not suffer from diffractive losses and (ii) engineer the electromagnetic vacuum density of states in this 3D optical micro-chip. This combined capability opens a new frontier in integrated optics as well as the basic science of radiation-matter interactions.

I review recent approaches to micro-fabrication of photonic crystals with a large 3D PBG centered near 1.5 microns. These include direct laser-writing techniques, holographic lithography, and a newly invented optical phase mask lithography technique. I discuss consequences of PBG materials in classical and quantum electrodynamics.



Growth and Spectroscopy of Semiconductor Quantum Dots

Jan Gaj

Physics Department, Warsaw University, Warsaw, Poland

The talk will be addressed to general public, including high school students. Semiconductor quantum dots attract a growing attention, as they can be applied in emerging new fields related to information technologies: quantum cryptography and quantum computing. A single semiconductor quantum dot approaches the ultimate limit of information storage density.

After a short motivation part, growth of semiconductor quantum dots by molecular beam epitaxy (MBE) will be described, in particular, spontaneous formation of self-assembled quantum dot systems. Basic characterization methods will be presented, including in-situ electron diffraction, atomic force microscopy, and high resolution electron transmission microscopy.

Then optical experiments will be discussed: how we select a single quantum dot from a dense ensemble, and use light to write information in the dot. Various experimental techniques will be described: from simple microphotoluminescence measurements to various time- and polarization-resolved experiments, including correlated photon counting. The experiments involve magnetic fields and low temperatures, as well as tunable laser providing ultra-short femtosecond light pulses. These advanced experimental tools allow us to study the evolution of the information recorded in a quantum dot, under influence of various perturbations, including in-plane anisotropy of quantum dots, electric and magnetic fields, etc. Finally, read-out of the information from the quantum dot will be described.

A Quarter-Century of Quantum Dots: From Science to Practical Implementation

Yasuhiko Arakawa

Institute for Nano Quantum Information Electronics, The University of Tokyo
4-6-1 Komaba, Meguro, Tokyo 153-8505 Japan
e-mail: arakawa@iis.u-tokyo.ac.jp

Following Esaki's pioneering work on super-lattices and quantum wells, the concept of quantum dots was proposed by Arakawa and Sakaki in 1982 for application to semiconductor lasers with the theoretical prediction of temperature insensitive threshold current characteristics. Full confinement of electrons in the quantum dots has brought up unique features of artificial atoms, such as discrete energy states and correlation effects due to spin/charging effects. This has resulted in a wide variety of experimental investigations into semiconductor physics and device applications.

Owing to recent progress in the self-assembled growth technique of high-quality quantum dots, high speed 1.3 μm quantum-dot lasers with temperature-insensitive characteristics were demonstrated by the University of Tokyo and Fujitsu. This successful achievement led to the launch of a curve-out type of venture company called QD Lasers Corporation in 2006. The quantum dot lasers will be in a real commercial market in the quite near future for telecom applications. In addition to nanophotonic device applications, single or coupled quantum dots are promising for quantum information devices, such as single photon emitters and quantum-bit devices, by manipulating single photon-electron interaction and quantum entangled states based on electron spins, charges, and nuclear spins.

In this presentation, we discuss the basic physics of the quantum dot and relevant recent advances for nanophotonics including quantum dot lasers, single artificial atom lasers and coherent light matter interaction quantum dots embedded in 2D/3D photonic crystal nanocavity. In addition, other potential applications such as bio-medical markers and solar energy technologies are described. Quantum dots are one of the most important nanostructures for the future "Green Society" which can be realized by highly efficient and low-power ubiquitous IT.

Nanoscience: From Semiconductor Quantum Dots and Wires to Biosensors

Gerhard Abstreiter

Walter Schottky Institut and Physik-Department, Technische Universität München, 85748 Garching, Germany

Nanoscience is based on highly interdisciplinary research and brings together scientists from physics, biophysics, chemistry, biochemistry, engineering and medicine. It is based on the control of condensed matter and biological systems on an atomic or molecular level, leading to new functionalities and applications in various fields. Our nano related research is embedded in the center of excellence "Nanosystems Initiative Munich" which concentrates on nanosystems for information technology and biomedical engineering. This includes the realization of novel semiconductor nanostructure devices based on so-called quantum dots and nanowires which allow the control of single charges, spins, and photons. These studies are basis for future information- and quantum information technologies. Another major research area is the development of novel biochemical sensors. After an introduction, I will present and discuss selected examples of both research areas.

This work has been supported financially by the German Research Association (DFG) via collaborative research center 631 and the excellence cluster Nanosystems Initiative Munich (NIM).

see: www.wsi.tum.de and www.nano-initiative-munich.de

Electron Spin Qubits and Spin-Photon Interface Using Quantum Dots

Seigo Tarucha

Department of Applied Physics, The University of Tokyo
ICORP Quantum Spin Information Project, Japan Sci. & Tech. Agency
Institute for Nano Quantum Information Electronics, The University of Tokyo, Tokyo, Japan

Manipulating and detecting photons, and electron spins have been intensively studied for implementing qubits in information transmission, and computing, respectively. Quantum state transfer or quantum media conversion (QMC) between these qubits is a strong requirement for constructing a comprehensive quantum network. Electron spin qubits with quantum dots (QDs) have recently been demonstrated using various techniques, and to scale up the qubits will be crucial as the next step. On the other hand, this achievement is motivating study on the photon-spin QMC in QDs, but the experiments have just started. In this talk I will review our recent progress in making multiple spin qubits and single photon-electron interface with QDs.

Electron spin resonance (ESR) is the fundamental concept of spin qubits, in which two Zeeman states are defined by a static magnetic field and superposed by an ac magnetic field. To manipulate individual electron spins in QDs in a scalable manner, both magnetic fields must be local to each QD. We have developed a technique of using a micro-magnet and ac electric field to meet this requirement. A micro-magnet placed on top of each QD is magnetized by application of external in-plane magnetic field to generate a field gradient out-of-plane and an excess in-plane field at the dot. Application of an ac electric field to the dot oscillates an electron inside to generate a local ac magnetic field only experienced by the electron. In addition, the ESR condition depends on the external magnetic field as well as the micro-magnet induced in-plane field. We use a double QD integrated with a micro-magnet to observe cw ESR peaks and Rabi oscillations of two individual spins, and extend the technique to triple QDs.

One of the prerequisites to implement the photon-spin interface is to detect a single photon-generated electron and reset it in a time scale faster than the spin-flip time in a controlled manner. We use a QD and a quantum point contact charge detector to demonstrate single-shot detection of single electrons generated by single photons. The photo-generated electron can be ejected from the dot in the tunable time range from shorter to longer than the spin-flip time. We then use a spin-dependent tunnel coupling of the dot to the leads in the spin-resolved edge states to distinguish the spin orientation of photo-generated electrons. We find that this technique works well for the short resetting time of photo-generated electrons.

Triple Quantum Dots

Andrew Sachrajda

Institute for Microstructural Sciences, National Research Council, Ottawa, Canada

In this talk I will briefly discuss two recent experiments. Triple Quantum dot few electron systems are potentially useful for studying novel physics, demonstrating quantum information functionalities such as entanglement and spin buses as well running simple algorithms. I will describe our new lateral triple dot in series layout, focusing on the excellent stability diagram tunability that we are able to achieve with it. In the second experiment I will discuss measurements of conductance fluctuations in a graphene monolayer across the electron-hole puddle regime near the charge neutrality point. I will demonstrate that at even fairly low magnetic fields the results are dominated by single electron charging of incidental Quantum Hall Quantum dots. From our measurements we are able to extract parameters for the size and range of the fluctuations.

Controlled Coupling and Occupation of Silicon Atomic Quantum Dots at Room Temperature

Robert A. Wolkow

Department of Physics, University of Alberta
National Institute for Nanotechnology, Edmonton, Alberta Canada

It is demonstrated that the zero-dimensional character of the silicon atom dangling bond (DB) state allows controlled formation and occupation of a new form of quantum dot assemblies - at room temperature. Coulomb repulsion causes DBs separated by less than ~2 nm to experience reduced localized charge. The unoccupied states so created allow a previously unobserved electron tunnel-coupling of DBs, evidenced by a pronounced change in the time-averaged view recorded by scanning tunneling microscopy. It is shown that fabrication geometry determines net electron occupation and tunnel-coupling strength within multi-DB ensembles and moreover that electrostatic separation of degenerate states allows controlled electron occupation within an ensemble.

M. Baseer Haider, M. Baseer Haider, Jason L. Pitters, Gino A. DiLabio, Lucian Livadaru, Josh Y. Mutus and Robert A. Wolkow, "Controlled Coupling and Occupation of Silicon Atomic Quantum Dots at Room Temperature", *Physical Review Letters* **102**, 046805 (2009).

Transient Shot Noise and Electron Counting in Double Quantum Dots

Frank Wilhelm

University of Waterloo, IQC and Department of Physics and Astronomy, Waterloo, Canada

Spin blockade is a clear signature of spin physics in transport in quantum dots. It blocks certain transport cycles by spin selection rules and thus allows only a finite packet of charges to be transmitted. The symmetries underlying spin blockade can be broken by either spin-flip cotunneling, or by a magnetic field gradient. I am going to describe a number of striking consequences of these physics:
i) Even with cotunneling, spin blockade configurations can be used for initialization of spin states that is much faster than direct spin relaxation.
ii) The transmitted charge will on average have fractional values reflecting the process branching ratios, even though there are no manybody correlations in this system.
The same physics can be recovered in the steady-state shot noise.

Based, in parts, on
F. Qassemi, W. A. Coish, and F. K. Wilhelm, *Phys. Rev. Lett.* **102**, 176806 (2009).

Phonon-induced Pure Dephasing of Singlet-Triplet Superpositions in Double Quantum Dots

Paweł Machnikowski and Katarzyna Roszak

Institute of Physics, Wrocław University of Technology, Wrocław, Poland

We will show that superpositions between singlet and triplet states of two electrons in double quantum dots undergo pure dephasing due to elastic phonon scattering. This mechanism originates from the fundamental principles of quantum mechanics: due to Pauli exclusion, transitions from the low-energy singly-occupied configurations to doubly-occupied states are allowed only for singlet states, while they are forbidden for triplet states. Although real transitions to these high-energy configurations are suppressed at low temperatures, two-phonon processes are possible in which the high-energy state is used only virtually and a phonon scatters on the electrons in an elastic way. As this scattering is possible only in the singlet state each scattering event supplies the phonon reservoir (environment) with information about the quantum state of the electrons. This distinguishability must lead to dephasing of any coherent superposition between singlet and triplet states.

This mechanism seems to be qualitatively different from any previously discussed processes of spin decoherence in QDs. In particular, it does not require spin-orbit coupling, hyperfine interaction, or any other direct or indirect spin-environment coupling. Calculations performed for a model gate-defined lateral GaAs/AlGaAs DQD show that the scattering process considerably contributes to spin decoherence at sub-Kelvin temperatures, yielding microsecond dephasing times, consistent with experimental observations.

K. Roszak and P. Machnikowski, arXiv:0903.0783v1.

Toward Topological Quantum Computing: Skyrmions in a Half-Filled Second Landau Level

Arkadiusz Wójs[1,2], Gunnar Möller[1], Steven Simon[3], and Nigel Cooper[1]

[1]*TCM Group, Cavendish Laboratory, University of Cambridge, UK*
[2]*Institute of Physics, Wroclaw University of Technology, Poland*
[3]*The Rudolf Peierls Centre for Theoretical Physics, University of Oxford, UK*

In the context of fractional quantum Hall effect, skyrmions are topological excitations of a two-dimensional incompressible electron liquid, carrying a single (fractional) quantum of electric charge and massive spin. A known example is the Laughlin $\nu = 1/3$ state in which the skyrmions have been both demonstrated experimentally and understood via its mapping onto a completely filled Landau level of composite fermions. Spin dynamics of the incompressible liquids in the Landau level, including the most prominent $\nu = 5/2$ state, are less explored. Adiabatic connection of the polarized phase to an intriguing Moore-Read "pfaffian" wave function with nonabelian quasiparticles has been convincingly demonstrated only recently. On the other hand, it is still not generally accepted if the ground state remains polarized unaided by the Zeeman spin splitting.

In this lecture we will present our recent results on the spin excitations of the $\nu = 5/2$ state. Exact diagonalization studies for up to 12 electrons with spin (matrix dimensions exceeding 10^9) reveal rotationally invariant unpolarized states at flux (i.e., Landau level degeneracy) around the Moore-Read ground state. These states exhibit spin textures, which we identify, based on the analysis of their charge and spin, pair an triplet correlation functions, as the positive and negative skyrmion excitations of the Moore-Read state (or of its particle-hole conjugate at the same filling factor). We devise a method to construct trial skyrmion wave functions for arbitrary, correlated, polarized many-body states, and obtain significant overlaps with the numerical skyrmion states from the exact diagonalization. An interesting aspect of the $\nu = 5/2$ state is that its skyrmions carry twice the charge of an elementary spinless quasiparticle. As the spin polarization at this filling factor is tuned from full to none, we observe a transition of the excitation spectrum that can be interpreted as binding of a pair of like-charged quasiparticles into a single skyrmion. We show that skyrmion states may be energetically competitive with the quasiparticles at low Zeeman splittings. Disorder and high quasiparticle density are also discussed as further mechanisms for depolarization.

Stability of Functionalized Carbon Nanotubes

Karolina Milowska, Magda Birowska, and Jacek A. Majewski

Faculty of Physics, University of Warsaw, Warsaw, Poland

Functionalization of carbon nanotubes (CNTs) with simple organic molecules plays an important role in applications of CNTs, either as electrical sensors of chemical and/or biological substances or as an enforcement of weak materials (like polymers) to obtain strong composite materials. Recently it has been observed a lot of research activity in these fields. We have performed extensive studies to determine the stability of the functionalized CNTs with simple organic molecules such as CH_n, NH_n, OH, and COOH. We discuss the dependence of the cohesive energies of functionalized CNTs, its deformations, and changes in the electronic structure on the density of the adsorbed molecules. All these factors influence the electrical and mechanical properties of the functionalized CNTs and are important for reliable description of the sensor electrical characteristics and also for modeling composite materials. Our studies are based on the *ab initio* calculations in the framework of the density functional theory. We use the generalized gradient approximation (GGA) for the exchange-correlation density functional and supercell geometry within the numerical package SIESTA.

Our studies reveal physical mechanisms of the binding of the studied groups to the CNTs. Generally, the stability of the functionalized CNTs is weakly dependent on the diameter of the CNTs, whereas the stability strongly decreases with the density of the adsorbed groups. In particular, we find that the NH_n and CH_n groups with n larger than two do not bind to the CNTs. In particular, it turns out that practically only CH_2 groups make reasonably strong bonds to the CNTs (CH_3 groups bind, but extremely weakly with bond length of 1.56 Å). In the case of CH_4 groups, we observe their dissociation into CH_2 and H_2 dimer placed in the surrounding of CNT; CH_2 binds to the CNTs, whereas H_2 remains unbound. The functionalization of CNTs with NH_n causes practically no deformation of the CNTs, whereas the CH_n groups attached to the CNTs cause reconstruction of the CNTs.

Interface States in Carbon Nanotube Junctions

Włodzimierz Jaskólski

Institute of Physics, Nicolaus Copernicus University, Toruń, Poland

Carbon nanotubes are one of the most promising materials to develop future nanoelectronics. A progress in this field towards real applications depends on the ability to form junctions between different nanotubes. Recently, the controlled synthesis of carbon nanotube intramolecular junctions has been reported. Intermolecular junctions present often interface states, which are commonly regarded as a drawback in device performance, but they may also provide a means of achieving diode behavior at the nanoscale.

We study the nature and origin of interface states in carbon nanotube intramolecular junctions between tubes. Such states appear usually around the Fermi level and are relevant for transport properties of carbon nanotube junctions. We focus on achiral junctions between (n,n) and (2n,0) tubes, which joined by n pairs of pentagon/heptagone topological defects.

Since the early studies of carbon nanotube junctions it was suggested and commonly accepted that interface states are due to topological defects. However, our results show that these states are not caused by the pentagon/heptagon defects but originate from the edge states of zig-zag nanoribbons and zig-zag (2n,0) tubes. We have found that the number of interface states increases with tube diameter following a multiple-of-three rule. By applying the Born-von Karman boundary condition to an interface between armchair- and zigzag-terminated graphene layers, we are able to precisely explain their number and their energies. Our results give a new vision on the nature of interface states and have implications in other systems, such as graphene vacancies or substitutional impurities.

ZnO Biosensing

Danek Elbaum

Institute of Physics, Polish Academy of Sciences, Warsaw, Poland

ZnO nanostructures were obtained using two diverse methods: sol-gel and electrosining.

ZnO nanocrystals nad ZnO/MgO core/shell nanocrystals have interesting biological properties (antibacterial, antifungal). ZnO nanocrystals have recently attracted a lot of attention as promising candidates for novel devices, due to a possibility of continuous tuning of optical and electronic properties by varying the particle sizes. They are also of interest for pharmaceutical industry, medicine and/or biology. Obtained nanocrystals were characterized structurally by AFM, TEM , X-ray diffraction and optically by absorption and emission.

We prepared ZnO nanocrystals in colloidal suspensions using a sol-gel method and observed a decrease of the reaction activation energy with an increase in the polarity of the applied solvent. Therefore, the growth rate was higher in a solvent with greater dielectric constant. With increasing nanocrystal sizes the absorption onset was red-shifted. An effective mass approximation model was used to determine the nanocrystal radii. The results were compared with sizes obtained from AFM analysis and a good correlation was found. Depending on conditions and reaction time, we obtained nanocrystals with radii ranging from 2 to 5 nm. Addition of MgO shell resulting in a more intense and stable visible emission that is characteristic of nanocrystalline ZnO. MgO prevents aggregation of ZnO nanoparticles. XRD patterns of powdered ZnO/MgO nanocrystals and TEM data proved wurtzite crystalline structure

Electrospinning is a method capable to produce fibers with diameters ranging from tens of nanometer to microns. Electrospun nanofibrous scaffolds have great potential in several biomedical applications, such as wound dressing, enzyme immobilization, drug delivery, tissue engineering, and they can serve as materials for biosensors. Semiconductor nanofibers are also candidates for applications in electronics and optoelectronics. By adding acetates of other metals, we obtained nanofibers doped with Co, Fe, Al, Mn, Mg. Structural characterization was performed by AFM, SEM, and X-ray diffraction. Additionally, optical characterization was done by cathodoluminescence and photoluminescence measurements at room temperature. XRD investigations proved that the nanofiber material is a wurtzite ZnO. AFM and SEM studies both revealed nanofiber diameters ranging from 100 to 300 nm. Moreover, SEM images of undoped ZnO show that the nanofibers consist of nanocrystallites which diameters from 10 to 50 nm as jointly determined by XRD and SEM . However, metal-doped nanofibers contain significantly smaller nanocrystallites. Moreover, preliminary PL studies of single nanofibers were performed. We observed increased crystal size and investigated the evolution of CL spectra with growing calcination temperatures.

Acknowledgements: The research was partially supported by the European Union within European Regional Development Fund, through grant Innovative Economy (POIG.01.01.02-00-008/08) and was partially supported by the Ministry of Science and Higher Education (Poland) through Grant No. N515 015 32/0997 and No. N N518 424036

Patch-Clamp Array Chips for Advanced Neurodegenerative Disease Models and Faster Pharmacological Development

Christophe Py

Institute for Microstructural Sciences, National Research Council, Ottawa, Canada

In-vitro models are used extensively to study the molecular mechanisms that regulate the transmission and processing of information in the brain through synaptic communication in neuronal networks. Ion channels are proteins embedded in cell membranes that regulate ion currents and are important therapeutic targets for pharmacological intervention. Their activity is traditionally monitored by the glass-pipette patch-clamping method, the importance of which was recognized in Neher and Sakmann's 1991 Nobel Prize in medicine, and that remains the gold standard of electrophysiology. In this method, a small-tipped glass pipette filled with electrochemically conductive (physiological saline) solution is sealed to a patch of cell membrane by suction and its voltage potential clamped with respect to a reference electrode immersed in the electrochemically conductive culture medium. Small currents resulting from ion channel activity across the membrane are then recorded. This technique has remarkable resolution but is an extremely laborious process and is very invasive to cells. This represents a bottleneck for high-throughput pharmacological screening and drug development, and considerable effort has been invested in automating patch-clamping. Recently, this has resulted in the development of planar patch-clamp chips, where the apex of the pipette is replaced by a microscopic hole micromachined in a self-supported film on which the cell is placed. The chip is then mounted in a two-chamber setup: the top one serving as the culture dish; the bottom one as the equivalent of the inside of the glass pipette and containing the physiological saline. Current planar patch-clamp chip technology, however, still does not address a second limitation of the patch-clamping technique, namely the difficulty in simultaneously recording the activity of several cells engaged in synaptic connectivity. This significantly restricts the power of in-vitro models for diseases whose symptoms are synaptic dysfunctions, such as Alzheimer's and other cognitive diseases.

NRC is developing a multiple-patch chip consisting of micro-holes patterned in self-supported membranes and integrated subterranean microfluidic channels aligned to them to miniaturize the glass-pipettes, as well as growth cues to guide cells in organized networks in alignment with the interrogation sites. I will show the different stages of development of the chip and actual electrophysiological activity recorded from cultured neurons. This chip will provide more powerful model to neurobiologists and electrophysiologists studying other diseases in which network activity plays an important role, such as cardiac arrhythmia. The control of networks into simple organized patterns also offers more direct models to advance computational neuroscience. Finally, in vitro studies of neuronal networks offer fascinating models to study the integrative information processing principle of the brain that may one day complement Boolean information processing. Thus, our neurochip may also help further the exploration of new computing paradigms.

Plasmons in Metallic Nanoparticles: Towards Enhancement of Metal-Nano-Modified Solar Cell Efficiency

L. Jacak[1], J. Jacak[1], J. Krasnyj[2], W. Jacak[1], R. Gonczarek[1]

[1]*Institute of Physics, Wrocław University of Technology, Wrocław, Poland*
[2]*Theor. Phys. Group., International University, Odessa, Ukraine*

The random-phase-approximation semiclassical scheme for description of plasmon excitations in metallic nanosphere is formulated in an all-analytical version. The spectrum of plasmons in metallic nanosphere is determined including both surface and volume type excitations and their mutual connections. It is demonstrated that the surface plasmons in nanosphere can be excited by the volume ones, while converselly not. The various channels for damping of surface plasmons are evaluated and the relevant resonance frequency shifts are compared with the experimental data for metallic nanoparticles of different dimensions located in dielectric medium or on the semiconductor substrate. The strong enhancement of the energy transfer from surface plasmon oscillations to the substrate semiconductor is explained in the regime of a near-field coupling in agreement with recent experimental observations for metallically nanomodified photo-diode systems.

Multi-Exciton Generation in CdSe Nanocrystals

M. Korkusiński, O. Voznyy, and P. Hawrylak

Institute for Microstructural Sciences, National Research Council of Canada, Ottawa, Canada

One of the potential routes toward improving the efficiency of semiconductor solar cells involves the use of semiconductor nanocrystals (NCs) where generation of many electrons and holes following the absorption of a single photon becomes possible [1-3]. In this MEG process, the excess energy of a highly excited exciton is converted into excitation of additional electron-hole pairs instead of being dissipated through lattice vibrations. Here we discuss the fundamental elements necessary to realize MEG - the exciton and bi-exciton - in a CdSe nanocrystal [4]. We compute the electron and hole states using the atomistic tight-binding approach with model surface passivation technique and the one-pair (exciton) and two-pair (bi-exciton) spectrum using configuration interaction (CI) approach including direct and exchange Coulomb interactions. The Auger processes mixing the low-energy bi-exciton and highly excited exciton states are treated exactly. Our results indicate that the simple picture of exciton and bi-exciton as excitations of s-shells does not apply to CdSe NCs. We find that the top of the valence band is composed of four quasi-degenerate states well separated from the rest by a gap. This degeneracy leads to the characteristic band of low lying exciton states, exciton fine structure, controlled by the electron-hole exchange interaction. For a bi-exciton, the degeneracy leads to a manifold of closely lying strongly correlated states, resulting in a fine structure of bi-exciton spectra. The bi-exciton fine structure leads to a Stokes shift in the bi-exciton absorption and emission spectra. The effect of Auger broadening is found to be very weak , resulting in only minor shifts of intensity and line broadening of emission spectra.

[1] A. J. Nozik, *Chem. Phys. Lett.* **457**, 3 (2008).
[2] R. D. Schaller, V. M. Agranovich, and V. I. Klimov, *Nature Phys.* **1**, 189 (2005).
[3] A. Shabaev, Al. L. Efros, and A. J. Nozik, *Nano Lett.* **6**, 2856 (2006).
[4] M. Korkusinski and P. Hawrylak, *in preparation*.

High Brightness Single Photon Sources Based on Photonic Wires

Jean-Michel Gerard

INAC/SP2M/Nanophysics and Semiconductors, CEA-CNRS joint lab, CEA Grenoble, France

We present a novel single-photon-source (SPS) based on the emission of a semiconductor quantum dot embedded in a single-mode photonic wire. This geometry ensures a very large coupling (>95%) of the spontaneous emission to the guided mode. Numerical simulations [1] show that a photon collection efficiency as large as 90% can be obtained for engineered nanowires with a tapered tip [2] and a metallic bottom mirror coated by a thin dielectric layer [3]. Experimentally, a record-high efficiency of 75 ±7% (for a NA=0.75 collection optics) has been measured for an InAs quantum dot embedded in such a nanowire, made of GaAs and defined by reactive-ion etching [4].

In the context of SPS, this novel approach, which provides spontaneous emission control over a wide spectral band, offers several important assets compared to cavity-based ones: 1) it can easily be applied to non-monochromatic emitters such as *F*-centers in diamond (or QDs at high temperature); 2) it is well suited to the development of wavelength tuneable SPS; 3) it is finally also very attractive for developing electrically pumped SPS; we will present original designs which should permit reaching SPS efficiencies well above 80%, whereas the best reported value to date is around 15%.

[1] I. Friedler et al.: "Solid-state single photon sources: the nanowire geometry", *Opt. Exp.* **17**, 2095 (2009).
[2] N. Gregersen et al.: "Controlling the emission profile of a nanowire with a conical taper", *Opt. Lett.* **33**, 1693-1695 (2008).
[3] I. Friedler et al.: "Efficient photonic mirrors for semiconductor nanowires", *Opt. Lett.* **33**, 2635 (2008).
[4] J. Claudon et al., *available on ArXiv*.

Light Emission From Site-Selectivley Tethered PbS(x) Nanocrystals on SOI-based Photonic Crystal Microcavities

Haijun Qiao, Keith A. Abel, Stephanie Flynn, Frank C.J.M. van Veggel and Jeff F. Young

Physics and Astronomy Department, Univerisity of British Columbia, Vancouver, Canada

Colloidal PbS and PbSe nanocrystals emitting at 1.5 microns are selectively bound to the antinode region of an L3 SOI-based photonic crystal microcavity using a novel processing scheme. The process will be desribed, and cavity-enhanced emission spectra 10X the background value are achieved. The saturation behaviour and temperature dependence of the emisison from surface-bound PbS(x) nanocrystals on SOI are contrasted with the emission properties of thick films of the colloidal nanoparticles. This work is aimed at the development of nonclassical light sources in silicon photonic circuits.

Atomistic Modeling of Multimillion Atom Nanostructures

Michał Zieliński

Instytut Fizyki UMK, ul. Grudziądzka 5, 87-100 Toruń, Poland

We present atomistic methodology for calculation of electronic and optical properties of multimillion atom nanostructures. This methodology combines the valence force field method for calculation of strain, the tight-binding method used to obtain single particle spectra and finally the configuration interaction method applied to calculate multi- and charged exciton energy and optical spectra. We illustrate our method on several examples including multiexciton complexes in self-assembled InAs/GaAs and charged excitons in InAs/InP quantum dots. We demonstrate necessity of atomistic calculation in such systems. We also discuss theoretical and numerical difficulties we had to overcome during the process of creation of the numerical programs package and issues related to high power computing involved in the calculation process.

Theory of Excitons in ZnO/ZnMgO Quantum Wells

Witold Bardyszewski

Institute of Theoretical Physics, University of Warsaw, ul. Hoża 69, 00-681 Warsaw, Poland

Literature reports on high quality ZnO/ZnMgO heterostructures opened new hopes for applications of theses materials for optoelectronic devices operating in the ultraviolet optical region and for and flexible electronics.Due to the large exciton binding energy and small effective Bohr radius pronounced excitonic features may be observed in the optical spectra in a very large range of quantum well widths even at room temperature.[1] Precise interpretation of the optical spectra is however hindered by the presence of built-in strain caused by the lattice mismatch with the substrate. Further ambiguity is introduced by the strong local electric field induced by the polarization charge density and the background doping.[2] Finally, the sp^3 hybridization of atomic orbitals in ZnO leads to the complicated structure of the conduction and valence bands. In particular the sequence of the valence band levels in the bulk ZnO, which is still a matter of controversy, may be strongly dependent on the built-in strain. In particular, taking into account the spin, the twofold conduction band level has Γ_7 symmetry while the sixfold top of the valence band is split by the crystal field and spin-orbit interaction into one twofold Γ_9 level and two Γ_7 levels. It is commonly believed that the topmost valence band level has Γ_9 symmetry although it was shown that in the regime of negative spin-orbit interaction, the sequence Γ_7 - Γ_9 - Γ_7 is also possible.[3] This ambiguity is related to the fact that the spin-orbit coupling in ZnO seems to be fairly small. The detailed model of the absorption spectra in the vicinity of the fundamental gap is therefore of fundamental importance in studying such systems. In this report we present a multiband exciton absorption model in ZnO/ZnMgO quantum wells which takes into account the details of the valence band structure. In our model we incorporate the **kp** coupling between valence subbands as well as the direct and exchange Coulomb interaction between the electron and hole [4]. The effect of the electric field is accounted for using proper potential profile of the quantum well while the built-in strain is incorporated via Rashba-Sheka-Pikus effective Hamiltonian. The Bethe-Salpeter equation for the two particle correlation function is solved in the basis of Landau orbitals corresponding to an optimized, fictitious magnetic field B directed along the QW growth axis. Using the Lanczos reduction procedure we obtain full absorption spectra from which the exciton binding energies and life-times may be deduced. The calculations are performed for the circular polarization of light (Faraday configuration). Our model may be useful in interpretation of experiments investigating the electronic structure near the fundamental gap of both ZnO and ZnMgO.

[1] T. Makino, Y. Segawa, M. Kawasaki, and H. Koinuma, *Semicond.Sci.Technol.* **20**, S78 (2005).
[2] S. Sasa, T. Tamaki, K. Koike, M. Yano, and M., *J. of Physics: Conf. Series*. **109**, 012030(2008).
[3] B.Gil, *Phys.Rev.* **B64**, 201310 (2001).
[4] M. Sobol, W. Bardyszewski, *Phys.Rev.* **B73**, 1 (2006).

Pure Dephasing of the Spin of the Electron Confined in a Quantum Dot: the Role of the Hyperfine-Mediated Interactions

Łukasz Cywiński

Institute of Physics, Polish Academy of Sciences, Warsaw, Poland

We have investigated decoherence due to pure dephasing of a localized spin qubit interacting with a nuclear spin bath. Although in the limit of a very large magnetic field the only decoherence mechanism is spectral diffusion due to dipolar flip-flops of nuclear spins, with decreasing field the hyperfine-mediated interactions between the nuclear spins become important. Taking advantage of their long-range nature, we have resummed the leading terms in an 1/N expansion of the decoherence time-evolution function (N being the large number of nuclear spins interacting appreciably with the electron spin).

For the case of the thermal uncorrelated bath we believe that our theory is applicable down to low magnetic fields (~10 mT in large GaAs dots) allowing for comparison with recent experiments on spin echo in GaAs quantum dot spin qubits [Koppens et al., *PRL* **100**, 246802 (2008)]. Within this approach we have calculated the free evolution and spin echo decoherence as a function of the number of the nuclei in the bath (i.e.~the quantum dot size) and the magnetic field. For the spin echo evolution we show that the dominant decoherence process at low fields is due to interactions between nuclei having significantly different Zeeman energies (i.e. ~nuclei of As and two isotopes of Ga in GaAs), and we find qualitative agreement with experiments performed at low B fields. Our theory for free induction decay in a narrowed nuclear bath is shown to agree with an exact solution for decoherence due to hyperfine-mediated interaction which can be obtained when all the nuclei-electron coupling constants are identical, and it is also in qualitative agreement with measurements in InGaAs quantum dots [Greilich et al., *Science* **313**, 341 (2006)]. We also find an agreement with an exact numerical simulation of spin echo in a system with N = 20 nuclear spins.

This work has been done in collaboration with Wayne Witzel, Viatcheslav V. Dobrovitski, and Sankar Das Sarma. Parts of it have been published in: Cywiński, Witzel, and Das Sarma, PRL 102, 057601 (2009), PRB 79, 245314 (2009).

Coulomb Interactions and Charge Storage in Self-Assembled CdTe Quantum Dots

Łukasz Kłopotowski

Institute of Physics, Polish Academy of Sciences, 02-668 Warsaw, Poland

Quantum dots (QDs) in charge-tunable structures are promising candidates for many novel devices such as quantum logic gates and single electron spin memories. The system also offers a unique possibility of studying QD morphology via the quantum confined Stark effect, which magnitude reflects charge distributions inside the dot. There is a large number of reports on charge-tunability, Stark spectroscopy, charge storage, and Coulomb blockade in III-V nanostructures, but papers considering II-VI systems are scarce, although obtaining occupation control of a magnetically doped II-VI QD is expected to provide electrical tuning of its magnetic properties.

In this report, we show results of photoluminescence experiments on QDs embedded in two types of structures: Schottky diodes and *p* - *i* - *n* junctions. From the magnitudes of Stark shifts we are able to infer values of the built-in dipole moment and electron-hole polarizability. We find that the sense of the dipole vector depends on the size of the dot: in large (small) dots it is parallel (antiparallel) to the growth axis. Polarizability values are roughly an order of magnitude smaller than in III-V QD reflecting a stronger exciton binding in more polar II-VI compounds. We observe an important decrease of the dipole moment upon dot charging. The decrease is larger in the case of charging with a hole than with an electron, which allows us to assume that repulsion between holes is stronger than between electrons. Moreover, analysis of charged excitons binding energies lets us conclude that electron-hole Coulomb attraction dominates over the repulsive interactions.

Our experimental results are supported with theoretical calculations. The dot is modeled as a disc with infinite barriers. Electron and hole energy levels are accounted for in a model based on effective mass approximation. Exciton transition energies are calculated using a full configuration interaction method. The results are in qualitative agreement with the experimental data.

Additionally, we demonstrate charge storage in an ensemble of dots. By proper modulation of the exciting laser and the bias voltage, we are able to optically write, store, and electrically read-out the accumulated charge. We investigate the storage time, which exceeds 10 ms and study the switching dynamics of the system, which occurs on the timescale of ~100 ns.

Quantum Dashes: Optical Properties and Application Prospects

Grzegorz Sęk

Institute of Physics, Wrocław University of Technology, Wrocław, Poland
Centre for Advanced Materials and Nanotechnology, WUT, Wrocław, Poland
e-mail: grzegorz.sek@pwr.wroc.pl

Semiconductor quantum dashes, which can be fabricated using the modern epitaxial technologies and the self-assembled growth mode, is a new class of nanostructures in a shape of strongly elongated in [1-10] direction quantum dots or finite length quantum wires. They have been developed within the last few years and already proven to offer a very beneficial properties from the point of view of exploiting them in the active region of infrared lasers improving their performance, e.g. decreasing the threshold current, enhancing the differential gain, and widening the wavelength tuning. However, there is still a rather limited published information available regarding many of their more fundamental physical properties. We will present the results of optical investigation of quantum dashes obtained in two different material systems (on GaAs and on InP). By employing techniques like modulation spectroscopy, micro-photoluminescnece and time-resolved photoluminescence combined with energy level calculations we will discuss several aspects related to possible extension of the application field for such asymmetric nanostructures:

- linear polarization properties of the so called columnar quantum dashes made of In(Ga)As on InP from the perspective of constructing a polarization insensitive quantum-dot-like semiconductor-based optical amplifier at the fibre telecommunication window of 1.55 μm,
- studies of photoluminescence form a single InAs/InP quantum dash of a high density ensemble able to emit at E, S and C bands spectral ranges and with a support of a few level rate equation model a detection of biexciton emission,
- ensemble and single InGaAs/GaAs quantum dashes optical properties including estimations on the oscillator strength, exciton to biexciton radiative lifetimes and the internal kinetics involving the carrier transfer from the discretized wetting layer to the dashes.

Quantum Dot Broadband Materials for Telecommunication Applications

Sylvain Raymond

Institute for Microstructural Sciences, National Research Council of Canada, Ottawa, Canada

Quantum Dot lasers have properties that are highly influenced by the large inhomogeneous broadening inherent to self-assembled layers. On the one hand this imposes a (low) limit on the peak gain of the device, potentially limiting their efficiency, on the other hand it provides a broad band gain profile which opens the door to exciting applications, for example multi-wavelength lasers and mode-locked lasers.

In this talk I will review the current state of the quantum dot laser project at IMS, focusing on the InAs/InGaAsP/InP material system emitting in the telecom range. A first key finding from experiments is that the anticipated penalties due to low peak gain are largely offset by the benefits of working with a zero-dimensional system, providing lasers with performance either comparable or better than current commercial devices. Using 'trimming' techniques developed at IMS, one can also tune the center of the 'action band' of the devices from the S-band all the way up to the U band (1475 - 1635 nm).

While the limitations of low peak gain have been mitigated, the benefits of the broad band gain are very promising for an array of potential applications. In a first embodiment, one can use a monolithic laser device to obtain a multi-wavelength laser with adjustable channel spacing compatible with the ITU grid. Up to 96 channels all within a 3 dB emission power band can be obtained in this way, with optical signal to noise ratio of 50 dB and relative intensity noise below -115 dB (-136 dB above 2 MHz). In a second embodiment, a monolithic Fabry-Perot laser is used to obtain a mode-locked laser with a high repetition rate (several tens of gigahertz) and ultra short pulse duration down to 312 fs. In certain conditions, these lasers also show a dual wavelength emission which opens the door to intriguing new opportunities.

Posters

Radius Dependent Shift of Surface Plasmon Frequency in Metallic Nanospheres: Theory and Experiment

W. Jacak[1], J. Krasnyj[2], J. Jacak[1], R. Gonczarek[1], L. Jacak[1], D.Z. Hu[3], and D. Schaadt[3]

[1]*Institute of Physics, Wrocław University of Technology, Wrocław, Poland*
[2]*Theor. Phys. Group., International University, Fontanskaya Doroga 33, Odessa, Ukraine*
[3]*Institute of Applied Physics/DFG-Center for Functional Nanostructures, University of Karlsruhe, Karlsruhe, Germany*

The theoretical description of oscillations of an electron liquid in metallic nanosphere is formulated within random-phase-approximation semiclassical scheme. The spectrum of plasmons in metallic nanospheres is determined including both surface and volume type excitations. The Lorentz friction of electrons due to irradiation of electro-magnetic (e-m) energy by plasmon oscillations is analyzed with respect to the sphere dimension. The resulting red-shift of resonance frequency due to plasmon damping turns out to be strongly sensitive to the sphere radius. The form of e-m response of the system of metallic nanospheres embedded in the dielectric medium is found. The theoretical predictions are verified by the measurements of light excitation in nanosphere colloidal water solutions, for Au and Ag with the radius of metallic components from 10 to 75 nm. Theoretical predictions and experiment data clearly agree in the radius dependence of the resonance red-shift and in the emergence of the first volume plasmon resonance in the e-m response of the system for big nanosphere radii.

Plasmons in Metallic Nanospheres in RPA-type Approach; Undamped Energy Transport by Collective Surface Plasmon Oscillations Along Metallic Nanosphere Chain

W. Jacak[1], J. Krasnyj[2], J. Jacak[1], W. Doderowicz[1], L. Jacak[1], D.Z. Hu[3], and D. Schaadt[3]

[1]*Institute of Physics, Wrocław University of Technology, Wrocław, Poland*
[2]*Theor. Phys. Group., International University, Fontanskaya Doroga 33, Odessa, Ukraine*
[3]*Institute of Applied Physics/DFG-Center for Functional Nanostructures, University of Karlsruhe, Karlsruhe, Germany*

The random-phase-approximation semiclassical scheme for description of plasmon excitations in metallic nanosphere is developed for a case of presence of dynamical electric field and a long chain of nanoparticles. It is demonstrated that only surface plasmons of dipole type can be excited by a homogeneous dynamical electric field. The irradiation-induced damping effects are analyzed with respect to the sphere dimension in near-field zone leading to Foerster type coupling between nanoparticles.. The collective sub-diffraction wave-type oscillations of surface plasmons in long chains of metallic spheres are described. The undamped region of propagation of plasmon waves along the chain is found in agreement with some previous numerical simulations.

Numerical Study of Metastable States in Type II Gaussian QDs

M. Tytus, W. Donderowicz, L. Jacak

Institute of Physics, Wrocław University of Technology, Wrocław, Poland

The metastable states (with angular momentum L=0, for rotational symmetry) against dipole e-m transitions are analyzed by numerical methods in Gaussian QD type II confinement in 2D electron systems (dot for electrons, antidot for holes, or conversely). The verification of previous analytical Hartree calculus is performed. Wide range of parameters including external magnetic field, and different bare potentials for electrons and holes is considered in order to model experimental situations (electrically defined type II QDs, self-assembled type I QDs converted to type II by strain). Formation of exciton in type II QDs is described also in lateral electric field. Comparison of Gaussian with singular Coulomb-type confinement of ionized acceptor or donor in 2D quantum well is presented.

Coherent Emission and Phonon-Related Effects in Double Quantum Dots

Anna Sitek, Katarzyna Roszak, Paweł Machnikowski

Institute of Physics, Wrocław University of Technology, Wrocław, Poland

Double quantum dots (DQDs) are systems of two semiconductor quantum dots (QDs) placed close to each other, so that the carriers confined in each dot become coupled either by tunneling through the inter-dot barrier (the system is then referred to as a quantum dot molecule) or by Coulomb couplings. The state space of such a system is obviously richer than that of a single QD and allows, e.g., for entanglement between the dots. Also the recombination and relaxation processes in DQDs show many features which cannot appear in individual QDs. In the case of radiative recombination, these include collective (superradiant) effects in the coupling between the confined carriers and their electromagnetic environment (radiation vacuum) [1]. In the case of phonon-related decoherence, new relaxation and dephasing channels are opened due to, among others, inter-dot excitation transfer [2] or "localization"-like dephasing of non-local superpositions [3].

In this contribution, we will present our recent results related to the specific decoherence processes in double quantum dots. We will discuss the collective radiative effects in the occupation decay as well as in the linear and non-linear optical response of the system [1,4]. We will describe the decay of entanglement in coupled and uncoupled double-dot structures [5]. We will also discuss the phonon-assisted excitation transfer between the dots. In addition, we will propose a unified approach to the numerical simulation of the system evolution under the joint action of radiative and phonon-assisted dephasing. We will show some effects related to the non-trivial interplay of collective emission and phonon-induced decoherence [6].

[1] A. Sitek and P. Machnikowski, *Phys. Rev*. **B 75**, 035328 (2007).
[2] E. Rozbicki, P. Machnikowski, *Phys. Rev. Lett*. **100**, 027401 (2008).
[3] P. Machnikowski, *Phys. Rev. Lett*. **96**, 140405 (2006).
[4] A. Sitek, P. Machnikowski, *arXiv*:0901.0879; *Phys. Rev*. **B 80** 115301 (2009).
[5] K. Roszak, P. Machnikowski, *Phys. Rev*. **A 73**, 022313 (2006).
[6] P. Machnikowski, K. Roszak, A. Sitek, *arXiv*:0908.0058.

The Photoluminescence Studies of Many Body Interactions in Two Dimensional Hole Gas

J. Jadczak[1], L. Bryja[1], P. Płochocka[2], A. Wójs[1], J. Misiewicz[1], M. Potemski[2]

[1]*Institute of Physics, Wroclaw University of Technology, Wroclaw, Poland*
[2]*Grenoble High Magnetic Field Laboratory, CNRS, Grenoble, France*
e-mail: Leszek.Bryja@pwr.wroc.pl

The experimental studies of low-temperature (T = 2 K), high-field ($B \leq 20$ T), polarization-resolved magneto-photoluminescence (PL) of an asymmetric w = 22 nm wide GaAs/GaAlAs quantum well are reported. The structure was fabricated by molecular beam epitaxy, and the two-dimensional hole gas was obtained by Carbon δ-doping in one of the barriers of the well. The sample was of a very good quality, with dark low temperature 2D hole concentration p = 1.92×10^{11} cm^{-2} and mobility μ = $1.71\times10^{5}cm^{2}/Vs$. The optical emission was excited above the barrier by an Argon ion laser. By increasing laser excitation power density we were able to slightly decrease the 2D hole concentration. The actual concentration was determined from parallel transport measurements in van der Pauw configuration. Recorded PL spectra (Fig. 1) reveal all three predicted [1] bound states of the positive trion (charged exciton): the singlet as well as both triplets ("bright" and "dark"). The neutral exciton peak was also identified, allowing an experimental determination of trion binding energies. At lower energies (below free excitons and trions) several lines attributed to the acceptor-bound excitons and trions were identified. The most intriguing of these lines emerges in the PL spectra only at sufficiently high fields ($B \geq 5$ T), initially below the singlet trion. When the field is increased, the line shifts linearly to higher energies (in contrast to the "shake-up" line [2]). In high fields, it crosses all trions and the exciton (Fig. 2). Its intensity decreases in lower temperatures (from T =4.2 K down to 50 mK in our experiment). Aided with the numerics, we attribute this transition to the combined exciton-cyclotron resonance (hole cyclotron replica of an acceptor-bound positive trion, $AX^{+}CR$). A similar effect was previously observed in PLE and reflectivity of a low-density electron gas [3].

[1] A. Wojs, *Phys. Rev*. **B 76**, 085344 (2007).
[2] L. Bryja et al., *Phys. Rev.* **B 75**, 035308 (2007).
[3] D. Yakovlev et al. *Phys. Rev. Lett*. **79**, 3974 (1997).

Fig. 1

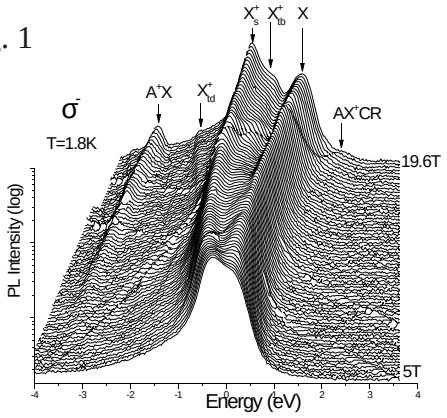
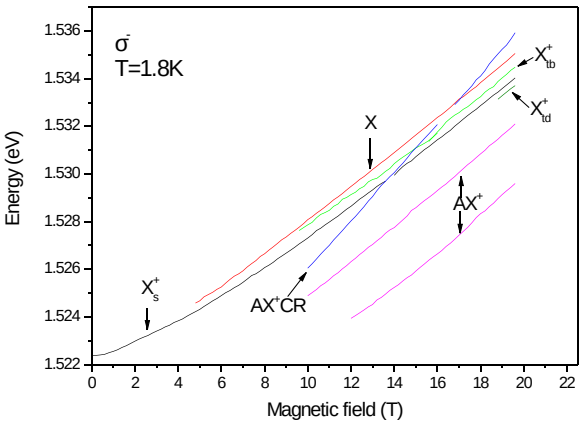


Fig. 2



Eight-band k•p Calculations of the Effects of the Composition Contrast on the Linear Polarization Properties of Columnar Quantum Dots

Janusz Andrzejewski[1], Grzegorz Sęk[1], Eoin O'Reilly[2], Andrea Fiore[3], and Jan Misiewicz[1]

[1] *Institute of Physics, Wroclaw University of Technology, Wrocław, Poland*
[2] *Tyndall National Institute, Lee Maltings, Cork, Ireland,*
[3] *COBRA Research Institute, Eindhoven University of Technology, Eindhoven, The Netherlands*

We present eight-band **k·p** calculations of the electronic and polarization properties of columnar $In_yGa_{1-y}As$ quantum dots (CQD) with high aspect ratio embedded in an $In_xGa_{1-x}As$ /GaAs quantum well. Our model accounts for the linear strain effects, linear piezoelectricity and spin-orbit interaction. We calculate the relative intensities of transverse-magnetic (TM) and transverse-electric (TE) linear polarized light emitted from the edge of the semiconductor wafer as a function of the two main factors affecting the heavy hole - light hole valence band mixing and hence the polarization dependent selection rules for the optical transitions, namely i) the composition contrast *y*/*x* between the dot material and the surrounding well, and ii) the dot aspect ratio. The numerical results show that the main driving parameter for tuning the polarization properties is the composition contrast. This is explained based on an analysis of the integrated biaxial strain over the CQD volume, which is shown to be a good figure of merit to predict and explain the TM to TE intensity ratio.

Time and Spectrally Resolved Photoluminescence of In(N)As Quantum Dots Embedded in GaIn(N)As/GaAs Quantum Well

M. Syperek[1], R. Kudrawiec[1], M. Baranowski[1], G. Sęk[1], J. Misiewicz[1], D. Bisping[2], B. Marquardt[2], M. Fischer[2], and A. Forchel[2]

[1]*Institute of Physics, Wrocław University of Technology, Wrocław, Poland*
[2]*Technische Physik, Universität Würzburg, Wilhelm-Conrad-Röntgen-Research Center for Complex Material Systems, Wurzburg, Germany*
e-mail: marcin.syperek@pwr.wroc.pl

It is expected that quantum dot (QD) based lasers can offer better perspectives in telecommunication applications than their QW-based counterparts. It is mostly due to theoretically predicted advantages like low threshold current, broad gain spectrum, high wavelength and temperature stability. A very good candidate for the laser application are self-organized InAs QDs grown on GaAs substrate, however in this materials system it is still difficult to achieve emission at 1.3 μm. An effective method to tune the emission from InAs QDs to longer wavelength is their overgrowth by GaInAs layer. It was also recognized that more controllable redshift of InAs QDs emission wavelength can be realized by the overgrowth of InAs QDs by GaInNAs, because incorporation of nitrogen into GaInAs simultaneously decreases the energy gap and reduces strains. We believe that similar effect can be achieved when N atoms are incorporated into the InAs QDs grown on the GaAs.

In this work we use time and spectrally resolved photoluminescence technique to study the influence of nitrogen incorporation into the InAs/GaInAs dots-in-the-well system. It is observed that the incorporation of a small nitrogen content into InAs/InGaAs system causes redshift of the ground state emission and changes in the intensity and broadening of the photoluminescence emission line depending on the growth process optimization. For the best growth parameter the ground emission of entire In(N)As/GaIn(N)As system is at 1.3 μm at room temperature and its intensity exceeds by about one order of magnitude the PL intensity from InAs/GaInAs system. Moreover, the temperature quenching of the PL emission line for optimized In(N)As QDs is much slower than for InAs QDs. The time resolved PL experiment shows that room temperature radiative recombination time for the optimized In(N)As QDs is ~500 ps, which is almost twice longer than for InAs/InGaAs system. It confirms that nitrogen inclusion does not necessarily deteriorate optical quality of the structure by introducing additional non-radiative recombination channels, which was expected in nitrogen containing structures. At low temperature it is observed that radiative recombination time is very similar for the optimized In(N)As QDs and InAs QDs (~1.25 ns) however for non-optimized In(N)As QDs it is ~1.6 ns and strongly varies with QDs emission wavelength. This difference is related with strain conditions under the QDs layer generated by the nitrogen presence in the structure but also growth condition. The strain conditions influence size and homogeneity of QDs ensemble which was additionally confirmed by the SEM picture.

Emission Properties of Strongly Asymmetric Single Quantum Dots Described by a Few Level Rate Equation Model

Paweł Podemski[1], Grzegorz Sęk[1], Anna Musiał[1], Jan Misiewicz[1], Sven Höfling[2], Alfred Forchel[2], Lianhe Li[3] and Andrea Fiore[3]

[1]*Institute of Physics, Wrocław University of Technology, Wrocław. Poland*
[2]*Technische Physik. University of Würzburg, Wilhelm-Conrad-Röntgen-Research Center for Complex Material Systems, Würzburg, Germany*
[3]*Ecole Polytechnique Fédérale de Lausanne, Institute of Quantum Electronics and Photonics, Lausanne, SWITZERLAND*
e-mail: pawel.podemski@pwr.wroc.pl

Different kind of self-assembled quasi-zero-dimensional structures called quantum rods (InGaAs/GaAs) and quantum dashes (in two different material systems: InAs/InP and InGaAs/GaAs) were studied. Quantum rods are columnar quantm dots with the aspect ratio significantly larger than 1 which is obtained by a close stacking growth technique of a short period supperlattice (an alternate growth of very thin InAs and GaAs layers on a seed quantum dot layer). Quantum dashes are a form of quantum dots with one lateral dimension elongated (here in the direction [0-11]), which is a direct result of the anisotropic strain field in the substrate, present during the epitaxial growth process.

In these structures, spectral lines connected with different exciton complexes confined in a single quantum rod/dash have been resolved in microphotoluminescence spectra. In order to describe their excitation power dependence and determine the exciton (X) to biexciton (XX) lifetimes ratio τ_x/τ_{xx} a rate equation model was used, taking into account the possible occupation of the higher energy states. The inclusion of the latter and tuning of the τ_x/τ_{xx} influence mainly the high excitation part of the intensity versus generation rate functions for both X and XX. This allows fitting the experimental data in a very broad excitation level range and determining the dynamic properties indirectly. For instance, an unusually high τ_x/τ_{xx} of about 4 has been obtained for InGaAs quantum rods which can be connected with fast spin-flip relaxation rate in such structures [1]. In the case of InGaAs quantum dashes, the obtained lifetimes ratio indicated a rather short exciton lifetime (τ_x/τ_{xx} of about 1), compared to the typical values observed for self-assembled InAs or InGaAs quantum dots. The latter, together with the observation of the biexciton sideband [2], being a fingerprint of fast quantum dash recombination rate (i.e., close to the neighbouring wetting layer lifetime values), suggest a rather weak confinement regime and enhanced oscillator strength in these dashes.

[1] G. Narvaez, G. Bester, A. Franceschetti, A. Zunger, *Phys. Rev*. **B 74**, 205422 (2006).
[2] P. Senellart, E. Peter, J. Hours, A. Cavanna, J. Bloch, *Phys. Rev*. **B 72**, 115302 (2005).

Electronic Structure and Optical Properties of InGaAs/GaAs Quantum Dot Based Tunnel Injection System: Experiment and Modelling

W. Rudno-Rudziński[1], K. Ryczko[1], J. Andrzejewski[1], G. Sęk[1], J. Misiewicz[1], E.M. Pavelescu[2], C. Gilfert[2], and J. P. Reithmaier[2]

[1] *Institute of Physics, Wrocław University of Technology, Wrocław, Poland*
[2] *Institute of Nanostructure Technologies and Analytics, Technische Physik, Universitaet Kassel, Kassel, Germany*
e-mail: wojciech.rudno-rudzinski@pwr.wroc.pl

The limited speed of the direct modulation due to relatively long times of the electron relaxation towards the quantum dots (QDs) ground state is a major drawback of the application of QD based lasers in fibre optics telecommunication. One of the most promising methods of alleviating this problem is the design of tunnel injection (TI) structures, where carries (in principle electrons) are injected by the means of tunnelling through a thin barrier from a quantum well (QW) directly to the QD ground state with the assistance of phonons. In this way not only the electrons reach the QD ground state much faster, but in larger numbers as well, since the QW collects carriers with much better efficiency, and thus the device has improved operating parameters.

We present the results of optical investigations of the properties of TI structures consisting of the $In_xGa_{1-x}As$ quantum well, being a reservoir of carriers and a layer of self-assembled $In_{0.6}Ga_{0.4}As/GaAs$ quantum dots, serving as the emitter. The application of various complementary spectroscopic techniques, supported by the calculations in 8-band **kp** formalism, has given a direct insight into the physical properties of the investigated structures. Photoreflectance spectroscopy as an enhanced sensitivity modulation technique has been used to determine the band structure and the carrier wavefunctions of this complex system. There has been studied the dependence on the emitter-injector energy levels separation, type of the well, and barrier height. The experimental results are verified by the calculations of energy levels and wavefunctions in a realistic 3D model, including strain and piezoeffect. That data is crucial for the determination of the possible channels of the carrier transfer, governing the properties of TI structures. The conclusions drawn from this technique have been tested by the photoluminescence excitation, which directly probes the carrier transfer processes, and the results confirmed the tunnelling of carriers from the well to the dots. Finally, the influence of the tunnelling on the emission properties is investigated by photoluminescence, performed at different temperatures, i.e. exciton and free carrier transfer regimes.

Contactless Electroreflectance of GaInNAsSb/GaAs Quantum Well Structures for Laser Applications

R. Kudrawiec[1], P. Poloczek[1], M. Gladysiewicz[1], and J. Misiewicz[1],

T. Sarmiento[2], H.P. Bae[2], H.B. Yuen[2], S.R. Bank[2], and James S. Harris Jr[2]

[1]*Institute of Physics, Wrocław University of Technology, Wrocław, Poland*

[2]*Solid State and Photonics Laboratory, Department of Electrical Engineering, Stanford University, Stanford, USA*

robert.kudrawiec@pwr.wroc.pl

Recently, the III-V-N compound systems with a small content of nitrogen (N<5%) have attracted a great attention due to both, its unusual fundamental properties and their potential for long wavelength optoelectronic device applications on GaAs substrates. Contactless electroreflectance (CER), is very powerful tool to investigate optical properties of semiconductor systems including the number of confined states and the bandgap lineup in QW structures (i.e., the conduction and valence band offsets) [1-3]. In this work this techniques has been applied to study the number of confined states and their energies for GaInNAsSb/GaAs single quantum wells (QWs) and step-like GaInAsSb/GaNAs/GaAs QW structures dedicated for laser applications at 1.3 μm and 1.5 μm. The experimental data have been compared with theoretical calculations which were performed in the framework of the electron effective mass approximation. In this way the energy level structure for GaInNAsSb QWs has been determined. In addition, the broadening of CER resonance, which corresponds to the quality of QWs, was investigated for various sets of QW samples annealed at different temperatures. The optimal annealing temperature has been found by analyzing the broadening of CER resonance and the intensity of photoluminescence from GaInNAsSb QWs.

[1] R. Kudrawiec, M. Gladysiewicz, J. Misiewicz, H.B. Yuen, S.R. Bank, M.A. Wistey, H.P. Bae, and J.S. Harris Jr, *Phys. Rev*. **B 73**, 245413 (2006).

[2] R. Kudrawiec, M. Motyka, M. Gladysiewicz, J. Misiewicz, H.B. Yuen, S.R. Bank, H. Bae, M.A. Wistey, and J.S. Harris Jr, *Appl. Phys. Lett*. **88**, 221113 (2006).

[3] R. Kudrawiec, S.R. Bank, H.B. Yuen, M.A. Wistey, L.L. Goddard, J.S. Harris, M. Gladysiewicz, M. Motyka, and J. Misiewicz, *Appl. Phys. Lett*. **90**, 131905 (2007).

Contactless Electroreflectance of AlGaN/GaN Heterojunction Structures Capped by a Thin GaN Layer

R. Kudrawiec[1,2], M. Gładysiewicz[1,2], M. Syperek[1,2], and J. Misiewicz[1,2], B. Paszkiewicz[2,3], R. Paszkiewicz[2,3], and M. Tłaczała[2,3]

[1]*Institute of Physics, Wrocław University of Technology, Wrocław, Poland*
[2]*Centre for Advanced Materials and Nanotechnology, WUT, Wrocław, Poland*
[3]*The Faculty of Microsystem Electronics and Photonic, Wroclaw University of Technology, Wroclaw, Poland*
e-mail: robert.kudrawiec@pwr.wroc.pl

AlGaN/GaN heterojunction structures have emerged as attractive transistors suitable for high-power and high-temperature electronics. In this work, uncapped and GaN caped AlGaN/GaN structures are investigated by contactless electroreflectance (CER). This technique, due to its absorption and differential character is an excellent tool to study the energies of optical transitions (including the excited state ones) in quantum wells as well as energies of bulk-like QW barriers. Because of its high sensitivity to the Franz Keldysh effect, this technique can be also used to determine the value of built-in electric fields in semiconductor structures. In CER spectra, a strong AlGaN resonance followed the Franz-Keldysh oscillation have been clearly observed [1]. The built-in electric field in the AlGaN layer has been extracted from the FKO period to be in the range of 0.3-0.5 MV/cm. Below the AlGaN-related transition, a clear resonance at the energy of ~3.6-3.8 eV (i.e. at much higher energy than the GaN band gap energy) has been detected in CER spectra. This resonance has been attributed to the optical transition within the GaN cap layer which creates a surface quantum well [2]. The observed experimental data have been compared with theoretical calculations which were performed within the electron effective mass approximation. Strain effects as well as the effect of spontaneous and piezoelectric polarization have been included in these calculations. It has been shown that the presence of surface GaN quantum well changes the band bending in this structure and influences the 2DEG concentration at AlGaN/GaN interface.

[1] R. Kudrawiec, M. Syperek, M. Motyka, J. Misiewicz, R. Paszkiewicz, B. Paszkiewicz, and M. Tłaczała, *J. Appl. Phys.* **100**, 013501 (2006).
[2] M. Motyka, M. Syperek, R. Kudrawiec, J. Misiewicz, M. Rudziński, P.R. Hageman, P.K. Larsen, *Appl. Phys. Lett.* **89**, 231912 (2006).

Photoluminescence and Photoreflectance of Mid- and Far-Infrared Low Dimensional Structures by Using Fourier Transform Spectrocrometer

M. Motyka, G. Sęk, and J. Misiewicz

Institute of Physics, Wrocław University of Technology, Wrocław, Poland
Centre for Advanced Materials and Nanotechnology, WUT, Wrocław, Poland

Modulation spectroscopy, due to its absorption and differential character, is an excellent tool to study the energies of optical transitions (including the excited state ones) in quantum well (QW) and quantum dots as well as energies of bulk-like QW barriers or intermediate layers. Such experiments have already been successfully employed to study GaSb-based QWs for infrared applications up to 2 μm [1,2] and including type II structures for even longer wavelengths [3]. Nevertheless, the standard modulation spectroscopy based on diffraction grating monochromators has some limitations due to several reasons like e.g. less sensitive detectors or less efficiency of the probing light sources in case of mid and far infrared (comparing e.g. to the tools used in the visible range) [4]. Because there is a growing interest and necessity to investigate structures designed for operation in mid and far infrared range (e.g. infrared detectors, quantum cascade lasers, etc.) it has been proposed to exploit modulation spectroscopy realized by using Fourier transformed spectrometer [4]. This approach has already been used to investigate mainly the bulk-like materials and layers. In this work we are demonstrating the application of FTIR modulation spectroscopy for investigation of low-dimensional structures like type I or II quantum wells designed for mid infrared spectral region (up to ~ 5 μm). High signal to noise ratio of the measured spectra shows that this approach might by very perspective for the characterization of electronic and optical properties of structures designed for longer wavelength QCLs at 10-15 μm and further into the infrared.

The work has been supported by the PBZ- MNISW-02/I/2007 Project and EU/EC Project Senshy within 7FP No 223998.

[1] M. Motyka, R. Kudrawiec, J. Misiewicz, M. Hümmer, K. Rößner, T. Lehnhardt, M. Müller, and A. Forchel, *J. Appl. Phys.* **103**, 113514 (2008).
[2] R. Kudrawiec, M. Motyka, J. Misiewicz, M. Hümmer, K. Rößner, T. Lehnhardt, M. Müller, and A. Forchel, *Appl. Phys. Lett*. **92**, 041910 (2008).
[3] M. Motyka, G. Sek, K. Ryczko, J. Misiewicz, T. Lehnhardt, S. Höfling, and A. Forchel, *Appl. Phys. Lett.* **94**, 251901 (2009).
[4] T.J.C. Hosea, M. Merrick, B.N. Murdin, *Phys. Stat. Sol.(A)* **202,** 1233 (2005).

Band Gap Discontinuities in GaInAsSb/Al(In)GaASb Quantum Wells Being the Active Region of Mid Infrared Lasers

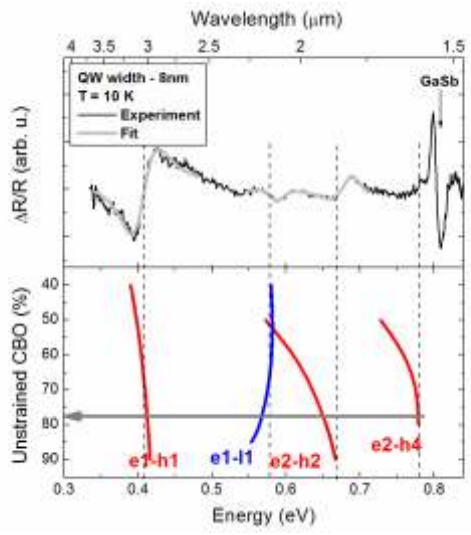
M. Motyka[1], G. Sęk[1], K. Ryczko[1], F. Janiak[1], J. Misiewicz[1], S. Belahsene[2], G. Boissier[2], Y. Rouillard[2]

[1]*Institute of Physics, Centre for Advanced Materials and Nanotechnology, Wrocław University of Technology, Wrocław, Poland*

[2]*Institut d'Electronique du Sud, Université Montpellier, Montpellier, France*

Semiconductor lasers with GaInAsSb/Al(In)GaAsSb quantum wells (QWs) on GaSb substrate operating in the wavelength region up to 3 μm and beyond are attractive light source for applications including remote sensing, pollutant detection, medical procedures or laser spectroscopy. In spite the room temperature cw operation has been demonstrated for such lasers the optimization of their performance is still limited by unfavourable band gap discontinuities ratio between the conduction and valence band, especially when going with the emission to longer wavelengths. Therefore, it is of crucial importance to be able to determine the band offsets (BO) in such structures reliably. We propose the use of modulation spectroscopy (in a form of photoreflectance) as a high sensitivity technique probing the higher order states in low-dimensional structures It is a method which combined with the energy level calculations offers unambiguous band offset determination in contrast to typically used PL studies. The latter detects usually the ground state transition only, which, as occurring between the relatively well confined electron and hole levels, is very weakly sensitive to the band offset ratio change. In contrast, the commonly observed in modulation spectra excited state related transitions and those involving the light holes give several experimental energies to be compared with the results of the calculations in which the BO ratio is treated as the only free parameter.

Figure shows an example of such a procedure performed for a quinary barrier $Ga_{0.35}In_{0.65}As_{0.32}Sb_{0.68}/Al_{0.25}Ga_{0.50}In_{0.25}As_{0.24}Sb_{0.76}$ QW. The top part is the low temperature photoreflectance spectrum whereas the bottom one is the result of calculations in a function of the BO in the conduction band thought for the unstrained materials (chemical band offset). The best agreement has been obtained for its value of about 78 %, which after including the strain (i.e. as in the real structure) recalculates into 65 % for the conduction band. The obtained BO values could be verified when determined for a QW of the same composition but different width, for which it expected to be the same. Similar studies have been performed for QWs with various quaternary and quinary barriers giving the insight on the BO dependence versus the change of the change of the well or barrier composition. The results have been confronted with the theoretical predictions based on the Van de Walle method. For instance, it has been obtained that the conduction band offset ratio (including the strain effect) would increase to about 90% for the same quantum well of $Ga_{0.35}In_{0.65}As_{0.32}Sb_{0.68}$ when the barrier is changed into quaternary $Al_{0.30}Ga_{0.70}As_{0.03}Sb_{0.97}$.



Optical Properties of GaSb-based Type II Quantum Wells Emitting in the Mid-Infrared Range

M. Motyka[1], G. Sęk[1], K. Ryczko[1], J. Misiewicz[1], T. Lehnhardt[2], S. Höfling[2] and A. Forchel[2]

[1]*Institute of Physics, Centre for Advanced Materials and Nanotechnology, Wrocław University of Technology, Wrocław, Poland*

[2]*Department of Applied Physics, University of Würzburg, Würzburg, Germany*

Mid-infrared lasers find increasingly applications during last years including for instance gas sensing for detection and control of the presence or concentration of harmful gases like CO_2, SO_x, NH_3, and many others. The benefits of laser based methods have been limited mainly by the lack of suitable laser light sources, which have to provide the sensing wavelength in single mode and continuous wave (cw) in order to provide the required wavelength control and intensity. The performance of semiconductor laser emitters based on type I quantum wells operating in mid-wave infrared wavelengths beyond 3µm are restricted by fundamental limitations like unfavourable carrier confinement or small band gaps (comparable with split-off gaps). Therefore, the type II heterostructures employing InAs-GaSb-AlSb family have been proposed as an alternative. This eliminates Auger processes by removing the resonance between energy gap and split-off gap and enhances electronic confinement. Hereby, we present fundamental optical and electronic properties of a type II GaSb/AlSb/InAs/InGaSb/InAs/AlSb/ GaSb quantum well system potentially able to cover spectrally the range of 2 to 10 µm (when the thickness of InAs layer is tuned for instance), and possible to be integrated in a photonic sensor unit for gas detection. Spectroscopic experiments at low temperatures, like photoluminescence and photoreflectance, allowed us the detection of the optical transitions, including the spatially indirect ones, and their unambiguous identification after the comparison to the energy level calculations. Based on that, conclusions regarding the band gap discontinuities in such a complex system could also be drawn.

Additionally, photoluminescence thermal quenching was analyzed which on the one hand showed that the emission can still be effective at room temperature, and on the other hand that the temperature shift of the optical transitions is significantly smaller than for type I QW system and dependent on the InAs layer thickness. The latter does not follow the energy gap temperature dependence which could be explained when considered that electrons and holes are confined in separate layers.

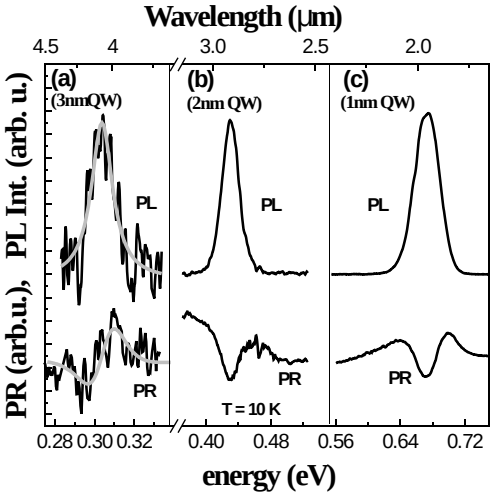


Fig. Low temperature (10K) PL and PR spectra for the GaSb/AlSb/InAs/GaInSb/AlSb/GaSb type II quantum wells with QW width equal to 3 nm (a), 2nm (b) and 1 nm (c).

Surface Photovoltage Spectroscopy of Low Dimensional Semiconductor Structures

Piotr Sitarek, Jan Misiewicz

Institute of Physics, Wrocław University of Technology, Wrocław, Poland
Centre for Advanced Materials and Nanotechnology, WUT, Wrocław, Poland

Surface photovoltage spectroscopy (a version with contacts) has been used for many years to study the properties of electronic states near the surface in bulk semiconductors. With the advent of crystal growth techniques, allowing the production of high quality semiconductor heterostructures, SPS spectroscopy found additional applications and it was used to study electronic states in heterostructures, quantum wells (QW's), quantum dots (QD's) and nanostructures.

We are using a contactless version of SPS. SPS, like electromodulation techniques (e.g. photoreflectance (PR) and contactless electroreflectance (CER), being nondestructive and contactless, but possesses some advantages over PR and CER.

The potential of contactless SPS we will show on three examples.

i) We will start with the results obtained from AlGaAs epitaxial layers with different Al content grown by MBE on GaAs substrate. We can show that using SPS technique it is possible to investigate direct bandgap in AlGaAs semiconductor up to 100% of Al.

ii) The need of realizing active layers for 1.3 μm lasers on GaAs substrate has recently led to intensive studies on long wavelength light emitting materials, e.g. GaAsSb. Several earlier studies have reported contradictory results on the value of GaAsSb/GaAs valence band offset. Here we present the optical studies of $GaAs_{1-x}Sb_x$/GaAs multiple quantum well structures with emission close to 1.3 μm. Under investigations were four structures which differ only with Sb content: 0.23, 0.26, 0.32 and 0.39. After detailed investigations we can show that the optical response of our structures shows weak type-I band alignment.

iii) As third ex ample we present a room temperature study of two 30-layer stacks of self-assembled InAs/GaAs quantum dots with different spacer layer thickness. Both PL and SPS spectra of stacked QDs structure with a thinner spacer layer in comparison to other structures show additional feature. QD features are more clearly visible in SPS spectra and show more features in comparison to PL ones.

Above studies demonstrate the considerable potential of SPS, PR and PL as complementary techniques for the contactless and nondestructive characterization of low dimensional structures at room temperature.

Influence of the Annealing Temperature on Excitation of Terbium Luminescence in Yttrium-Aluminum Oxide Films Deposited onto Porous Anodic Alumina

M. Bański[1], A. Podhorodecki[1], J. Misiewicz[1], J. Serafińczuk[2], and N.V. Gaponenko[3]

[1]*Institute of Physics, Wroclaw University of Technology, Wrocław, Poland*
Centre for Advanced Materials and Nanotechnology, Wrocław University of Technology, Wrocław, Poland
[2]*Faculty of Microsystem Electronics and Photonics, Wroclaw University of Technology, Wroclaw, Poland*
[3]*Belarusian State University of Informatics and Radioelectronics, Minsk, Belarus*

In this work we investigate the excitation mechanism and influence of the annealing temperature on this process terbium-doped yttrium-aluminum oxide films fabricated by spin-on deposition onto porous anodic alumina. An interest in the synthesis of light-emitting materials in PAA arises from its unique tailor-made honey-comb structure, strong luminescence of the embedded impurities and great photonic density of states at direction along the channels of the pores. The samples were annealed at the temperatures from 400 to 1100°C, covering the range of the formation of the amorphous and crystalline phases of Al_2O_3 and $YAlO_3$. A strong terbium photoluminescence (PL) was observed for all samples revealing a spatial homogeneity of the PL intensity within 10%. An influence of the annealing temperature on the terbium PL related to $^5D_4 \rightarrow {}^7F_J$ (J = 3, 4, 5, 6) transitions of Tb^{3+} ions was studied using 2D photoluminescence excitation (PLE) and time-resolved spectroscopy. Moreover, a comparison of the thermal quenching data for the most intensive $^5D_4 \rightarrow {}^7F_5$ luminescence band of Tb^{3+} ions in the fabricated amorphous and crystalline matrices was performed for the temperature range of 10 - 300 K. Based on obtained data, mechanisms of Tb excitation and its dependence on the annealing conditions were proposed and discussed.

Direct Evidence of the Energy Transfer from Silicon Nanocrystals to Nd Ions and the Carriers Relaxation Pathways in Their Local Surrounding

A. Podhorodecki[1], G. Zatryb[1], J. Misiewicz[1], F. Gourbilleau[2], J. Cardin[2], and C. Dufour[2]

[1]Institute of Physics, Wroclaw University of Technology, Wrocław, Poland
Centre for Advanced Materials and Nanotechnology, WUT, Wrocław, Poland
[2]CIMAP, UMR CNRS 6252, Ensicaen 6 Bd Maréchal Juin, 14050 Caen Cedex 4, France

In this work a direct experimental evidence of the excitation energy transfer from the silicon quantum dots (Si-QD's) to Nd ions has been given based on photoluminescence and photoluminescence excitation measurements in the wide spectral range. Moreover, it has been shown that the excitation of Nd ions is possible and even more efficient from the higher energy levels in the vicinity of Si-QD's which lie close in resonance with the $^4I_{9/2} \rightarrow {}^4D_{3/2}$, $^4D_{5/2}$ absorption band of Nd ions. Moreover, it has been found that the excitation power density plays an important role in the temperature dependence of PL intensity both for Nd as well Si-QD's emission, where for high excitation fluxes emission intensity increases with the temperature up to 150 K. It has been proposed that this is due to the existence in relaxation mechanism additional processes related to recovery of the carriers captured at the defect states in the vicinity of Si-NC's.

Surface- and Volume-related Excitation Mechanism of Eu-doped GaN Nanocrystals

A. Podhorodecki[1], R. Kudrawiec[1], J. Misiewicz[1], M. Nyk[2], W. Stręk[2]

[1]*Institute of Physics, Wroclaw University of Technology, Wroclaw, Poland*
Centre for Advanced Materials and Nanotechnology, WUT, Wrocław, Poland
[2]*Institute of Low Temperature and Structure Research, Polish Academy of Sciences*
Wroclaw, Poland

Influence of the dopant position on the excitation mechanism of Eu^{3+} ions doped into nanocrystalline GaN powder has been investigated by using photoluminescence and photoluminescence excitation spectroscopy. It has been found, that depending on the grain sizes (surface to volume ratio in fact), different dopants excitation mechanisms can dominates. In the case of nanograins, it has been proposed that surface plays very important role and the dominant excitation of Eu^{3+} ions is via the local charge transfer from the oxygen atoms adsorbed post growth at the GaN nanocrystals surface.

Thick GaN Layers from Hydride Vapor Phase Epitaxy Examinated by Means Micro-Raman Spectroscopy

Ryszard Korbutowicz, Joanna Prażmowska, Marek Tłaczała

Faculty of Microsystem Electronics and Photonics, WUT, Wrocław, Poland
WUT Research and Technology Centre, Długa str. 65, 53-633 Wrocław, Poland
Centre for Advanced Materials and Nanotechnology, WUT, Wrocław, Poland

Gallium nitride is a very attractive material for optoelectronic devices such as blue and ultraviolet light sources, UV detectors and for high temperature/power electronics. In the nature there are no native crystals of the gallium nitride, synthesis is very difficult and it is hard to obtain single crystals with good properties. Crystallization of freestanding GaN substrates can be made for example: by high-pressure synthesis, by sublimation method, ammonothermal method or flux method. However, the size of GaN crystals obtained in these methods is still too small for practical use. The current largest freestanding GaN substrate is obtained by growing a thick GaN layer on a sapphire substrate using Hydride Vapour Phase Epitaxy (HVPE) and separating the grown layer from the sapphire substrate. Since for gallium nitride devices manufacturing alternative substrates almost exclusively were used, dislocation and defects were generated. It results from mismatch lattices and thermal expansion coefficients of GaN and substrates crystals.

Raman scattering measurements are very sensitive, sophisticated and useful method for determination of materials parameters, especially gallium nitride GaN. This is a good method of qualitative and quantitative analyze of the matter, since the spectra of scattered light in a Raman mode (inelastic) are like fingerprints - are unique and allow to indentify the material (kind of atoms and molecules) and its parameters, for example residual strains (compressive and tensile) and doping. It is important especially for gallium nitride since nitrides devices, like laser diodes, high power and high temperature transistors, because their properties are very sensitive to stress. The need for use of alternative substrates, such a sapphire (Al_2O_3), silicon (Si) or silicon carbide (SiC), which have lattice parameters and thermal expansion coefficients different from GaN, leads to the formation of strains and defects in epitaxial GaN layers. The presence of residual strain can be important for yield of optoelectronic devices. Micro-Raman spectroscopy is one of the sensitive methods for giving information about the stress in epilayers.

From the measured Raman spectra modes intensity and shift the distribution of the residual strain, compressive stress - degree of epitaxial structures relaxation, homogeneity of the phonon mode emission lines as well as the presence of defects and quality of GaN crystals can be determined. Possibility of the microRaman spectroscopy applications in area of gallium nitride epilayers analyzes, especially determination of the stress and the stress distribution as well as strains in epitaxial structures. It can give information about the surface's crystal quality. Micro-Raman spectroscopy is one of the sensitive methods for giving information about the stress in epilayers. These huge possibilities of quality and quantity estimation arise from characteristic reaction of atoms and molecules - i.e. their vibrations and Raman spectrum intensity depends on the inelastic scattered photons quantity.

This work has been supported in a part by the Polish Ministry of Science and Higher Education under the grants no. R0201802, PBZ-MEiN-6/2/2006, NN 515360436, by the European Union within European Regional Development Fund, through grant Innovative Economy (POIG.01.01.02-00-008/08), the Centre for Advanced Materials and Nanotechnology of the Wrocław University of Technology and Wroclaw University of Technology statutory grant.

Epitaxial Growth and Characterization of InGaAsN/GaAs Heterostructures Dedicated to Optoelectronic Devices

Damian Pucicki, Beata Ściana, Damian Radziewicz

Faculty of Microsystem Electronics and Photonics, WUT, Wrocław, Poland
WUT Research and Technology Centre, Długa str. 65, 53-633 Wrocław, Poland
Centre for Advanced Materials and Nanotechnology, WUT, Wrocław, Poland

Nitrogen incorporation into GaAs-based epilayers has received interest especially due to a band gap decreasing of resultant material. Small fraction of nitrogen makes (In,Ga)(As,N) alloys useful materials for optoelectronic devices grown on GaAs substrate. For photodetectors there is a possibility to extend the range of detectable wavelengths beyond the GaAs cutoff at 870 nm [1, 2]. Unfortunately, (In,Ga)(As,N) compounds suffer from deterioration of structural, optical and electrical properties with increasing nitrogen fraction in these semiconductor alloys [3, 4, 5, 6]. Therefore achieving the high quality of (In,Ga)(As,N)/GaAs heterostructures requires MBE (Molecular Beam Epitaxy) or LP-MOVPE (Low Pressure - Metalorganic Vapour Phase Epitaxy) techniques. Our work is focused on optical, electrical and structural properties of diluted nitrides. The technological parameters and characterization of epilayers with small nitrogen content obtained by Atmospheric Pressure MetalOrganic Vapour Phase Epitaxy (AP-MOVPE) are presented.

We investigated the influence of the growth temperature T_g and the III/V vapour phase ratio X_g= u-DMHy/ (u-DMHy + AsH_3) on fraction of the nitrogen in Ga(As,N) epilayers. The content of the InAs phase in (In,Ga)As layers grown at low temperatures was also determined for further elaboration of the AP-MOVPE growth of quaternary alloys (In,Ga)(As,N). The structural properties of the obtained Ga(As,N)/GaAs heterostructures were examined using the HRXRD. To determine the electrical properties of the structures the C-V and E-CV measurements were performed. Photovoltaic spectroscopy, photoluminescence and photoreflectance spectroscopy were used for optical characterization.

For the Ga(As,N)/(In,Ga)(As,N)/GaAs devices heterostructures the etching procedures, Schottky and ohmic contacts evaporation technique and the thermal treatment of the metal contacts were elaborated. Under our growth conditions we achieved Ga(As,N)/GaAs heterostructures suitable for photodetector MSM and PIN photodetectors fabrication. The dc I-V and spectral characteristics of these devices were measured and discussed.

[1] I. A. Buyanova, W. M. Chen, B. Monemar, *MRS Internet J. Nitride Semicond. Res.* **6**, 2, (2001).

[2] J. Wu, W. Shan, W. Walukiewicz, *Semiconductor Science and Technology* **17** (2002).

[3] J. F. Geisz, D. J. Friedman, *Semiconductor Science And Technology* **17** (2002).

[4] S.G. Spruytte, C.W. Coldren, J. S. Harris, W. Wampler, P. Krispin, K. Ploog, M. C. Larson, *J. App. Phys.* **89**, 8 (2001).

[5] C. H. Fischer, P. Bhattacharya, *Journal Applied Physics* **96**, 8 (2004).

[6] I. A. Buyanova, M. Izadifard, W. M. Chen, A. Polimeni, M. Capizzi, H. P. Xin, C. W. Tu, *Appl. Phys. Lett.* **82**, 21 (2003).

This work has been supported in a part by the Polish Ministry of Science and Higher Education under the grants no. R0201802, PBZ-MEiN-6/2/2006, NN 515360436, by the European Union within European Regional Devel-opment Fund, through grant Innovative Economy (POIG.01.01.02-00-008/08), the Centre for Advanced Materials and Nanotechnology of the Wrocław University of Technology and Wroclaw University of Technology statutory grant.

Investigation of Deposition Initial Step Influence on the Properties of Gallium Nitride Layers

J. Prażmowska[1,2,3], A. Podhorodecki[3,4], R. Korbutowicz[1,2,3], A. Szyszka[1,2,3], R. Paszkiewicz[1,2,3], J. Misiewicz[3,4] and M. Tłaczała[1,2,3]

[1]*Faculty of Microsystem Electronics and Photonics, WUT, Wrocław, Poland*
[2]*WUT Research and Technology Centre, Długa str. 65, 53-633 Wrocław, Poland*
[3]*Centre for Advanced Materials and Nanotechnology, WUT, Wrocław, Poland*
[4]*Institute of Physics, Wrocław University of Technology,Wrocław, Poland*

Gallium nitride is a semiconductor material widely applied for fabrication of electronic and optoelectronic devices, as well as chemical sensors. Despite of the devices commercial availability, the problem of good quality layers and substrates fabrication is still topical. Difficulties are caused by mismatch of thermal extension coefficients and lattice constants between GaN and applied alternative substrate. The most critical step of deposition is its initial stage. The nitridation mechanism of sapphire substrates and its influence on the growth and properties were investigated in Helicon wave plasma assisted technique [1]. GaN main layer properties are also dependent on buffer layer preparation. The decomposition of GaN nucleation layer [2] and influence of nitridation and buffer design on polarity were evaluated [3].

Gallium nitride layers were deposited on Al_2O_3 substrates, nitridated in the solution of ammonia and nitrogen in the proportions of NH_3:N_2 (1:10) at 1050 ^{o}C. Various times of nitridation were applied, in comparison purposes. Samples treated for 5, 10 and 15 minutes were chosen and named as sample #1, #2 and #3, respectively. Then layers were placed in 450 ^{o}C and nucleation layer (NL) was deposited. The duration of NL epitaxy was equal for all samples (6 min). HCl diluted in nitrogen (400 sccm/min) and ammonia flows were 8 and 400 sscm/min, respectively.

The morphology, crystalline quality and optical quality of HT-GaN layers were evaluated by application of Scanning Electron Microscopy imaging, High-Resolution X-Ray Diffractometry and photoluminescence, transmission, and reflectance measurements.

Time of sapphire substrate surface nitridation influenced the size of NL islands. The highest and smallest in diameter grains were remarkable for sample #1 but nitridation time of 5 min did not assure uniform preparation of sample surface. NLs of samples #1 and #2 were not continuous. The largest grains were observed for sample #2, islands of sample #3 NL had comparable sizes to that of sample #2 but were overgrown by smaller grains and formed continuous NL. Nitridation time of 15 min did not provide proper NL structure to obtain good quality of HT-GaN what could be observed in SEM images. Sample #3 exhibited extended surface morphology what indicated on its poor crystalline quality. SEM images of HT-GaN revealed terraces and artifacts on surfaces of sample #1 and #2, respectively.

XRD Θ/2Θ -patterns revealed preferred orientation in the 00.1 growth direction of HT-GaN (samples #1 and #2). Θ/2Θ -pattern of polycrystalline sample #3 consisted of additional peak from (10.1) GaN, additionally (00.4) peak was substantially weaker compared to patterns of other samples.

This work has been supported in a part by the Polish Ministry of Science and Higher Education under the grants no. R0201802, PBZ-MEiN-6/2/2006, NN 515360436, by the European Union within European Regional Development Fund, through grant Innovative Economy (POIG.01.01.02-00-008/08), the Centre for Advanced Materials and Nanotechnology of the Wrocław University of Technology and Wroclaw University of Technolo-gy statutory grant.

[1] Kim K S, Kim K B and Kim S H, *J. Cyst. Growth* **233** 167 (2001).
[2] Koleske D D, Coltrin M E, Allerman A A, Cross K C, Mitchell C C and Figiel J J *Appl. Phys. Lett*. **82** 1170 (2003).
[3] Namkoong G, Doolittle W A, Brown A S, Losurdo M, Giangregio M M and Bruno G *J. Cryst Growth* **252** 159 (2003).

Fabrication of Ohmic Contact Based on Platinum to *p*-type Compositionally Graded AlGaAs Layers

W. Macherzyński, M. Wośko, B. Paszkiewicz, B. Ściana, R. Paszkiewicz, and M. Tłaczała

Faculty of Microsystem Electronics and Photonics, WUT, Wrocław, Poland
WUT Research and Technology Centre, Długa str. 65, 53-633 Wrocław, Poland
Centre for Advanced Materials and Nanotechnology, WUT, Wrocław, Poland

AlGaAs/GaAs heterostructures are commonly applied for fabrication of semiconductor devices such as Heterojunction Bipolar Transistor, Monolithic Microwave Integrated Circuit, infrared light-emitting diode, laser diode, infrared photodetector and solar cell.

Stable and low-resistance ohmic contacts are critical for performance and reliability of the devices. Their preparation and characterization require many technological efforts. Ohmic contacts with low specific resistance to *p*-type AlGaAs are essential for microwave and optical devices such as bipolar transistors, *p-i-n* diodes and diode lasers. The metallization should have smooth surface and good interface morphology, very low contact resistance, sharp edges and good thermal stability to meet the demand of the modern devices. One of the most important criteria for an ohmic contact is its thermal stability which is usually assessed based on the test measurements performed at typical temperature for investigated material (400^{o}C for GaAs).

We focused on the development of low resistance ohmic contact based on platinum to *p*-type compositionally graded AlGaAs layer. Application of GaAs cap layer was unavoidable because it prohibits the oxidation of AlGaAs layer oxidation and improves the properties of the metallic contact to semiconductor. Previous works indicated that the use of low doped GaAs cap layer did not fulfil requirements for good quality contact fabrication. Thus, the heavy doped GaAs cap layers, with thickness of 20 nm, have to be applied.

Novel metallization scheme was proposed for ohmic contact formation to compositionally graded *p*-type AlGaAs. A metal multilayers of Ti/Pt/Au, Pt/Ti/Pt/Au and Pt/Ti/Ni/Au were deposited by thermal evaporation using electron gun and resistance heater. The contacts were sequentially annealed by rapid thermal annealing system in N_2 atmosphere at various temperatures (in the range from 350^{o}C to 550^{o}C). The duration of annealing step was 2 minutes. The as-deposited Pt/Ti/Pt/Au and Pt/Ti/Ni/Au multilayer metallizations had resistivities of $1.4 \cdot 10^{-5}$ $\Omega \cdot cm^2$ which have been gradually deteriorated after each subsequent annealing. The current-voltage characteristics of the ohmic contacts to compositionally graded *p*-type AlGaAs epitaxial layers were studied and discussed.

This work has been supported in a part by the Polish Ministry of Science and Higher Education under the grants no. R0201802, PBZ-MEiN-6/2/2006, NN 515360436, by the European Union within European Regional Development Fund, through grant Innovative Economy (POIG.01.01.02-00-008/08), the Centre for Advanced Materials and Nanotechnology of the Wrocław University of Technology and Wroclaw University of Technology statutory grant.

Index of Names