International School on Spin-Optronics

PROGRAM AND ABSTRACTS

St. Petersburg, Russia, July 10-14, 2012

2nd International School on Spin-Optronics,
July 10-14, 2012, St. Petersburg, Russia

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Preface

The second International School on Spin-Optronics (ISSO-2012), which is held in St. Petersburg, 9-14 July 2012, is a joint event of three Marie-Curie International training network (ITN) projects: SPIN-OPTRONICS, CLERMONT4, and INDEX. This School organized by the Ioffe team of SPINOPTRONICS follows the first one (ISSO-2010) which took place in Les Houches (France). The School in Saint-Petersburg has a wider range of topics than ISSO-2010. Its scientific program includes more than 60 invited, oral and poster presentations. Outstanding physicists of our time are among the speakers. Such accumulation of a great number of world-leading scientists, extraordinary for a network school, has become possible due to the joint effort of three ITNs, each of those developing one of the advanced areas of nanophotonics.

CLERMONT4 is the oldest project among these ITNs belongs to the series of "CLERMONT" networks started in 1999. The project is largely responsible for the stunning progress in the physics of exciton-polaritons in microcavities during the recent decade. CLERMONT has composed by 15 research groups from 5 European countries representing the universities of Cambridge, Sheffield, Southampton, Durham, Madrid, Rome, Heraklion, Paris, Montpellier, Clermont-Ferrand, Swiss Federal Polytechnical School at Lausanne, and the French National Research Center. This network trains over 20 young researchers working on physics and applications of exciton-polaritons. Two series of international events have been started by the CLERMONT community, namely, the international conferences on Physics of Light-Matter Coupling in Nanostructures and international schools on Nanophotonics and Photovoltaics.

SPIN-OPTRONICS project has been initiated in 2009. It focuses on an emerging field of spin-related phenomena. The project aims to control precisely the polarization of photons by spin-dependent microscopic interactions in semiconductor nanostructures. For instance, single quantum dots allow storing on long-time scale and modifying the spins of individual carriers with redelivering them under the form of polarized photons. In the same spirit they can be used to generate the polarized entangled photon pairs in single photon emitters. Other interesting approach is quantum structures made of diluted magnetic semiconductors, possibly hybridized with non-magnetic semiconductors. The structures can be the basis of ultra-fast optical memories and other smart photonic devices.

INDEX is the youngest member of this consortium; it has started in November 2011. It trains a new generation of scientists in the field of indirect excitons, offering a multidisciplinary program on the boundary of electronics, photonics, and spintronics. The main objectives of the INDEX project are: i) studying the fundamental properties of cold exciton gases; ii) creating innovating technologies of novel optoelectronic devices based on the exploring of the indirect excitons. This combination guarantees the strong knowledge in both quantum physics of bosonic quasi-particles in solids and modern technology. The location of research teams of INDEX spreads over two continents.

It is important to underline that the successful development of spinoptronics is closely related to the progress in two other projects. The semiconductor microcavities, traditionally studied by CLERMONT, are the prototype systems, where spin-dependent microscopic interactions and optical emission are entangled by the strong light-matter coupling. Exciton-polariton condensates can demonstrate ultra-fast spin dependent optical response with ultra-low threshold. The indirect excitons, the basic subject of INDEX, also potentially allow a long time scale storage and manipulation of a coherent ensemble of spins in excitonic condensates. The meeting of the ITN consortium was organized to take advantage of these mutual interests.

This summer school attracts participants from 25 research groups, from Europe and United States, academy and industry. The contributing groups are world recognized leaders in their research fields. That gives a unique opportunity to acquire a very deep knowledge of the basic physics and the state of the art in rapidly developing research fields, as well as to establish tight scientific relationships. We hope that our summer school will open a new route for training, researches, and transfer of knowledge through the union of three ITN networks.

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Tatiana Shubina — Maria Vladimirova
Sergey Ivanov

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CALENDAR OF EVENTS

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12.30 – 14.00	Lunch
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15.30 – 16.00	Coffee Break
16.00 – 17.30	**Seminar session 2**: Polaritonics
18.00 – 20.00	Welcome Party

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Ioffe Physical Technical Institute, St. Petersburg, Russia

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LECTURES

 Tu-1L

Fundamentals of spin physics in semiconductors

M.I. Dyakonov

Laboratoire Charles Coulomb, Université Montpellier 2, CNRS, France

This lecture presents a brief survey of spin physics in semiconductors together with the historic roots of the recent activity in researching spin-related phenomena.

 Tu-2L

Quantum optics in photonic wires: Basics and application to "ultrabright" single-photon sources

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Over the last 20 years, major efforts have been devoted to the tailoring of the optical properties of semiconductor emitters using optical microcavities and photonic crystals.

We have recently introduced photonic wires as a novel resource for solid-state CQED. I will review recent studies which demonstrate an excellent control over the spontaneous emission of InAs quantum dots (QDs) embedded in single-mode GaAs photonic wires.

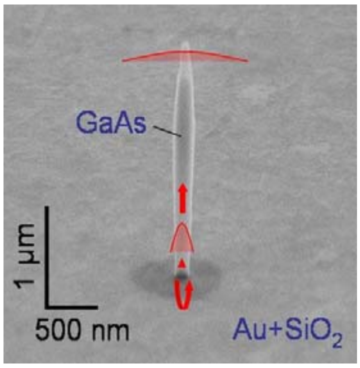

Fig.1. Electron micrograph of a photonic nanowire QD single-photon source

On the basic side, we have demonstrated a strong inhibition (x 1/16 [1]) of QD SpE in thin wires ($d<\lambda/2n$) and a nearly perfect coupling of the SpE to the guided mode ($\beta>0.95$ for $d\sim\lambda/n$) in circular photonic wires [2]. The polarization of QD SpE can also be tailored by playing with the shape of the cross section of the photonic wire. For elliptical cross sections, a strong (>90%) linear polarization oriented along the long axis of the ellipse is observed [3].

A single QD in a photonic wire is thus an attractive system to explore the physics of the "one-dimensional atom" and build novel quantum optoelectronic devices. Quite amazingly, this approach has for instance permitted (*unlike* microcavity-based approaches) to demonstrate jointly for the first time in a QD single photon source a record-high efficiency (72%) and a high purity of the single photon emission process ($g^{(2)}(0) < 0.01$) [4].

This work has been done in collaboration with J Claudon, J Bleuse, M Munsch, NS Malik, P Jaffrennou (CEA Grenoble), N Gregersen, Y Chen and J Moerk (DTU Fotonik, Copenhagen), P Lalanne (Institut d'Optique, Palaiseau).

[1] J. Bleuse *et al*, Phys. Lett. Lett. **106**, 103601 (2011)
[2] I. Friedler *et al*, Opt Exp **17**, 2095 (2009)
[3] M. Munsch *et al*, Phys. Rev. Lett. (to appear 02/2012)
[4] J. Claudon *et al*, Nature Photon. **4**, 174 (2010)

Resonant photonic crystals and quasicrystals

E.L. Ivchenko
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A periodic structure is called the *resonant photonic crystal* if (a) it forms a grating for the Bragg diffraction of light and (b) the dielectric response of at least one of its composite materials as a function of the frequency has a pole. In such systems the normal light waves are polaritons. Similarly one can define *resonant photonic quasicrystals* and other aperiodic deterministic sequences. Multiple quantum wells (MQWs) are ideal model systems for one-dimensional photonic crystals and quasicrystals. In this lecture we discuss the exciton polaritons and optical properties of periodic and aperiodic quantum-well (QW) structures.

Among long-period QW structures, of particular interest are the resonant Bragg structures or resonant Bragg refectors with the period d satisfying the Bragg condition, $q(\omega_0)d = \pi$, at the exciton resonance frequency ω_0. Depending on the number of wells N they reveal either the superradiant regime or the photonic crystal regime. In the former case both the amplitude and the halfwidth of reflection spectral peak are enhanced by a factor of N, while in the latter the structure has a well pronounced stop-band. The similar resonant Bragg condition for the quasiperiodic Fibonacci MQWs has the form $q(\omega_0) = G_{hh'}/2$, where $G_{hh'} = (2\pi/d)(h + h'/\tau)$ is the diffraction vector with the integers h, h' equal to two successive Fibonacci numbers (d is the average inter-well distance). The Fibonacci MQW structure tuned to this condition also exhibits both the superradiance and photonic stop-band with the following important difference: (i) for a small number of wells, the superradiant reflection peak has a remarkable structured dip in the middle, and (ii) at large N, a single stop-band is replaced by two equivalent stop-bands separated by an allowed exciton-polariton band. Linear and nonlinear reflectivity spectra measured from high-quality GaAs/AlGaAs QWs with spacings satisfying a Fibonacci sequence are in good agreement with excitonic polariton theory.

In the lecture, emphasis is placed on similarities and differences between optical properties of the quasicrystals, being the third form of solid matter, and those of conventional crystals and amorphous materials. Similarly to periodic systems, the two-wave approximation is often efficient to describe, within narrow frequency intervals, the light propagation in a quasicrystalline medium. Moreover, sometimes it is even instructive to introduce effective allowed bands and forbidden gaps (or stop-bands) for light waves propagating in such medium. The resemblance to disordered materials reveals in properties of photonic crystalline approximants of quasicrystals. With increasing the thickness of the approximant supercell, the optical spectra provide an evidence for the localization of light waves. Important specific features of the photonic quasicrystals with small values of the exciton nonradiative damping rate are a scaling and self-similarity of optical spectra which are completely absent in crystalline and amorphous materials.

 We-1L

Bose-condensation of dipolar excitons in lateral traps in heterostructures

V.B. Timofeev
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Spatially indirect, dipolar excitons photoexcited in coupled and single quantum wells under electrical bias applied normal to heterolayers constitute a rather promising object for realization of excitonic Bose-Einstein condensation (BEC). When critical conditions for both temperature T and concentration N (or pumping intensity P) are achieved, BEC occurs spontaneously in a reservoir of rather long-lived and cold gas of interacting dipolar excitons collected in a lateral trap. BEC is manifested by the abrupt appearance in the luminescence spectrum of a narrow line of dipolar excitons collected in a trap and condensed in the vicinity of $\boldsymbol{k} \cong 0$. This phenomenon is accompanied simultaneously by the formation of spatially-symmetric luminescent spot pattern within a perimeter of a trap. Spatial pattern structure and its visibility is strongly temperature dependent in accordance with found phase diagram. The observed effect of the linear polarization of luminescence by the Bose–Einstein condensate of dipolar excitons accumulated in the ring lateral traps is a manifestation of spontaneous symmetry breaking under Bose–Einstein condensation.

Dipolar exciton condensate accumulated in a ring trap exhibits large-scale off-diagonal spatial coherence confirmed by measuring of the 1st order correlator $g^{(1)}$(r, r’) by means of two-beam interference experiments with the use of cw and pulsed photoexcitation. Statistics of photons emitted by exciton Bose-condensate (the 2d order correlator, $g^{(2)}(\tau)$) have been studied at condensation threshold in the temperature range of (0.45÷4.2) K. Photon “bunching” has been observed at the Bose condensation threshold. At the excitation pumping well above the threshold, when the narrow line of exciton condensate begins to grow in the luminescence spectrum, the photon bunching is decreasing and finally vanishes with further excitation power increase. In this pumping range, the photon correlation distribution becomes Poissonian reflecting the single quantum state nature of excitonic Bose condensate. The effect of a magnetic field on a spinor dipolar exciton bose-condensate has been presented and discussed in comparison with the same observed phenomenon for spinor exciton-polariton condensate in microcavitiy.

Condensate and Quasiparticle Transport in a Bilayer Quantum Hall Excitonic Superfluid

J.P. Eisenstein[1], D. Nandi[1], A.D.K. Finck[1], L.N. Pfeiffer[2], and K.W. West[2]
[1]*California Institute of Technology, Pasadena, CA 91125 USA*
[2]*Princeton University, Princeton, NJ 08544 USA*

Bilayer two-dimensional electron systems support an excitonic quantized Hall state when the separation between the layers is sufficiently small and the total number of electrons in the system matches the degeneracy of a single spin-resolved Landau level created by an applied perpendicular magnetic field. In this novel phase of matter, the ground state of the system consists of an exciton condensate in which electrons in one layer are bound to holes in the other. An energy gap separates this condensate from charged quasiparticle excitations. The system possesses many remarkable properties including a quantized Hall effect, a Josephson-like interlayer tunneling, linearly dispersing collective modes, and vanishing Hall resistance when electrical currents flow in opposite directions through the two layers.

In this talk I will describe our recent experiments in which direct control over exciton transport in the condensate is achieved. These experiments rely on the use of the multiply-connected Corbino transport geometry to eliminate complications associated with the conducting edges states at the sample boundary and to directly prove that charge-neutral excitons can easily move through the otherwise insulating bulk of the 2D system. In addition, I will discuss how the transport of charged quasiparticles above the energy gap can proceed alongside the exciton transport in the condensate when the temperature, layer separation, or drive voltage is increased.

These experiments open the way to a variety of new experiments on a unique superfluid, one with a neutral condensate but charged excitations.

Indirect Excitons

A.A. High, J.R. Leonard, M. Remeika, A.T. Hammack, Sen Yang, M.M. Fogler, and L.V. Butov

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K.L. Campman, M. Hanson, and A.C. Gossard

Materials Department, University of California at Santa Barbara, Santa Barbara, CA 93106-5050, USA

An indirect exciton is a bound pair of an electron and a hole confined in spatially separated layers. Long lifetimes of indirect excitons allow them to cool down to low temperatures below the temperature of quantum degeneracy. This gives an opportunity to study cold exciton gases. We will present spontaneous coherence and condensation, phase singularities, spatial ordering, and spin textures in a cold excitons gas [1, 2].

Indirect excitons are dipoles and their energy can be controlled by voltage. This gives an opportunity to create a variety of potential landscapes for indirect excitons and use them as a tool for studying the physics of excitons. We will present spontaneous coherence and condensation of excitons in a trap [3].

[1] A.A. High, A.T. Hammack, J.R. Leonard, Sen Yang, L.V. Butov, T. Ostatnický, A.V. Kavokin, and A.C. Gossard, arXiv:1103.0321

[2] A.A. High, J.R. Leonard, A.T. Hammack, M.M. Fogler, L.V. Butov, A.V. Kavokin, K.L. Campman, and A.C. Gossard, arXiv:1109.0253

[3] A.A. High, J.R. Leonard, M. Remeika, L.V. Butov, M. Hanson, and A.C. Gossard, arXiv:1110.1337

Spin manipulation in III-V/II-VI heterovalent structures

A.A. Toropov
Ioffe Physical-Technical Institute, St. Petersburg 194021, Russia

The development of novel multifunctional spintronic devices implies employment of magnetic semiconductor components because, in contrast to ferromagnetic metals, several important properties, such as carrier type (n or p), carrier density, and carrier spin polarization can be readily controlled in semiconductor materials. Recently, significant efforts have been made in developing ferromagnetic III-V-based semiconductors, such as GaMnAs [1], InMnAs [2], or InMnSb [3], which have already opened a number of fundamental issues in magnetism and magnetotransport. However, the common problem of these materials is that the temperature of a III-V:Mn layer cannot be raised above ~300º C without creating metallic inclusions and, hence, the overgrowth of perfect nonmagnetic III-V compounds is impossible. This circumstance sets severe constraints on the design of the magnetic heterostructures based on III-V semiconductors alone. The promising materials to be combined with the magnetic III-V compounds are II-VI compounds (ZnSe for GaMnAs, CdSe or ZnTe for InMnAs, and CdTe for InMnSb), whose optimal growth temperature is below 300º C and lattice constant is very close to that of the respective III-V material. Therefore, the understanding of the details of III-V/II-VI heterovalent interfaces and their functionality in spintronic devices acquires special importance. In this context, a critical issue is understanding of the transmission of spin information through the heterovalent junction separating chemically different materials.

In this lecture I'll review previous and very recent results on electronic and spin-dependent properties of III-V/II-VI heterovalent structures. The following phenomena, approaches, and structures will be considered.

- Engineering of electronic band offsets at heterovalent interfaces.
- Diffusive and coherent transfer of spin through a heterovalent interface between bulk materials [4,5].
- Spin-dependent tunneling in electronically coupled heterovalent quantum wells (QWs) [6-8].
- Proximity effects emerging e.g. when a III-V ferromagnetic layer is interfaced with an antiferromagnetic II-VI layer [9].
- Exchange interaction of carriers confined in nonmagnetic III-V QWs with Mn ions in II-VI magnetic barriers [10].

[1] M. Wang *et al.*, Appl. Phys. Lett. **93**, 132103 (2008)
[2] D. Chiba *et al*, Science **301**, 943 (2003)
[3] C.E. Feeser *et al.*, J. Vac. Sci. Technol. B **30**, 032801 (2012)
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A highly efficient single photon - single quantum dot interface

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A quantum dot (QD) in a microcavity is a promising system to build a solid-state quantum network. It can be an efficient quantum light source as well as a quantum memory, a Bell-state analyser or a remote photon entangler when the QD embeds a spin. However, for these applications, one needs that every photon emitted by the QD is collected or, symmetrically, that every photon sent onto the device interacts with the QD. In this talk, we will present important steps we have recently made in this direction by deterministically inserting a QD in a cavity and controlling its spontaneous emission.

We first report on the fabrication of ultrabright sources of indistinguishable single photons using single QDs coupled to pillar cavities in the weak coupling regime. Large pillar cavities are used to obtain an external mode out coupling close to unity and to minimize dephasing processes in the QD surrounding. We compensate for large cavity mode volumes by precisely locating the QD at the maximum of the electromagnetic field using a deterministic lithography method [1]. By selecting QDs with high quantum efficiencies, we fabricate sources of indistinguishable single photons with measured brightnesses up to 0.78 collected photon per pulse, in a numerical aperture as small as 0.4. The Hong Ou Mandel experiment is implemented and demonstrates the indistinguishability of the photons with a mean wave-packet overlap up to 75%.

In a second part, we report on resonant reflectivity measurements performed under continuous wave excitation on high quality factor pillars operating in the strong coupling regime. Absolute reflectivity measurements show that the QD-micropillar system presents a coupling efficiency of 65 % and that the optical nonlinearity starts at an intracavity photon number around 0.2 only. Thanks to this very large coupling, we measure in real-time very small electrostatic changes around the QD down to the microsecond time scale.

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Quantum entanglement mediated by plasmon-polaritons

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This talk starts with a tutorial introduction to the field of plasmonics in nanostructures. Plasmon-polaritons are produced by the coupling of plasmons in metallic nanostructures to electromagnetic fields which decay out of the metallic interfaces. Molecules, quantum dots, defect centers or other semiconductor nanostructures with a discrete electronic spectrum, when are close to a metallic nanostructure, behave as qubits coupled to plasmon-polaritons. We present here a study of the quantum properties of such a system.

In a first step, we use classical electrodynamics for obtaining all the ingredients required in the quantum mechanical description of the system. By means of the adequate quantization procedure, one can analyze the physics determining the conditions under which the open system of qubits and plasmon-polaritons is in a strong- or in a weak-coupling regime.

Later, we concentrate on the generation of entanglement between two of those qubits mediated by the plasmon-polaritons of a metallic waveguide. A V-shaped channel milled in a flat metallic surface is much more efficient for this purpose than a metallic wire. We study important experimental aspects as the role of the misalignments of the dipole moments of the qubits or the influence of a coherent external pumping, needed to achieve a steady state entanglemen. A careful analysis of the quantum-dynamics of the system by means of a master equation shows that two-qubits entanglement generation is essentially due to the dissipative part of the effective qubit-qubit coupling provided by plasmon-polaritons.

Optical pumping of carrier and nuclear spins in quantum dots

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The mesoscopic spin system formed by about 10 000 nuclear spins in a semiconductor quantum dot offers a unique setting for the study of many-body spin physics in the condensed matter. The dynamics of this system and its coupling to electron spins is fundamentally different from its bulk counter-part as well as that of atoms due to increased fluctuations that result from reduced dimensions. In recent years, the interest in studying quantum dot nuclear spin systems and their coupling to confined electron spins has been fuelled by the fascinating nonlinear (quantum-) dynamics of the coupled electron-nuclear spin system and its implication for possible applications of such systems in quantum information processing.

In this talk, we review experimental work performed over the last decades in studying this mesoscopic, coupled electron-nuclear spin system and discuss how optical addressing of electron spins can be exploited to manipulate and read-out quantum dot nuclei. We conclude by speculating how this recently gained understanding of the quantum dot nuclear spin system could in the future enable experimental observation of quantum mechanical signatures or possible collective behaviour of mesoscopic nuclear spin ensembles.

This work has been carried out in collaboration with the LPN-CNRS Marcoussis (France), ETH Zurich (Switzerland), NIMS Tsukuba (Japan) and the Ioffe Institute St. Petersburg (Russia).

Optical control of individual magnetic atoms in a semiconductor quantum dot

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The decrease of the structure size in semiconductor electronic devices and magnetic information storage devices has dramatically reduced the number of atoms necessary to process and store bits of information. Information storage on single magnetic atoms would be an ultimate limit. Diluted magnetic semiconductors combining high quality semiconductor structures and the magnetic properties of Mn atoms (S=5/2) offer the possibility to couple magnetic atoms through their exchange interaction with carriers and are model systems for the study of these devices.

With quantum dots doped with Mn atoms, the optical probing of a single atomic spin in a solid state environment become possible using optical micro-spectroscopy techniques: The state of a photon emitted or absorbed by a II-VI semiconductor quantum dot containing an individual Mn atom is directly related to the spin state of the atom. This is due to the exchange interaction between the confined electron-hole pair and the Mn spin: the electron-hole pair acts as an effective magnetic field along the quantum dots' growth axis that lifts up the degeneracy between the six (2S+1) Mn spin states. Depending on the Mn spin orientation, the recombination of an injected electron-hole pair emits a photon with a given energy and polarization. An individual Mn atom embedded in a II-VI semiconductor quantum dot may act as an optically addressable spin based memory. The next step would be to control the coupling between such ultimate memories: a carrier mediated interaction between two Mn spins inserted in the same quantum dot is one step towards this challenging goal.

In this talk, we will show how the photons emitted by an individual CdTe/ZnTe quantum dot containing one or two Mn atoms can be used to probe the dynamics of the Mn spins. We will also discuss how the resonant optical injection of spin polarized carriers can be a tool to control these localized spins. After a description of the spin structure of the system formed by the interaction between a controlled number of confined carriers and one or two Mn spins [1], we will present photon correlation [2] and time resolved optical pumping experiments [3] on individual quantum dots allowing probing the dynamics of these few interacting spins. Finally, we will show that under a strong resonant optical field, the energy of any spin state of one or two Mn atoms can be independently tuned using the optical Stark effect [4]. Each optical transition in a Mn-doped quantum dot behaves like an isolated two-level quantum system well described in a dressed atom picture. In the ground state, the laser induced shift could be used for a coherent manipulation of the spin of the Mn atoms.

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Quantum dot spins: an optical investigation

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Resonant laser spectroscopy is a powerful tool to investigate the spin properties of semiconductor quantum dots (QD). It allows access to both the spin of charge carriers (electrons and holes) trapped in the QD as well as to the nuclear spin ensemble.

In this talk I will discuss a peculiar but very prominent feature of the nuclear spin system of highly and inhomogeneously strained InGaAs/GaAs QDs that is revealed particularly by resonant laser spectroscopy: The strain induced quadrupolar moments of the nuclear spin lead to an additional term in the hyperfine Hamiltonian representing non-collinear interactions between electron and nuclear spins. In the presence of laser excitation resonance locking effects are observed allowing for resonant nuclear spin polarization. I will finish by giving an outlook for the potential application of this optical feedback to the nuclear spin ensemble for narrowing its random fluctuations.

Advanced spectroscopy investigations in ZnO-based heterostructures

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In this lecture I will review some of the most interesting results obtained by cw and time-resolved spectroscopy using high quality bulk zinc oxide, ZnO-related hetero-structures, ZnO-related wire-like and two-dimensional micro-cavities. Results presented here are chosen among the own result of my group and in the fresh literature of the field.

During this lecture I will successively emphasise in particular:

- Light propagation in bulk ZnO the near band gap energy region where polariton effects mediate the group velocity [1,2]
- Observation of Quantum Confined Stark Effect in ZnO-ZnMgO quantum wells grown along the polar orientation [3,4]
- Experimental observation of selection rules at the scale of the optical properties of non polar ZnO-ZnMgO (M-Plane grown) quantum wells [5]
- Experimental observation of optical properties of non polar ZnO-ZnMgO (M-Plane grown) quantum wells free non-radiative recombination processes [6]
- Polariton lasing in ZnO nanorods [7]
- Polariton lasing in ZnO-based 2D microcavities [8,9]
- In-plane polariton migration in 2D microcavities [10]

I am very grateful to Prof. Alexey Kavokin from the University of Southampton and Dr. Tatiana Shubina from the Ioffe Institute for so many in-depth discussions. I would also like to acknowledge a long list of colleagues in France, among which are Drs. Thierry Guillet, Jesus Zuniga Perez, Sophie Bouchoule, Fabrice Semond, Christelle Brimont, and many others for their relevant contributions to the slides of this presentation.

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Sa-2L

Manipulating polariton condensates on a chip

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Recent advances in the growth of high finesse microcavities capable of supporting increased photon lifetimes, have made condensation of solid state polariton quasiparticles, built from mixing semiconductor excitons with microcavity photons possible. In a condensed phase, polariton gas has been shown to exhibit superfluid behaviour favouring the establishment of long range order and opening new prospects of quantum manipulation of extended polariton condensates. Recent experiments on manipulation of such quantum fluids have relied on statically imprinted potentials exploiting photonic confinement in micropillar and wire structures. Here, we explore the possibility of manipulation of two-dimensional polariton condensates on a semiconductor microcavity chip using optically imprinted external potentials as shown in Figure 1. The control is achieved on the fly by optically injecting polaritons onto the chip with specific spatial profile to create potential energy landscape in which condensate propagates. We present, tomography technique which can be used to directly visualise formation of such spontaneously created quantum fluid. Beyond the very rich physical phenomena of quantum fluids the ability of their manipulation reveals their great potential for integrated semiconductor-based interferometric devices.

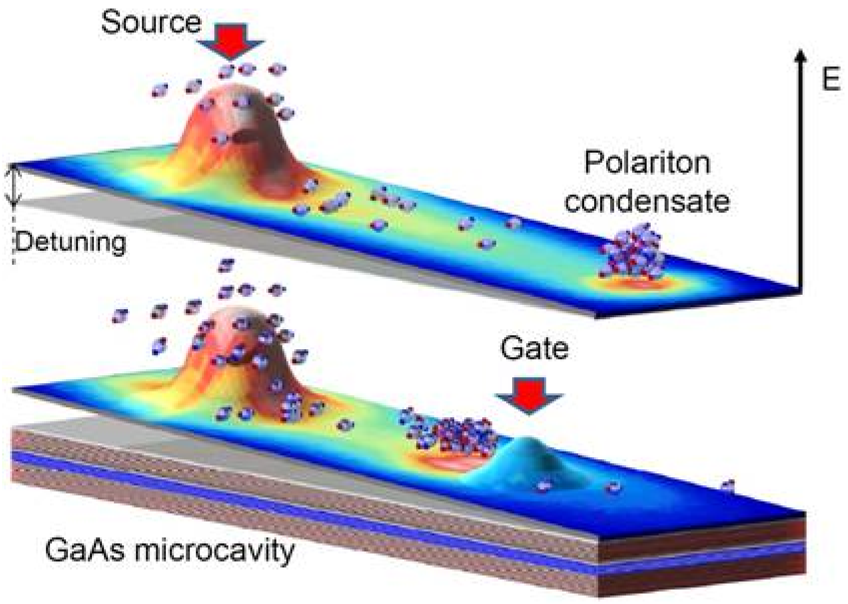

Figure 1. On chip gating of the polariton condensate flow.

SEMINARS

Coherent nonlinear optical spectroscopy of spin effects in semiconductors and magnetic materials

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Among a broad variety of nonlinear optical phenomena, quite a distinguished role can be attributed to those processes which lead to the frequency conversion. The simplest examples are coherent processes of 2^{nd}, 3^{rd} and higher order optical harmonics generation. They are defined by higher order susceptibilities and therefore are more symmetry sensitive in comparison to linear optical phenomena. For example, second harmonic generation (SHG) is strongly anisotropic even in cubic crystals. In this talk we are going to discuss how magnetic field, spins and spin ordering can contribute to harmonics generation in several groups of semiconductors and magnetic materials.

Until recently, there were no detailed studies of harmonics generation at low temperature in broad spectroscopic range in applied magnetic fields. We performed such studies in fields up to 10 T at 2 K and higher temperatures. In GaAs, we found that application of a magnetic field induces new features in the optical SHG spectrum above the band gap [1]. A series of sharp SHG lines was observed in the spectral range from 1.52 to 1.77 eV that we attributed to Landau-level quantization of the band energy spectrum. Calculations revealed that magneto-optical spatial dispersion that comes together with the electric-dipole term is the dominant mechanism of this nonlinearity.

Basically different mechanisms of optical SHG induced by an external magnetic field were identified experimentally by studying the diluted magnetic semiconductors (Cd,Mn)Te [2]. For paramagnetic compounds the SHG response is governed by spin quantization of electronic states. The mechanisms can be identified by the distinct magnetic field dependence of the SHG intensity which scales with the spin splitting in the paramagnetic case as compared to the B^2 dependence in the diamagnetic case.

The third group of materials we discuss is europium chalcogenides EuSe and EuTe [3]. They are magnetic semiconductors with crystallographic and magnetic structures distinctly different from those of GaAs and CdTe. $4f^7$ states of Eu^{2+} ions lie above the $4p^6$ and $5p^6$ states of Te^{2-} ions in EuSe and EuTe, respectively. Analysis of the electronic structure and selection rules showed that SHG is forbidden in the electric dipole and electric quadrupole approximations. Nevertheless in EuSe and EuTe we observed SHG signals in the presence of an applied magnetic field in the vicinity of the band gap of 2.2-2.4 eV. Detailed study allowed us to conclude that the SHG signals arise due to the *ferromagnetic* component of the magnetic structure. ZnO is known for its complicated exciton structure which we studied in zero and applied magnetic field. We found that the applied magnetic field can induce new contributions to the SHG by itself and due to the so-called magneto-Stark effect.

We shall discuss some examples of harmonics generation by spontaneous spin ordering (no magnetic field applied) in antiferromagnetic and ferromagnetic materials.

This work is supported by the RFBR, the DFG-RFBR joint project, and the Programs of the Russian Academy of Sciences.

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Delay and distortion of light pulses by excitons studied by time-of-flight spectroscopy

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Optical dispersion at exciton resonances results in a delay of light transfer due to variation of group velocity [1]. This phenomenon has been observed by time-of-flight spectroscopy in different semiconductors [2-4]. This light retardation is currently of particular interest because it is one of the ways to obtain the so-called “slow light”, which is needed for optical communication and data processing [5]. Besides, this effect is important for a set of optoelectronic devices – high-frequency ones or those, where the light should propagate a long distance.

The advanced seminar is aimed to present the time-of-flight spectroscopy studies of wide-gap semiconductors – GaN and ZnO. The experiments were performed using the pulses of tunable ps and fs lasers, propagating through high-quality crystals and registered by a Hamamatsu streak camera. They have revealed that significant light delay about ~1% of the light velocity in vacuum exists near an exciton resonance. This delay is accompanied by distortion of a pulse shape in the time-energy plane. The light transmitted through the GaN crystals contains both ballistic and diffusive components [3]. However, weaker replicas, observed in the time-resolved images due to the reflection of light pulses from the sample boundaries, propagate purely as exciton-polaritons. Their modeling gives excitonic parameters inherent for bulk GaN [6].

ZnO differs from GaN by the presence of numerous lines of donor bound excitons. In this semiconductor, the maximal delay of the higher-energy pulse edge approaches 1.6 ns at 3.374 eV for L=0.3 mm [7]. The general curvature and delay are controlled by the exciton-polariton resonances, while the bound exciton lines provide dips cutting the pulses into several parts and induce extra light retardation nearby. The simulation of the pulse shapes in the time-energy plane has been done assuming the linear regime and using the Gabor transformation. It has been found that: i) the homogeneous width of the exciton-polariton resonances is as small as 3 μeV at low temperature (2 K); ii) the inhomogeneous width cannot exceed 0.5 meV for the A excitonic series. The time-of-flight studies of ZnO done over a wide temperature range demonstrate the strong influence of resonant scattering by phonons on the light delay in polar semiconductors. The homogeneous width of the exciton-polaritons in ZnO derived from the temperature dependencies of the pulse propagation approaches ~1-2 meV at 300 K. This value is well consistent with the theoretical estimation done taking into account the renormalization of the exciton-polariton homogeneous linewidth due to the interaction with optical and acoustical phonons. It is revealed that the output signal at the room temperature is an exclusively scattered light for a 0.3-mm length. The delay of this signal significantly decreases due to the high group velocity at the energy of the scattered photons.

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Slow light: An instructive story

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The notion of "slow light" has been introduced into scientific language at the very beginning of our century, when Prof. L. Hau with her team from Harvard University have managed to reduce the group velocity of light by more than 7 orders of magnitude, down to 17 m/s. The authors of this research took advantage of the effect of electromagnetically induced transparence (EIT), which may provide, in a three-level system with Λ-like energy diagram, a narrow spectral feature needed to obtain anomalously high dispersion of the refractive index.

This fascinating achievement was met enthusiastically by scientific community. The experiment of Prof. Hau was reproduced in different modifications, and a few new approaches to "slow light" have been proposed. As often happens, at the leading edge of development of an as-discovered phenomenon, scientific journals are inclined to be more liberal with respect to related manuscripts. As a result, soon after this discovery, there have appeared some publications in which the well-known effects of retarded response of optically nonlinear media were ascribed to group velocity reduction.

In this lecture, we will briefly consider examples of such mis-interpretation. Among them are the slow-light effects based on the EIT in degenerate Λ-scheme and on the so-called coherent population oscillations. These stories look curious and instructive, in the light of the famous medieval principle known as "Occam's razor", which sounds as "Entities should not be multiplied beyond necessity". As applied to physical research, it means that if some phenomenon is explained comprehensively, one should not make additional assumptions to be able to explain it in a more sophisticated way.

1D polaritonics

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Creation of the spintronic devices based on polariton transport needs a simple and reliable way of creation of the polariton one dimentional channels. This can be achieved by the patterned metallization of the top surface of the structure, which is a straightforward process that puts few constraints on possible device geometry and provides the opportunity to exercise an additional element of control through the application of electric fields that modify the energy of the polaritons through the Stark effect.

Possibility of 1D confinement allows to propose a variety of spinoptronics components, including polariton neuron and polariton transistor consisting of several segments covered by independent metallic gates which allows independent tuning of Stark shifts at each segment, that can be used to exercise control over the propagation of the signal in this structure.

In the talk we will give an overview of physics of one- dimensional polaritons and consider its possible applications.

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Half-Integer Topological Defects as Magnetic Monopoles in Polariton Condensates

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Abstraction is a common tool in physics, serving the better comprehension of complex phenomena. The most evident example is the atom, encompassing an intricate underlying structure of electrons and hadrons, the latter themselves composed of quarks and gluons. This internal structure can of course be completely neglected while discussing the properties of gases in statistical physics. Such multi-level abstraction is especially ordinary for solid-state physics, where excitons are formed from electrons and holes, themselves being complicated elementary excitations formed from several electronic levels of atoms constituting the solid. The excitons can be described as massive quantum particles, which can couple with photons and form new particles of an even higher level of abstraction - composite bosons called exciton-polaritons.

When a Bose-Einstein condensate [1] (BEC) is formed, one can consider its weak excitations as elementary particles (called bogolons), forgetting the nature of the underlying bosons. But the weak elementary excitations are not the only kind of interesting perturbation which can occur in a BEC. The topological defects [2] resulting from the non-linearity of the Gross-Pitaevskii equation and the irrotationality of the macroscopic condensate wavefunction are currently (and since quite a long time) in the focus of intense theoretical and experimental research, and will be the main topic of the present work. We shall see how their behavior can be described in terms of relativistic "material points" and "point charges" (an easy way) or in terms of underlying local spin dynamics (a harder way). The importance of such analogies as "magnetic charges" will thus become especially clear.

We will discuss the behavior of single half-solitons and half-vortices in spinor polariton condensates in the presence of an effective magnetic field (induced by the energy splitting between polarizations in wire and planar cavities). We will show that such topological defects behave as "magnetic charges", accelerating along the field [3]. Such a behavior is a special feature of half-integer topological defects, which also applies to the so-called oblique half-solitons [4]. We will see that their stability is maintained thanks to the spin anisotropy of polariton-polariton interactions [5]. Moreover, in the presence of an in-plane effective magnetic field integer topological defects may become unstable and split into half-integer ones, which will separate in real space due to the interaction with the field. We propose a practical way to create integer (or half-integer) topological defects in wire and planar cavities in a controlled way, in order to study their natural separation paving the way towards "magnetricity".

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Photo-induced Faraday rotation in n-GaAs microcavities

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It is well established that nuclear spins in semiconductors can be efficiently manipulated and detected optically. This is made possible by hyperfine interaction between conduction band electrons and nuclei. However, the presence of the photo-created carriers required until now for such experiments does affect the behavior of the nuclear spins. Here we demonstrate that nuclear spin polarization can be detected in the "darkness", that is long after photo-induced spin polarization has been lost. The idea of such experiment has been proposed in 80s [1]: nuclear spins are cooled well below lattice temperature by circularly polarized pumping (dynamic nuclear polarization technique), then the pump beam is switched off and the resulting spin polarization in the longitudinal magnetic field is monitored via Faraday rotation of the probe beam. This rotation results mainly from the conduction band splitting in the Overhauser field generated by spin polarized nuclei.

For practical realization of such measurements a high-Q microcavity was designed and grown in order to provide sufficient interaction length between the light and n-GaAs active layer. The n-doping close to metal to insulator transition ($n_e \approx 2\times10^{16}\ cm^{-3}$) ensures stronger polarization of the electron gas via optical orientation and thus in this system we also achieve up to 19° Faraday rotation due to electron spin polarization in the absence of the external magnetic field. On the other hand, this allows investigating nuclear spin dynamics in the presence of degenerate electron gas. Such configuration is potentially interesting since slow relaxation of nuclei is expected, but only few experimental data are available.

Our first results allowed for the quantitative determination of the Faraday rotation efficiency due to nuclear and electron magnetization and comparison with the model. On the other hand the dynamics of nuclear spins in n-GaAs appeared to be quite complex and unexpected.

(i) We observed that spin relaxation of nuclei in the darkness depends strongly on the magnetic field. Even at strong field (B~200 G) nuclear spin relaxation is faster than predicted by Korringa mechanism (~10 minutes), and at low field it appears to be much faster (1 min). (ii) Faraday rotation signal resulting from nuclear magnetization has two components. In addition to conventional slowly decaying signal, we observe a rapidly decaying rotation (10 s) with the opposite sign. Tentative explanation in terms of polarization of nuclei by holes localized on acceptor sites is proposed.

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Josephson oscillations between exciton condensates in electrostatic traps

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The Josephson effect is a remarkable phenomenon that has been observed in systems as diverse as superconductors, superfluid Helium, trapped ultra-cold atomic gases. Since Josephson oscillations appear naturally as the state oscillation between the macroscopic wave functions of two weakly linked condensates, they have been predicted for bosonic excitations in solids as well, like polaritons and excitons [1]. However, unlike the polaritons, which have a photonic component allowing for easy detection, excitons stay dark unless they recombine radiatively. So far, it is unclear how the exciton Josephson effect could be observed. Here, we propose a possible experiment [2].

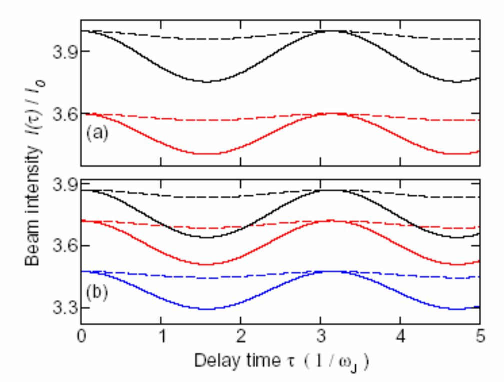

Figure 1. Predicted beam intensity vs delay time for the proposed correlated photon counting setup. Dashed and solid lines refer to increasing values of the inter-trap dipole energy difference. (a) Red and black curves indicate increasing values of fringe visibility. (b) Black, red, and blue lines indicate increasing values of temperature.

Condensed excitons are predicted to emit coherent light. If Josephson oscillations occur between two exciton traps, in principle they can be probed by measuring the interference of the beams separately emitted from the traps. However, in the time interval before recombination, the photons emitted are too few to allow to resolve the signal of their time correlation and one has to average it over many replicas of the same experiment [3]. We show that this ensemble average blurs the signature of the Josephson effect but in the relevant case of exciton "plasma" oscillations. For the latter the tunable dipole energy difference between electrostatically defined exciton traps [4] controls fringe visibility, providing a means for detection.

This work is done together with L. J. Sham. Financial support from Marie Curie ITN INDEX is gratefully acknowledged.

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Dynamics of ultra-cold indirect excitons in a trap

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The realization of microscopic traps for ultra-cold exciton gases constitutes a key step for fundamental studies, notably to explore collective quantum phenomena, but also for applied research as it allows for the development of exciton based opto-electronics devices. In recent years, important progress has been made with the so-called spatially indirect excitons confined in double quantum wells (DQW). Techniques to capture indirect excitons have been developed, e.g. stress or magnetically induced traps. In addition, a series of experiments has shown that the quantum confined Stark effect, i.e. the interaction between the well oriented electric dipole of indirect excitons and an external electric field, provides a direct access to exciton trapping. Indeed, indirect excitons are high-field seekers and then captured by electric field gradients imprinted in the plane of a DQW. Hence, devices employing micro-patterned gate electrodes have lead to an unprecedented degree of control over the transport of indirect excitons, however at the cost of highly-demanding lithographic processes.

Here, we introduce an alternative to the state-of-the-art technology in order to control the confinement of spatially indirect excitons. Precisely, we show that the optically controlled injection and spatial patterning of charges trapped in a field-effect device can create dynamically and on-demand potential landscapes where ultra-cold and dense gases are captured. Trapped charges locally modify the internal electric field and create optically defined potential gradients. Thus, arbitrary confinement geometries are directly created simply by shaping the spatial profile of a laser excitation. We then realized hollow and ring traps for indirect excitons, i.e. traps with circular and ring-shaped potential barriers respectively, but also artificial one-dimensional lattices.

Optically injected charges yield trapping potentials with depths in the range of several meV. The resulting traps do not vary over time such that laser sequences may be utilized to first imprint a confining potential where indirect excitons are subsequently injected optically. In the high-density regime, the relaxation dynamics reveals that confined gases are well thermalized. For our experiments realized at 350 mK quantum statistical effects are then theoretically predicted, consequently we discuss the quantum coherence of trapped exciton gases.

Experimental progress towards probing the ground state of an electron-hole bilayer by low-temperature transport

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Closely spaced two-dimensional electron and hole gases are of significant interest when the layer separation approaches the excitonic Bohr radius (~10nm in GaAs). The ground state phase diagram of such a system is anticipated to be rich, including an excitonic superfluid predicted over 30 years ago [1], a BEC-BCS crossover and density modulated phases including charge density waves and Wigner crystals [2].

Experimental realisation however, has proven extremely difficult. Only recently has it been possible to design independently contacted electrically generated electron-hole bilayers (EHBLs) where exciton formation is considered likely. Devices have reached carrier densities less than 5×10^{10}cm^{-2} in each layer and a separation of 10–20nm in a GaAs/AlGaAs based system [3,4]. In these EHBLs, the interlayer interaction can be stronger than the intralayer interactions.

In these devices, the interlayer interaction can be probed directly using the Coulomb drag technique. A current is passed in one layer, and momentum transferred to the other layer is detected as a voltage. Experiments have revealed that the Coulomb drag on the hole layer shows strong nonmonotonic deviations from the behaviour expected for Fermi-liquids at low temperatures [3,4]. Simultaneously, an unexpected insulating behaviour in the single-layer resistances (in a highly "metallic" regime with $\rho<<h/e^2$) also appears in both layers despite electron mobilities of above ~10^6cm^{2}V^{-1}s^{-1} and hole mobilities above ~10^5cm^{2}V^{-1}s^{-1} [5]. Experimental data also indicates that the point of equal densities ($n=p$) is not special.

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Spin coherence of electrons and holes in ZnSe-based quantum wells

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Coherent spin dynamics of electrons and holes have been studied by a picosecond pump-probe Kerr rotation technique in ZnSe-based quantum well (QW) structures with a binary material of QW. Samples with low-density two-dimensional electron and hole gas have been chosen. Long-living spin coherence both of holes (≈1ns) and electrons (up to 32 ns) was observed at low temperatures of 1.8 K when the resident carriers are localized well width fluctuations. Two sets of samples were have been examined: (1) structures with $ZnSe/Zn_{0.82}Be_{0.08}Mg_{0.10}Se$ single QW (thickness varying from 7 to 19 nm) surrounded by an additional $Zn_{0.71}Be_{0.11}Mg_{0.18}Se$ barriers were nominally undoped having concentration of resident electrons (2DEG) of $5x10^9 cm^{-2}$; (2) structure containing $ZnSe/Zn_{0.89}Mg_{0.11}S_{0.18}Se_{0.82}$ single QW with concentration of two dimensional hole gas (2DHG) of $3x10^{10}$ cm^{-2}.

The time-resolved pump-probe Kerr rotation technique with selective excitation of the trion or exciton states was used. Experiments were performed in magnetic fields 0–5 T applied in the plane of the structure (the Voigt geometry). The sample temperature was tuned in a range 1.8–270 K. The long-lived electron spin beats with dephasing time up to 32 ns have been observed in the structure with 2DEG under resonant trion excitation. In case of the resonant excitation of the exciton (detection at trion resonance) the maximum dephasing time was 21 ns. The electron spin beats were visible up to room temperature. The spin dephasing rate increases linearly with temperature in the temperature range 10 - 170K. It means that Dyakonov-Perel spin relaxation mechanism on k-linear spin splitting of the conduction band dominates for these temperatures. The observed decrease of the zero-field peak in the signal of the resonant spin amplification relatively to the other peaks we assign to the anisotropic spin relaxation of electrons at high levels of excitation.

The long-lived hole spin beats with dephasing time ≈1ns (T=1.8K and B=0.5T) have observed in the structure with 2DHG. The electron spin beats with fast spin relaxation time ≈10 ps have observed simultaneously with hole spin beats at magnetic field B≈3T. An additional above-barrier illumination leads to appearance of long-lived electron spin beats, while the amplitude of the hole beats was decreasing.

 We-5s

Spin-flip Raman scattering in type-I quantum dots with direct and indirect band structure

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The spin structure of neutral and negatively charged excitons and fundamental spin interactions of carriers confined in InAs-based quantum dots (QDs) are characterized by means of the resonant spin-flip Raman scattering (SFRS). The SFRS spectroscopy is a suitable optical technique to probe the characteristics of spin structures as it provides the direct measurement of the *g* factor. Hereby, both direct band-gap (In,Ga)As/GaAs and the novel indirect band-gap (In,Al)As/AlAs QDs with type-I band alignment are studied.

The spin-flip scattering processes of the electron, heavy-hole and exciton depend on the symmetry of the crystal lattice, QD potential and magnetic field confinement as well as the type and excitation state of the carrier complex. The spin-flip scattering in InAs-based QDs is shown to be frequently based on the mixing between light-hole and heavy-hole states, induced by strain and dot shape anisotropies, as well as the level mixing resulting from the coupling of a tilted magnetic field to a nonzero in-plane magnetic moment of the electron and/or heavy-hole. In singly charged (In,Ga)As/GaAs QDs a novel optical resonance excitation is observed where an incident photon excites an electron-hole pair and simultaneously the resident electron to an excited Fock-Darwin state; in this excited carrier complex the electrons mutually change their spin states thus yielding an electron-SFRS. Since strong magnetic fields, close-to-Faraday geometries, and large-diameter QDs are necessary to initiate that process, it can be compared to the quantum well phenomenon of an exciton-cyclotron resonance.

The undoped (In,Al)As/AlAs quantum dots with indirect band gap provide an indirect exciton which is formed by a Γ-point hole and an electron at the X-point, whereby both are located within the QD. These excitons have remarkable dynamical properties: their radiative recombination time and spin lifetime exceed hundreds of microseconds. By tailoring the composition profile and size of the QDs not only the exciton recombination dynamics can be controlled, but also a mixing between electron levels from direct and indirect valleys can be obtained. Due to the level mixing the indirect exciton is optically addressable, thus, its spin properties are specified by the resonant SFRS. The *g* factor tensor components of the electron, hole, and exciton indicate a high QD symmetry, where spin-orbit interaction and valence band mixing are negligible. The experimental results of the spin structure characteristics are compared to theoretical predictions.

Tunable transition energies, entangled photon pairs and coherent control of the exciton using quantum dots in diodes

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We have developed a *p-i-n* diode structure that allows vertical electric fields of 500 kV/cm to be applied to InAs/GaAs quantum dots without tunnelling-induced quenching of radiative emission. This allows us to tune their transition energies by 25meV, in principle allowing all dots in an inhomogeneously broadened ensemble to emit at the same energy (R. Patel *et al*, Nature Photonics 4, 632 (2010)).

We have found that this large electric field is also a promising way to control the neutral exciton's fine-structure splitting (*s*). We find *s* shifts linearly with field at a remarkably similar rate for all dots, even if they differ in wavelength or *s* at zero field (A. J. Bennett *et al*, Nature Physics 6, 947 (2010)). In a large fraction of the dots we can tune *s* to a minimum value where we observe an avoided crossing in the two exciton energy levels and rotation of the eigenstates in the plane of the sample. When *s* is reduced to a few micro-eV efficient emission of polarization entangled photon pairs occurs with a fidelity of 71%.

The use of a static electric field is useful for entangled photon pair emission, but perhaps uniquely amongst the various methods for tuning *s* this mechanism allows dynamic control. In one experiment we have used a quasi-resonant laser to excite a certain spin-state in the exciton and then through application of sub-nanosecond electrical pulses coherently manipulated this state by modulating *s.* The induced phase shift is proportional to the area of the electrical pulse. If working near the minimum in *s*, a spin flip can be achieved by simultaneous rotation of the eigenstates. (A. Boyer de la Giroday *et al*, Phys. Rev. B 82, 241301R (2010)).

Electrical Control of the Spin Relaxation in Quantum Wells

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We have measured the electron spin relaxation time in (111)-oriented GaAs quantum wells (QW) by time-resolved photoluminescence spectroscopy [1]. By embedding the QWs in a PIN or NIP structure we demonstrate the tuning of the conduction band spin splitting and hence the D'Yakonov-Perel spin relaxation time with an external electric field applied along the growth direction [2].

The application of an external electric field of 50 kV/cm yields a two-order of magnitude increase of the spin relaxation time which can reach values larger than 30 ns; this is a consequence of the electric field tuning of the spin-orbit conduction band splitting which can almost vanish when the Rashba term compensates exactly the Dresselhaus one [3].

The measurements under a transverse magnetic field demonstrate that the electron spin relaxation time for the three space directions can be tuned simultaneously with the applied electric field.

The role of the Dresselhaus cubic terms on both the temperature dependence of the effect and the anisotropy of the spin relaxation will be discussed.

The electron spin dynamics in (111) quantum wells will be compared to the well known spin physics for (001) and (110) QWs.

The tuning or suppression of the D'Yakonov-Perel electron spin relaxation demonstrated here for GaAs/AlGaAs quantum wells is also possible in many other III-V and II-VI zinc-blende nanostructures since the principle relies only on symmetry considerations.

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Electron and exciton spin dynamics in quantum dots

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The advanced seminar is aimed at the analysis of the spin coherence generation, manipulation and detection processes in semiconductor quantum dots by means of optical pulses.

The following problems will be addressed:

1. Selection rules and basic principles of optical orientation in semiconductors and semiconductor nanostructures.
2. Optical transitions in quantum dots: two-level model, transformation of electron wavefunction by the optical pulse, Rabi oscillations. Impact of selection rules: quantum disks vs. spherical nanocrystals.
3. Optical control of electron spins in quantum dots.
4. Spin Faraday, Kerr and ellipticity effects in quantum dots. Role of ensemble inhomogeneity.
5. Electron spin precession in the external magnetic field.
6. Spin accumulation caused by the train of pump pulses. Resonant spin amplification and mode-locking of electron spin coherence. Nuclei-induced electron spin precession frequency focusing.

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Coherent optical control of a single hole spin

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The spin of a heavy-hole confined to an InAs/GaAs quantum dot is a potential qubit. Compared to an electron spin, the hole is more robust against nuclear spin induced dephasing due to the suppression of the contact hyperfine interaction. A key prerequisite for any qubit is the ability to rotate the pseudo-spin about two axes.

Here we demonstrate the full coherent optical control of a single heavy-hole confined to an InAs/GaAs quantum dot. Larmor precession about an external in-plane magnetic field provides one axis of rotation, whilst the rotation induced by a picosecond laser pulse provides a rotation about the out-of-plane optical axis.

In the experiments, the dot is embedded in the intrinsic region of a ni-Schottky diode. A vertical electric-field is applied such that the electron tunneling is fast (~100 ps) and the hole tunneling is relatively slow (~4 ns), but fast compared to the repetition period of the laser (~13 ns). A magnetic field is applied in Voigt geometry.

The dot is excited by up to three circularly polarized laser pulses. The first, the preparation pulse, resonantly excites the bright neutral exciton with a pulse-area of π. This prepares a spin-polarized electron-hole pair. When the electron tunnels from the dot, it leaves a hole with a Larmor precession synchronized with the preparation pulse. The mechanism is similar to the Hanle effect, and will be discussed in the talk. The final pulse, the detection pulse, has a pulse-area of π and is resonant with the hole-trion transition. The polarization selects either hole spin up or down state creating a trion conditional on the hole-spin, which is detected as a change in photocurrent. Larmor precession of the hole-spin about the external magnetic field is observed by measuring the photocurrent as a function of the time-delay between the preparation and detection pulse. From the Larmor precession we infer that a hole spin with a coherent component has been prepared, and that the hole has an in-plane g-factor of $g_h = 0.079(4)$.

To control both the amplitude and phase of the Larmor precession, a third control pulse is used. This circularly polarized pulse selects the hole-spin up state and drives a hole-trion Rabi rotation through an angle of 2π. If there is no decoherence, the system returns to the hole-spin sub-space having acquired a detuning dependent geometric phase-shift of upto π, rotating the spin about the optical axis, with a gate-time of 14 ps. Experiments demonstrating this optical rotation will be presented.

To summarize, full coherent optical control of a single hole spin is demonstrated using a geometric phase approach and a photocurrent detection technique. Further details of this work can be found in refs. [1], and rival works in refs. [2].

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Nuclear magnetic resonance in single quantum dots

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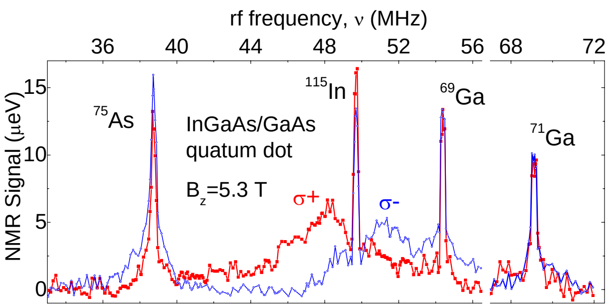
Much new solid state technology for single-photon sources, detectors, photovoltaics and quantum computation relies on the fabrication of strained semiconductor nanostructures. Development of such devices depends on techniques allowing structural analysis on the nanometer scale. However, commonly used microscopy methods are destructive, leading to the loss of the important link between the obtained structural information and the electronic and optical properties of the device. A possible solution is development of non-invasive nuclear magnetic resonance (NMR) techniques. Since most nuclei used in optically active III-V semiconductor nanostructures possess quadrupole moments, optically detected NMR (ODNMR) so far proved difficult in semiconductor nano-structures due to significant strain-induced quadrupole broadening of the spectra. As a result control of nuclear spins using NMR has only been achieved in strain-free nanostructures, like GaAs/AlGaAs semiconductor quantum dots (QDs) [1-3].

Here, we develop new high sensitivity techniques that move ODNMR to a new regime, allowing high resolution spectroscopy of as few as 10^5 quadrupole nuclear spins [4]. Furthermore, related techniques allow the study of coherent dynamics of nuclear spins: inhomogeneous spectral broadening is found to lead to suppression of nuclear spin magnetization fluctuations thus extending spin coherence times.



The dramatic enhancement of sensitivity achieved in our ODNMR technique is based on the use of broadband radio-frequency (rf) excitation, with specially designed spectral pattern. Using this approach, NMR spectra with rich structure are measured on single InGaAs/GaAs and InP/GaInP QDs. In InGaAs QDs contribution from all four isotopes can be resolved (see Fig.). Sharp peaks originate from transitions between +1/2 and -1/2 spin states unaffected by strain; their amplitudes provide information on chemical composition of the dot within the volume sampled by a single electron. Broad spectral bands appearing on both sides of the indium peak originate from satellite transitions (that involve nuclear spin levels with projection >3/2 or <-3/2). The shape and linewidths of these bands reflect magnitude and distribution of strain inside the quantum dot.

The new ODNMR methods have potential to be applied for non-invasive investigations of a wide range of materials containing quadrupole nuclei beyond single nano-structures. Such techniques will also directly address the task of understanding and control of nuclear spins on the nanoscale, one of the central problems in quantum information processing.

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Optical control of Mn^{2+} ions in GaAs

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A pathway to optical spin manipulation in semiconductors is to implement magnetic ions in and exploit the strong exchange interaction between an electron (hole) and a magnetic ion. GaAs doped with Mn acceptors of low concentration (below 10^{18} cm^{-3}) represents an attractive model system for investigation of carrier-magnetic ion interaction. First, Mn in GaAs is an acceptor where the p-d exchange interaction with the valence band hole significantly changes the energy structure of the acceptor complex. Second, s-d interaction with photoexcited electrons localized in the vicinity of Mn acceptor provides the channel for the spin transfer between the electron and Mn systems. Partial compensation by residual shallow donors with a concentration of about $10^{16}cm^{-3}$ leads to appearance of ionized acceptors (Mn^{2+} ions) located in the vicinity of donors if not illuminated by light. Isolated Mn^{2+} ions possess very long spin relaxation time (~ 10 μs) and therefore can be used for realization of spin storage.

Here we present an overview of recent investigations of electron spin dynamics in paramagnetic GaAs:Mn. The results include experimental data from time-resolved Kerr and Faraday rotation, time-resolved photoluminescence and spin-flip Raman scattering [1,2]. We show that optical orientation of Mn ions is possible under application of low magnetic field, which is required to suppress the manganese spin relaxation. The optically oriented Mn^{2+} ions maintain the spin and return part of the polarization back to the electron spin system providing a long-lived electron spin memory.

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Spin states and spin excitations in quantum Hall bilayers

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Electron correlation in quantum Hall bilayers at total filling fraction $\nu_T = 1$ leads to an inter-layer correlated phase and, in the limit of vanishing tunneling gap, superfluid-like behavior in counter-flow transport [1]. Such an inter-layer correlated quantum Hall state can be understood as a Bose-Einstein condensate of interlayer excitons by making a particle-hole transformation in one of the two layers [1]. An intriguing phase diagram is expected to develop from the interplay between changes in temperature, spin orientation and Coulomb interactions.

In this talk, we present evidence of excitonic coherence from measurements of spin-flip excitations by inelastic light scattering experiments [2,3]. We shall focus, in particular, to the limit of vanishing tunneling gap. In this case, we find that above a critical temperature the appearance of spin-flip excitations reveals the melting of the inter-layer excitonic phase and the emergence of a competing Fermi sea of composite fermions (CF) driven by intra-layer electron correlation [3]. Below a critical magnetic field the CF phase is partially spin polarized. We find that an inter-layer coherent state emerges from both fully and partially spin polarized CF phases. We discuss possible scenarios for the finite-temperature interplay between these different phases including the possibility of a finite-temperature phase transition. Finally we present recent experiments revealing anomalous behaviors of the magneto-luminescence in the vicinity of $\nu_T = 1$. [4]

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GaAs single quantum dot embedded into AlGaAs nanowire

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We report on study of the photoluminescence spectra (PL) taken from quasi one-dimensional and quasi zero-dimensional semiconductor heterostructures. The structures were grown by molecular-beam epitaxy in (111) direction and are cylindrical nanowires based on $Al_{0.3}Ga_{0.7}As$, of 20 – 50 nm in diameter and 0.5 – 1 mkm in length. Inside the nanowires there were one or two GaAs quantum dots, of 2 nm thick and 20 – 50 nm in diameter. We studied a single nanowire, several (3 - 4) nanowires and arrays of many nanowires as well. The PL spectra were registered as a function of the intensity of optical excitation and external magnetic fields.

In the spectra of the array of nanowires we observed two PL bands extending from 1.8 to 1.95 eV and from 1.65 to 1.8 eV. These bands are connected with carrier recombination in a large array of nanowires and quantum dots respectively. In the PL spectra of several nanowires in these spectral ranges we observe several irregular distributed very sharp lines. The line-width of these lines was lower than our spectral resolution.

In the spectra of a single nanowire at very low optical excitation we observed a doublet of very narrow lines which should be related to recombination processes in a single quantum dot. We relate these lines to the annihilation of exciton and biexciton in a single dot. The biexciton binding energy has been found to be ~ 8 meV. The validity of the interpretation of this line as the biexciton recombination is supported by intensity dependence of these spectra and by calculation of the biexciton binding energy.

The intensity of the exciton and biexciton lines saturates at very small excitation densities (<10 mkW/cm^2). Biexciton line intensity grows superlinearly at low excitation densites, and at further increase of the excitation intensity all lines in this spectrum are saturate, at very higher excitation intensity (> 1 mW/cm^2) all lines begin to broaden. In several samples a line of trion recombination in the quantum dot was observed at nearly 1 meV below the exciton line. In magnetic fields we observed diamagnetic shift of all the lines and their Zeeman splitting. The biexciton line shows a fine structure.

At very small excitation intensities in the structures containing two quantum dots, we observed spontaneous jumps of the exciton PL line position. The magnitude of the jumps reached ±0.5 meV. As the intensity of the excitation increases the frequency of the jumps increases, and at sufficiently high excitation intensities these jumps manifested as a broadening of the exciton line.

Additionally, we observed a linear polarization of the exciton emission line in (110) direction that reaches 30-50%. The nature of this polarization is puzzling, since the spectra were observed in the (111) direction. We discuss the possible causes of the effect, including spontaneous deformation of the nanowires and giant piezoelectric effect.

Single photon emission and cavity-coupling in semiconductor quantum dots

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Quantum dots (QD) coupled to optical microcavities behave as single photon emitters where the emission linear polarization and antibunching time are continuously controlled by the energy detuning between the quantum dot and the cavity mode. The case of InAs/GaAs QDs coupled to a photonic crystal microcavity is described in some detail and compared to InP/InGaP uncoupled QDs. The polarization rotation spans over 160º and is interpreted in terms of hybridization between the QD and the cavity states. The observed reduction of the antibunching time for decreasing detuning demonstrates that the enhancement of the spontaneous emission rate, originated by Purcell effect, acts in the same way as increasing the pumping rate on the antibunching time.

By photoluminescence excitation (PLE) measurements we observe the effective coupling between two QDs located near the cavity center and separated by 1,4 μm. The inter-dot coupling is mediated by the photonic crystal cavity mode. The two dots are simultaneously coupled to the cavity for detuning range in the order of 1 meV, as shown by Purcell effect. In this range, quasi-resonant excitation at the "p-states" of each of the QDs results in an emission intensity increase of the other one. Coherent coupling between the two QDs is believed to be the most probable inter-dot interaction mechanism due to the similar saturation behaviour in both emission processes (intra- and inter-dot excitation) upon increasing the excitation intensity. The strength of the effective inter-QD coupling is estimated around 30 μeV.

The present results open the possibility to obtain single photon emitters with continuous control of their emission properties and to use distant solid state qubits in quantum logic operations.

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POSTERS

Aharonov-Bohm quantum rings in microcavities

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Progress in nanolithography and epitaxial techniques has resulted in burgeoning developments in fabrication of semiconductor nanostructures and optical microcavities. Cavity quantum electrodynamics addresses the interaction of an emitter embedded inside a microcavity with cavity modes and the emission spectrum of the system. The luminescence spectrum of a microcavity coupled to a single quantum-dot-based emitter has been studied both theoretically and experimentally by a number of different research groups [1, 2]. The system possess a rich multiplet structure, which maps transitions between quantized dressed states of the light-matter coupling Hamiltonian.

There is a considerable current interest in non-simply-connected nanostructures, quantum rings, which have been obtained in various semiconductor systems. The fascination in quantum rings is partially caused by a wide variety of purely quantum mechanical effects, which are observed in ring-like nanostructures [3]. The star amongst them is the Aharonov-Bohm effect, in which a charged particle is influenced by a magnetic field away from the particle’s trajectory, resulting in magnetic-flux-dependent oscillations of the particle energy. Recently it was shown that an external lateral electric field, which is known to reduce the ring symmetry and suppress the energy oscillations for the low-energy states, modifies optical properties of the ring [4]. Namely, the application of a weak electric field leads to magneto-oscillations of the degree of polarization of optical transitions between the ground and first excited states which are typically in the THz range. When a magnetic flux through the ring is equal to a half-integer number of flux quanta, these transitions are linearly polarized with polarization vector normal to the direction of the external electric field and their frequencies are completely controlled by the magnitude of the applied electric field. This provides additional means of tuning the ring emission spectrum.

In the present work we examine a microcavity with an embedded Aharonov-Bohm quantum ring, which is pierced by a magnetic field and subjected to a lateral electric field. Emission properties of such a system under continuous pumping are studied theoretically. We calculate the luminescence spectrum of the system using the Lindblad master equation approach and demonstrate that it is strongly influenced by the pumping intensity and the quality factor of the cavity. An additional degree of control can be achieved by changing the angle between the polarization plane of the pump and the external electric field. Optical properties of the considered system demonstrate a rich behaviour which can be controlled by the applied external electric and magnetic fields. These fields govern the electron spectrum and optical selection rules in a ring, which can be easily tuned to match the cavity modes.

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Polariton OPO ignition and decay on a microcavity pillar

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Exciton-photon mixtures (polaritons) in semiconductor microcavities display a variety of non-linear phenomena due to excitonic Coulomb interactions, including ultrafast Optical Parametric Oscillation (OPO)[1, 2]. Here we present a method for igniting a polariton OPO in confined geometries (a 40-µm-diameter pillar), which allows studying the full dynamics of its creation and decay, lasting for more than 2 ns,[3] and tracing the development of the modes in the pillar.

Exciting with a continuous wave (cw) laser, we use an additional ultrafast resonant pulse to create a dense excitonic population that produces two effects: a) a blue-shift of the lower polariton branch (LPB), bringing it into resonance with the cw laser placed at the LPB inflection point, and b) an increment of the population at the energy of the signal state of the OPO, contributing to the stimulated scattering process. This short probe-pulse switches the OPO on for nanoseconds.

The sample is a 5λ/2 AlGaAs-based microcavity with a Rabi splitting Ω_R=9 meV. It is kept at 10 K and excited with a cw Ti:Al_2O_3 pump laser (E_p=1.5416 eV) under OPO conditions and probed with a 2 ps-long Ti:Al_2O_3 laser (E_{pb}=1.5450 eV). Time- and spectral-resolved experiments are performed with a streak camera. A reflective spatial light modulator is employed to control the probe profile and direction.

Time resolved spectroscopy reveals the formation dynamics of several polariton ring modes during the first 500 picoseconds after the pulsed excitation. The transient behaviour of the modes development is strongly dependent on the spatial probe-pulse location on the top surface of the pillar. If the probe excitation is at the centre of the pillar, the modes are not resolvable up to ~600 ps, when a ring-shaped mode emerges along the pillar edge. On the other hand, placing the probe at one side of the top surface, a strong spatial oscillation in the mode position (with a ring-sector shape) from the pulse spot to its diametrically opposite location is obtained. This behaviour, lasting ~500 ps, reflects a collective oscillation of the polariton population inside the pillar until a full ring-shaped, whispering-gallery mode becomes dominant and decays during the next 1.5 ns.

The shape of this whispering-gallery mode has been fully characterized under cw OPO conditions. The higher spectral resolution of the cw experiments reveals the existence of two additional weaker modes lying at slightly higher energies. A tomographic analysis over the surface allows a complete characterization of the modes and their spatial distribution over the pillar geometry.

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Exchange bias in Co/MnF_2 heterostructures

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The investigation of nanostructured materials is one of fast-paced branch of modern physics. Nowadays much attention is paid to the investigation of ordered magnetic nanostructures such as arrays of dots or wires, which are considered as promising materials for high-density memory systems and other spintronic applications. It is widely known that exchange interaction between ferromagnet (FM) and antiferromagnet (AFM) layers leads to the exchange bias effect, which results in the shift of magnetic hysteresis loops. Despite widespread application of this effect in spin valves, a number of relevant important issues still remain unclear.

Relatively simple and at the same time informative method for studying the magnetic properties of nanostructures is the technique based on the magneto-optical Kerr effect (MOKE). The essence of the effect is the polarization plane rotation of linearly polarized light reflected from the magnetized material. In this work, the MOKE technique was applied to investigate magnetization reversal and anisotropy of the exchange biased cobalt – manganese fluoride (FM-AFM) heterostructures in a wide temperature range.

The heterostructures of Co/MnF_2/CaF_2/Si(111) were grown by molecular beam epitaxy. Crystal structure of the samples was studied by electron and x-ray diffraction, and their morphology - by scanning probe and electron microscopies. As expected, the temperature dependences of coercivity and bias are indicating that the effects associated with exchange interaction between FM and AFM manifests only below Neel temperature of MnF_2. The temperature dependences were measured at the series of samples with different (from 20 to 2 nm) thicknesses of AFM layer. It was found that exchange bias in the structures examined is decreasing with MnF_2 layer thickness until it reaches a critical thickness of 2.5 nm, below which no bias was observed.

Finally the azimuthal dependences of coercivity and exchange bias field were obtained. This study of the structures grown on Si(111) revealed that there are three maxima of the exchange bias field. This fact could be due to the multidomain structure of MnF_2 (111) layer with three preferential easy axes orientations. Taking into account this circumstance, it is planned to investigate similar structures grown on Si(001), which have less number of MnF_2 crystal domains.

Drag in a resonantly driven polariton fluid

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We study the linear response of a coherently driven polariton fluid in the pump-only configuration scattering against a point-like defect and evaluate analytically the drag force exerted by the fluid on the defect. When the system is excited near the bottom of the lower polariton dispersion, the sign of the interaction-renormalized pump-detuning classifies the collective excitation spectra in three different categories [1]: linear for zero, diffusive-like for positive, and gapped for negative detuning. We show that both cases of zero and positive detuning share a qualitatively similar crossover of the drag force from the subsonic to the supersonic regime as a function of the fluid velocity, with a critical velocity given by the speed of sound. In contrast, for gapped spectra, we find that the critical velocity exceeds the speed of sound. In all cases, the residual drag force in the subcritical regime depends on the polariton lifetime only. Also, well below the critical velocity, the drag force varies linearly with the polariton lifetime, in agreement with previous work [2], where the drag was determined numerically for a finite-size defect.

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Interacting 2D exciton-polariton condensate with a 1D line-defect: coherence and polarization issues

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We study the coherence properties of polariton condensates in a 2D GaAs microcavity, which contains line defects caused by photonic disorder. The presence of this disorder divides the optically-created polariton population into two separate 2D condensates, with the defect itself acting as a 1D condensed system.

Marked differences in the emission characteristics of the 2D and 1D systems are obtained by different pumping conditions in the optical parametric oscillation (OPO) regime. Pumping resonantly at the 2D lower polariton branch, at its inflection point, condensation is observed in both sub-systems, 2D and 1D, despite the fact that the line defect is not being directly pumped. On the other hand, when the excitation laser is tuned in resonance with the defect dispersion, the OPO is selectively achieved in the 1D system and condensation does not occur in the 2D branch.

We perform first order correlation measurements on the line defect under both conditions. For the latter case, we observe a short spatial decay of the coherence as predicted in Ref. [1] for 1D systems, but with an additional modulation due to the photonic disorder in the sample [2]. However, when the system is pumped resonantly at the 2D branch, the 1D coherence length increases considerably and the modulation becomes less important as compared with the situation where only 1D condensation is achieved. These findings suggest that the presence of the 2D condensed polaritons screens the disorder and heals its effects.

We also investigate the polarization of the system when we pump resonantly the 2D branch. We observe that, for a circular polarized pump, not only the 2D system inherits the polarization from the laser, as is characteristic for resonant stimulated scattering processes [3], but also the 1D system acquires the same state of polarization, evidencing that there is spin memory in the relaxation processes from the 2D to the 1D system. On the other hand, pumping with linearly polarized light, elliptically polarized emission is obtained for the 2D condensate with the major axis of the ellipsis rotated with respect to that of the pump, similarly to the results of Ref. [4]. It is noticeable that the rotation angle is different for the 2D and 1D condensates, probably due to the different TE/TM splitting in those systems.

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 We-6p

Microscopic mechanism of the magnetic-field-induced heavy-hole mixing in symmetric [111] quantum dots

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Semiconductor quantum dots grown along high-symmetry $z' \| [111]$ axis have attracted lately huge interest due to the exceptionally small anisotropic splitting of excitonic radiative doublet and efficient generation of entangled photons [1]. Recent experiments [2] have revealed unusual fine structure in the longitudinal magnetic field ($\boldsymbol{B} \| z' \| [111]$): the emission spectra of charged and neutral excitons contain four lines, two emitting in σ^+ and two in σ^- polarizations. This effect is explained by the magnetic-field-induced mixing between the heavy-hole states with different angular momentum projection $\pm 3/2$ onto the growth axis z'. This mixing is allowed in the C_{3v} point group, symmetry relevant for [111] quantum dots. As a result, the heavy-hole Zeeman splitting in the basis $|3/2\rangle', |-3/2\rangle'$ is described by the 2×2 matrix with the off-diagonal element related to the effective hole *g*-factor g_{h2}. In conventional [001]-grown structures $g_{h2} = 0$, while the experimental data presented in Ref. [2] demonstrate that $|g_{h2}| \approx 0.5$ for the studied samples.

In this work we propose a microscopic mechanism describing the off-diagonal *g*-factor g_{h2} for trigonal quantum dots. The quantum dot shape is modeled as a pyramid with the equilateral triangle base. Such geometric shape is characterized by C_{3v} point symmetry and well correlates with the shape of the dots studied in Ref. [2]. As an in-plane confinement we use a parabolic potential with the angular term responsible for the triangular symmetry. To simulate confinement along the z' direction we apply a simple model of the hole quantization in the uniform electric field, the corresponding hole wave functions have no symmetry with respect to a sign change of the z' coordinate. We use Luttinger Hamiltonian in the spherical approximation with the magnetic field included in the framework of the perturbation theory. The in-plane component of the hole wave functions in the absence of magnetic field is calculated using variational method or by direct numerical solution of Schrodinger equation in the infinite triangular 2D potential. As a result we obtain the analytical expression for the off-diagonal *g*-factor in the following form

$$g_{h2} = C(\gamma_1, \gamma_2) \frac{h}{a}, \tag{1}$$

where γ_1, γ_2 are the Luttinger parameters, *a* is the lateral size of the dot and *h* is its height. Coefficient *C* depends on the dot geometry. Estimations show that the absolute values of g_{h2} range from 0.5 to 3 for reasonable quantum dot parameters in a good agreement with experimental data.

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Faraday rotation induced by spin polarized electrons and nuclei in n-GaAs microcavity

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The rotation of the plane of polarization of light upon transmission through a magnetized medium is known as Faraday rotation (FR). In non-magnetic semiconductors Faraday rotation can be produced by optically orienting the spin of electrons [1]. By using optical orientation of electron gas in n-doped bulk GaAs ($n_e \approx 2\times10^{16}\ cm^{-3}$) confined in a microcavity (Q=19000), we obtained Faraday rotation up to 19° in the absence of magnetic field. This strong rotation is achieved because the light goes multiple round trips in the microcavity and is orders of magnitude larger than the rotation measured in n-GaAs of similar concentration [2,3]. From the depolarization of Faraday rotation by a transverse magnetic field (Hanle effect) we deduce electron spin relaxation time of about 160 ns which is close to the value reported for n-GaAs [2,4].

We measured the degree of electron spin polarization by optically cooling the nuclear spin system and measurement of the Knight shift, and from the degree of polarization of photoluminescence. From the photoinduced Faraday rotation and the degree of spin polarization of electrons, we determined the efficiency of n-GaAs in producing Faraday rotation (Faraday rotation cross-section).

We also observed experimentally Faraday rotation induced by optically cooled nuclear spins up to 0.2°. Faraday rotation due to optically cooled nuclear spins persists up to 5 minutes in the absence of optically created electron spin polarization. The dynamics of nuclear spin polarization is monitored in laboratory time and is found to be non-monotonous and has two components: one which decays fast (τ_s~10s) and another which decays slowly (τ_s~200s).

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We-8p

Built-in electric field determination for δ-Mn doped low-temperature GaAs

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Manganese delta-doped GaAs layers can be used in spintronic devices as a source of spin-polarized holes. The carrier mobility in such kind of layers is much more than for bulk (GaMn)As [1].

We investigated series of GaAs samples with various Mn sheet concentration (θ_{Mn}) defined in the monolayer (ML) unit. The concentration was varied from 0 to 0.4 ML with the step about 0.1 ML. All samples were grown on semi-insulating GaAs (001) substrate. The growth was carried out in the following way: First, 0.4 um gallium arsenide undoped buffer layer was grown using MOCVD method at 650ºC. Next, with the help of pulse laser sputtering of a metallic Mn target in the flow of arsine the δ-layer of manganese was formed at 400ºC. Then, at the same reduced temperature the 30 nm GaAs cap-layer was grown by laser sputtering of undoped GaAs wafer. Such a small temperature of growth allowed us to avoid diffusion and significant segregation of Mn.

Low temperature galvanomagnetic measurements demonstrated the presence of anomalous and planar Hall effect and anisotropic magnetoresistance in the samples [1, 2]. It was an evidence of ferromagnetism in the investigated δ-Mn doped GaAs structures.

To determine built-in electric field for δ-Mn doped GaAs structures we used photoreflectance (PR) technique – a contactless type of optical modulation spectroscopy. A photoreflectance spectrum was the dependence of the relative changes in the reflectivity coefficient, due to the modulation of the HeNe laser pump beam, on the photon energy of the monochromatic probe light. At room and nitrogen temperature in PR spectra we observed well defined Franz–Keldysh oscillations. The period of these oscillations increased with Mn sheet concentration. Using the method published in [3] we determined the required electric field. Its smooth increase with θ_{Mn} demonstrated the lineshape like one calculated in [4] within the semiclassical approximation. So, using nondestructive photoreflectance technique we observed the increase of built-in electric field from 14 to 25 kV/cm with increasing Mn concentration from 0 to 0.4 ML.

The authors wish to thank B.N. Zvonkov for the growth of the samples.

This work is supported by RF President grants for young PhD (MK-3996.2011.8 and MK-5198.2012.2).

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Nuclear spin-lattice relaxation in metallic phase of n-GaAs

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First experiment on optical orientation of electron and nuclear spins in semiconductors [1] was conducted more than 40 years ago. Since than, there were many results, both theoretical and experimental, concerning electron – nuclear spin systems. It is a common belief that free conduction – band electrons do not provide an effective channel for spin relaxation of lattice nuclei [2]. However, relaxation of nuclear spins in semiconductors by free Fermi – edge electrons has never been experimentally studied in weak magnetic fields (below 1 kG).

Our main goal was to understand the nuclear spin dynamic in metallic phase of bulk n – type GaAs and its temperature and magnetic field dependence. We have investigated nuclear spin relaxation in bulk n – type GaAs with doping concentration $9 \cdot 10^{16} cm^{-3}$. All measurements are done using optical orientation method at various low temperatures (2 to 30 K) in oblique magnetic fields from 0 to 1200 G.

Our experiment consisted from 3 stages. First, injection of spin – polarized electrons with circularly polarized light in a oblique magnetic field where depolarization is abrupt. Electrons in return dynamically polarize nuclei. After that, pumping is switched off for a different time intervals. During this period nuclear filed B_N is decreasing due to the spin – lattice relaxation. In the last stage pumping is switched on again and we detected the circular polarization of the photoluminescence, which is proportional to the mean electron spin. Temperature dependence of T_1 was obtained by repeating this procedure for a various temperatures inside cryostat (from 2 to ~ 30 K). Similar procedure was used to determine magnetic field dependence of T_1 where the pump switching off was followed by a change of magnetic field from measuring field to a various magnetic fields (from 0 to 1200 G).

We found that at the high magnetic field (above 100 G) nuclear spin – lattice relaxation is determined by Korringa mechanism [3], i.e. hyperfine scattering of Fermi – edge electrons. As at low temperature the number of electrons with free spins is proportional to temperature, this mechanism predicts linear temperature dependence of the relaxation rate, which was indeed observed in our experiments. At low magnetic fields (below 100 G) another relaxation mechanism exists, which is 10 times more effective. Since the temperature dependence of $1/T_1$ is still linear at low fields, it can be concluded that this mechanism is also related to the Fermi – edge electrons.

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 We-10p

Effect of external strain on the effective magnetic field of Mn in gallium arsenide

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Semiconductor structures containing magnetic impurities are the focus of many research laboratories in connection with attempts to create devices using the spin degrees of freedom. Gallium arsenide doped with manganese ions is of particular interest since the compounds GaAs and on its basis are the most studied semiconductors, and manganese ions - have large spin angular momentum equal to 5/2. The purpose of this paper is experimental and theoretical study of spin orientation of the holes localized on the manganese centers in gallium arsenide in the presence of external strain and the external magnetic field. We have studied two types of samples: a paramagnetic ones with the bulk concentration about 10^{17} cm^{-3} and ferromagnetic structures , where the concentration of manganese is a few atomic percent . The degree of circular polarization of hot and cold photoluminescence (PL) was studied in external magnetic fields and uniform deformations at low temperatures both theoretically and experimentally.

To describe the paramagnetic samples we take into account the exchange interaction of a hole, localized on Mn with the five valence electrons of manganese. As results the 24-fold degenerate state splits into 4 sublevels, and at low temperatures in an external magnetic field, the polarization degree reduced in the magnetic fields due to the mixing of wave functions. The deformation mixes the wave functions and provides an additional depolarization of the PL.

In ferromagnetic samples, due to high concentrations of manganese, the hole wave functions overlap and form an impurity band. To describe our experimental data we assumed that the hole interacts with effective exchange field of manganeses. The external strain and the magnetic field reorient the internal exchange field. Because of the small value of the magnetic anisotropy coefficients, the orientation of the spins along the external magnetic field occurs at more low magnetic fields comparable with paramagnetic samples. Uniaxial compression works for a magnetic moment along the axis of compression, so that we can change the value of the external magnetic field required for saturation.

Thus we demonstrated the possibility of reorientation of the spins of the holes localized on the manganese by the external strains in paramagnetic samples. In the ferromagnetic structures Ga(Mn)As we observed orientation of the exchange field by external deformation and magnetic fields.

Micro magneto luminescence of single charge tunable GaAs droplet dots: Coulomb interactions and optical selection rules

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While in non-intentionally doped samples due to charge fluctuations the neutral X^0 exciton and the positively (negatively) charged exciton $X^+(X^-)$ are observed in the same spectrum [1] deterministic charging of quantum dots with single electrons in charge tunable structures enables control of charge in the quantum dots and has led to many fascinating discoveries in quantum dot photonics and spin physics [2]. Here we demonstrate the first electrical charge control in novel, strain-free GaAs quantum dots in AlGaAs barriers grown on n^+-(001) substrates by molecular droplet epitaxy [3].

The charge states are clearly identified by fine structure analysis: in transverse magnetic field we observe four linearly polarized emission lines for the charged excitons in contrast to a Zeeman doublet for X^0. As the dark X^0 transition appears for $B_x > 1T$, we can extract the bright-dark splitting of X^0 in the order of ~ 0.3-0.5 meV, considerably larger than in GaAs interface fluctuation dots (0.1meV [4]) due to the stronger carrier confinement. Additionally we extract the absolute values of electron and the hole transverse g-factors $g_{h,x}$. For pure heavy holes, we expect $g_{h,x} \approx 0.03$ [5]. We find surprisingly high hole values of up to $g_{h,x} \approx 0.5$ that indicate a strong degree of heavy-hole (HH) to light-hole (LH) mixing that varies considerably from QD to QD. HH-LH mixing is important for optical selection rules, carrier spin pumping, the strength of the hole-hyperfine interaction and bright-dark X^0 mixing.

The evolution of the dark and bright X^0 transitions in an applied transverse magnetic field reveals a surprising interplay of Zeeman and Coulomb interactions [6]:

i) the splitting of the bright transition is tuneable and vanishes for this QD at applied transverse magnetic field ~ 3T, which makes this structure attractive for entangled photon pairs experiments [7];

ii) the fine structure splitting of the dark transition δ_2 deduced from the model is of the same order of magnitude as δ_1 while the reported δ_2 in InGaAs QDs is one order of magnitude smaller than δ_1, with typical value ~ 1.4 μeV [8].

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Effect of nuclear spin fluctuations and dynamic nuclear polarization on shape of Hanle curves in (In,Ga)As/GaAs quantum dots

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Optical orientation of electron spin in semiconductors is followed by the dynamic nuclear spin polarization (DNSP) due to contact Fermi interaction. The DNSP causes back effect on the electron spin polarization, which is evidenced, in particular, in the W-like peculiarity of Hanle curve describing the dependence of circular polarization of photoluminescence (PL) in transverse magnetic field. This complicated shape of Hanle curve is usually treated in the framework of spin-temperature approach assuming the thermal equilibrium in nuclear spin system [1]. An electron localized in a quantum dot interacts with limited number of nuclear spins that results in increasing role of statistical fluctuations of hyperfine interaction, which affect the Hanle curve in the absence of DNSP [2]. In present work, we demonstrate experimental results showing that the nuclear spin fluctuations considerably modify the Hanle curve even in the presence of DNSP. We studied a heterostructure containing 20 sheets of self-assembled (In,Ga)As/GaAs quantum dots. Each quantum dot contains one resident electron on average due to δ-doping of GaAs barriers with donors. Degree of circular polarization of PL of the quantum dots is determined by the averaged over time projection of electron spin on the direction of PL detection. The transverse magnetic field is varied within ±100 mT. The experiments have been performed in steady-state excitation conditions, as well as under modulation of intensity and polarization of the excitation. The later experiments allowed us to study the dynamics of polarization of nuclear spins and its effect on Hanle curve. To study the influence of weak effective magnetic field (Knight field) acting on nuclei from optically orientated electron spin, we applied an additional small longitudinal magnetic field parallel to the optical axis. Theoretical analysis of the results obtained shows that the standard model [1] does not describe in principle the shape of Hanle curves and its variation with the change of longitudinal magnetic field. We developed a simplified vector model based on precession of electron spin about effective magnetic field, which is the sum of external magnetic field, DNSP-field, and the field of nuclear spin fluctuations. Theoretical simulations in the framework of the model allowed us to reproduce the Hanle curves experimentally observed for all the longitudinal magnetic field applied and for all the modulation conditions used. Analysis of the time evolution of Hanle curves gave information about the relaxation rates of transverse and longitudinal components of nuclear spin polarization. We also estimated from the modeling the magnitudes of Knight field and of effective field of the nuclear spin fluctuations in the quantum dots under study.

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ZnO polariton laser

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Semiconductor-based microcavities appear as a prolific system for studying light-matter interaction between a spatially-confined photonic mode and an excitonic resonance. The quasiparticles arising from this coupling (microcavity-polaritons) have enabled in the last years the observation of new lasing regimes as well as polariton Bose-Einstein condensates, vortices and lately solitons. In this panorama ZnO appears as an alternative material to more mature ones, such as GaAs or CdTe, with larger oscillator strengths and enhanced exciton stability. These two properties render ZnO very interesting for studies and applications where large particle densities and/or high temperatures are required. However, the fabrication of ZnO-based microcavities is still challenging and it often requires the use of either nitrides or dielectric materials for the DBRs. Indeed, polariton lasing was demonstrated for the first time in a ZnO-based microcavity only in 2011 [1, 2].

In this work we report on the optical study of a fully-hybrid ZnO-based microcavity in which we combine a high quality active region made up of bulk ZnO and a high cavity quality factor, thanks to the use of two dielectric DBRs. Indeed, the Q-factor of the cavity measured by micro-reflectivity exceeds systematically 1000. Furthermore, as the ZnO active region has a wedge shape a large range of detunings between the cavity and the excitonic mode is accessible. Polariton lasing, as characterized by a strong (typically a factor 5) linewidth reduction, a small blueshift compared to the Rabi splitting (typically 30 times smaller), and an increased intensity emission (four orders of magnitude increase) will be reported. The study of the lasing regime as a function of temperature and detuning will be presented and the differences with respect to other materials, arising due to ZnO peculiarities, will be emphasized.

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Magnetooptical Study of Spin Injection in Heterovalent III-V / (II,Mn)-VI Structures with Asymmetric Double Quantum Well

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Performing injection of spin polarized charge carriers is mandatory for the realization of most of the components proposed for spin electronics [1]. Since the very beginning of this exciting new field of research, heterovalent structures consisting of GaAs-based active layers topped by a II-VI diluted magnetic semiconductor (DMS) zone playing the role of spin aligner [2] are considered of high-interest in view of achieving effective injection of spin-polarized carriers into the active region of the device.

In this poster we present the detailed study of circularly polarized excitonic magneto-photoluminescence (M-PL) of coupled double GaAs/AlGaAs quantum wells in heterovalent structures with a ZnMnSe/Zn(S)Se spin filter on the top. We demonstrate that, for properly chosen structure parameters, we can observe a well saturated degree of circular polarization for the PL emission as high as 60% (Fig. 1), indicating a proper spin aligner working and an even higher spin injection efficiency of the optically pumped electrons across the heterovalent interface. The dependence of the degree of circular polarization on the exciting photon energy is also presented and discussed.

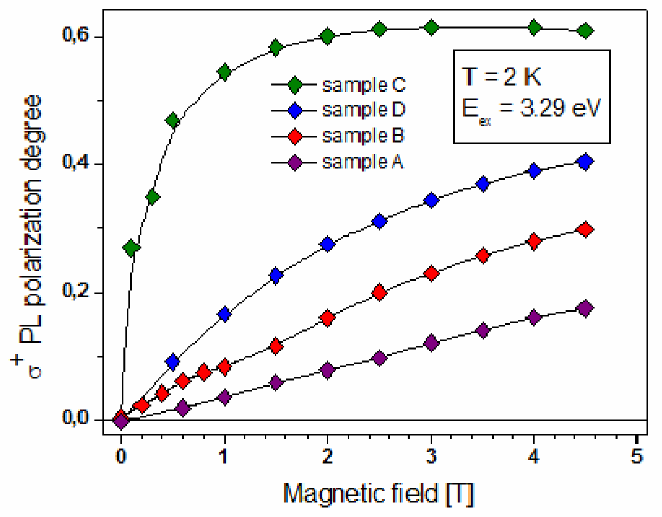

Figure 1: Degree of σ^+ circular polarization as a function of the applied external magnetic field in Faraday configuration, for different samples.

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 We-15p

Spin Dynamics in CdSe/CdS Colloidal Nanocrystals

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Spin dynamics in chemically synthesized thick-shell CdSe/CdS NCs was studied by polarization-resolved static PL and PL decay technique in high magnetic field at low temperature. Firstly, we demonstrate that the PL of an ensemble of thick-shell CdSe NCs mainly arises from charged exciton states. Secondly, we report the first direct measurement of spin-flip rate of charged excitons in thick-shell CdSe/CdS NCs. The spin-flip rate of charged excitons is much longer than that in conventional thin-shell CdSe NCs and shows surprisingly quadratic magnetic field dependence. Additionally, time-resolved circular polarization degree at 150 ns was simulated according to a simple two-level model. The fitted g-factor (1.15) allows us to confirm that thick-shell CdSe/CdS NCs are positively charged.

 We-16p

Ratchet effects in graphene and quantum wells with lateral periodic potential

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The subject of this work is terahertz radiation induced electric currents in two-dimensional electronic systems with a spatially periodic noncentrosymmetric lateral potential. Such systems being driven out of thermal equilibrium are able to transport particles even in the absence of an average macroscopic force. This directed transport, generally known as the ratchet effect, has a long history and is relevant for different fields of physics, chemistry and biology. Ratchet effects whose prerequisites are simultaneous breaking of both thermal equilibrium and spatial inversion symmetry can be realized in a great variety of forms ranging from mechanical systems to molecular motors to electric transport in low-dimensional semiconductor systems.

We theoretically studied the ratchet effect in semiconductor quantum well and graphene, both with a superimposed macroscopic asymmetric lateral potential. The ratchet currents appear in these systems due to combined action of spatially periodic potential and spatially modulated radiation intensity. The parameter of system asymmetry is determined by the phase shift between lateral profiles of electronic potential and the radiation electric field.

We have performed the phenomenological analysis of the ratchet effect and demonstrated that ratchet current consists of polarization-dependent (sensitive to linear and circular radiation polarization) and polarization-independent contributions. Microscopic analysis shows the presence of two mechanisms of the polarization-independent ratchet current formation: the generation of current in the course of energy relaxation and due to elastic scattering processes. We demonstrate that the first mechanism, related to Seebeck effect, is suppressed at low temperatures. The difference in electron energy dispersion between two considered systems leads to different ratchet current frequency dependence, which also strongly depends on the type of scattering. In graphene, two realistic mechanisms of electron momentum relaxation are considered: short-range scattering and Coulomb scattering. For a short-range potential, there are polarization-independent and circular ratchet currents, while the linear polarization leads to no ratchet current. For the Coulomb scattering, the linearly-polarized radiation generates the ratchet current only for the polarization vector parallel to the lateral-potential modulation direction.

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Indistinguishable and entangled photons generated by a light-emitting diode

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We present results showing that photon pairs from a quantum dot LED emitted in the same excitation cycle are entangled - with record high fidelity for an electrically driven source - and indistinguishable from photons from subsequent cycles [1].

Our device is a GaAs p-i-n diode with InAs quantum dots in a planar optical cavity, cooled down to ~5K and electrically excited by applying d.c. voltage. To measure the entanglement fidelity and two-photon interference properties polarisation-and time-resolved second-order correlations were measured using a fibre based setup and superconducting single photon detectors (SSPDs). We measure an entanglement fidelity of 0.85 ± 0.01 which is the highest reported for an electrical device. We attribute this to the small fine-structure-splitting (2.0 ± 0.2 μeV) of the quantum dot exciton state, good rejection of uncorrelated background light in our fibre setup, and the fast SSPDs that can resolve the evolution of the entangled state well.

Two-photon-interference was measured for the biexciton (XX) and exciton (X) photons separately. We find peak visibilities of 0.57 ± 0.04 (XX) and 0.52 ± 0.03 (X) respectively, indicating that a majority of our photons are indistinguishable and interfere if they arrive simultaneously at the interferometer output beamsplitter. Based on a model we conclude that the visibility is mainly limited by the photon coherence time and detector jitter. Improvements in indistinguishability could be achieved using smaller, electrically faster devices in pulsed mode and optical cavity effects to enhance the spontaneous emission rate.

We would like to point out that for indistinguishable entangled photon pairs, the coincident detection of oppositely polarised photons at the output of a two-photon interferometer such as the one used here corresponds to an entanglement swapping operation, creating entanglement between remaining photons. Based on the measured entanglement fidelities and two-photon interference visibilities we estimate that entangled photons may be created in this way with fidelity of 0.56.

In conclusion, we have showed that electrically generated photons originating from the same radiative decay cycle are entangled with each other and indistinguishable from photons in the subsequent cycles. These are two necessary requirements for e.g. entanglement swapping and the implementation of the feed-forward technique for quantum logic, and could in the future lead to the implementation of scalable, electrically operated devices for optical quantum computing and communication.

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 We-18p

Theoretical aspects of magnetic resonance spectroscopy monitored via optical detection of single negatively charged nitrogen-vacancy defects centers in diamond

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Fluorescence photons emitted by a single negatively charged nitrogen-vacancy (NV) defect centers in diamond are correlated in time. A simple theory of the correlation is presented including the same formalism photon antibunching from coherent Rabi oscillations and photon bunching due to incoherent quantum transitions between electronic levels. The correlation method is applied to the seven-, and ten-level model of single negatively charged nitrogen-vacancy (NV) defect centers in diamond, that are based on parameters from recent measurements [1]. The models takes into account the triplet-triplet character of the optical and microwave transitions of the center based on Hamiltonian that includes spin-orbit, spin-spin and strain interactions and described with the help of a model based on the optical-microwave Bloch equations.

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Semi-classical and quantum mechanical analysis of electron-nuclear spin dynamics in quantum dots

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Evolution of quantum mechanical system containing huge number of degrees of freedom cannot be implemented with an exact solution. Therefore quantum mechanical consideration is often replaced by a semi-classical model, in which the evolution of whole system can be determined with respect to classical trajectories of each particle of the system. However, the limits of applicability of latter approach have to be stated. We consider here the evolution of spin of an electron localized in a quantum dot interacting with spins of crystal lattice nuclei of this dot via hyperfine interaction.

Excitation of singly charged quantum dots by a periodic laser-pulse sequence significantly changes the dynamics of electron-nuclear spin system leading to formation of highly ordered nuclear spin state and focusing of electron spin precession about a magnetic field into modes synchronized with laser pulse repetition [1]. A mechanism for nuclear-induced electron spin synchronization has been suggested in Ref. [2]. The model developed there is based on semi-classical Bloch type equations of motion for electron and nuclear spins. On the other hand, the applicability of Bloch equations, originally developed for large magnetic moments $M \gg 1$, have to be examined for describing the evolution of electron spin $S=½$. Motivated by this we compare two approaches, the semi-classical and quantum mechanical one. The latter is based on solution of corresponding von Neumann equation [3,4]. The goal is to consider the dynamics of electron-nuclear spin system in absence and presence of external magnetic field as well as in presence of periodic pumping.

We show that both approaches quantitatively coincide in describing the dephasing of electron spin initially polarized by a single pump pulse at zero and nonzero magnetic field. The dynamics of average electron and nuclear spin polarization is also coincides when pumping by periodic pulse sequence in the absence and in the presence of magnetic field applied in Faraday geometry. Both the models also predict the effect of nuclear-induced electron spin synchronization in Voigt geometry of magnetic field application. However, semi-classical model predicts remarkably faster rise and saturation of electron spin polarization and, therefore, quantitative difference with quantum mechanical model. Finally, we discuss the possibility to modify semi-classical equations of motion of electron and nuclear spins to allow one for modeling the electron-nuclear spin dynamics in a quantitative numerical agreement with quantum mechanical approach.

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 We-20p

Suppression of spin dephasing by spin-orbit coupling in (110)-grown quantum wells

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We study the spin dephasing of high-mobility electron gas in semiconductor quantum wells (QWs) and show that the electron spin dynamics drastically depends on the QW crystallographic orientation. It is demonstrated that, in (110)-grown QW structures, the spin dephasing is efficiently suppressed by the Dresselhaus spin-orbit coupling. In (001) QWs, the spin dephasing can be slowed down by the external magnetic field applied in the QW plane, which results in the spin-orbit Hanle effect.

In the wide range of temperature, carrier density, and mobility, the spin dephasing of electron gas is governed by D'yakonov–Perel' mechanism. The mechanism is based on the precession of individual electron spins in the Rashba and/or Dresselhaus effective magnetic fields stemming from structure and bulk inversion asymmetries, respectively. In (110)-grown structures, the Dresselhaus field points along the QW normal and does not cause alone the precession of the normal spin component. Therefore, the spin dephasing is usually attributed to the constant or spatially fluctuating Rashba field lying in the QW plane. We show that the Dresselhaus field in (110) QWs drastically modifies the spin dephasing. It leads to the dynamic coupling of the in-plane and out-of-plane spin components [1] and can efficiently slow down the spin dephasing. In the collision-dominated regime, even small Dresselhaus field increases the normal spin component generated at *cw* excitation with the circularly polarized light by the factor of 2. In high-mobility structures, the suppression of spin dephasing by the Dresselhaus field becomes even more pronounced. We obtain that, in this case, the normal component of the steady-state spin polarization linearly increases with the Dresselhaus field strength.

We demonstrate that, in high-mobility (001)-grown QWs, the spin dephasing is slowed down by applying the external in-plane magnetic field. In such structures, both the Dresselhaus and Rashba fields lie in the QW plane. Therefore, the external field can completely compensate the effective field at a certain point of the Fermi circle leading to a spin accumulation, which results in the anomalous Hanle effect [2]. In contrast to the collision-dominated regime, where the external in-plane magnetic field is known to cause the spin depolarization, the field dependence of the spin polarization in high-mobility QWs is nonmonotonic and has a sharp maximum. It is shown that the position of the Hanle curve maximum can be used for a direct measurement of the Rashba and Dresselhaus effective fields.

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 We-21p

Investigation of the anisotropic optical response of non-polar III-nitride microcavities aimed for strong coupling regime

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III-nitride heterostructures with non-polar surface orientation promise higher quantum-efficiencies compared to their polar counterparts due to the absence of quantum-confined Stark effect, where a large built-in electric field decreases the electron and hole wave-function overlap [1]. In view of realizing non-polar III-nitride microcavities, the possibility to keep a high exciton binding energy and oscillator strength for thick quantum wells (compared to the exciton Bohr radius) favors the light-matter interaction strength, while the optical anisotropy imprinted by the hexagonal symmetry gives rise to an exceptional polarization-dependent coupling regime. The latter has been comprehensively investigated in a recent paper on a GaN/AlGaN-based microcavity structure grown by molecular beam epitaxy on a bulk GaN substrate [2]. Therein, the coexistence of the weak and the strong coupling regimes at the same sample position appearing along orthogonal polarization planes for different exciton transitions was traced back to the joint influence of anisotropic distribution of exciton oscillator strength and birefringence.

In the present study, we analyze the optical response of non-polar III-nitride microcavities with varying architectures within a 4x4 transfer matrix algorithm taking fully into account the optical anisotropy [3]. More precisely, the design of the III-nitride based bottom Bragg reflector is assumed to affect the strain state and thus optical anisotropy of the pseudomorphically overgrown cavity section including the quantum wells. The impact of strain on the exciton positions and oscillator strength is modeled using a k.p approach and allows to investigate the nature of the light-matter coupling regime depending on the polarization of the probing light. It turns out that depending on the design, different excitons can be promoted to the weak or the strong coupling regime in one or both polarization directions. Optical anisotropy in non-polar GaN-based microcavities is thus revealed to be a unique playground to engineer the nature of the coupling regime.

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Optical Characterization and Dynamics of Single ZnO Tetrapods

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ZnO is one of the most attractive wide band-gap emitter materials with a direct band gap of 3.37 eV at room temperature and a large exciton binding energy (60 meV), which allows UV lasing action to occur at room temperature [1]. Among various ZnO structures, tetrapods are of particular interest [2] because they possess remarkable optical, electronic and mechanical properties.

In this work we present the emission spectra of individual crystalline pure ZnO tetrapods, measured by both time-resolved and time-integrated photoluminescence (PL) spectroscopy as a function of temperature, from 13K to room temperature, and pump power, from 280-1000 μW, paying special attention to the dynamics of the PL and the temperature dependence of both, energy and decay time.

We observe that at room temperature the PL spectra are dominated by the free exciton (FX) recombination. The power-dependence results show that the PL intensity increases with power and a red-shift occurs at high powers due to carrier heating. In the temperature dependence for a constant power, we observe a blue-shift of the FX emission decreasing the temperature. At low temperatures, the PL spectra show both surface and bulk bound excitons. Concerning the dynamics study, we observe that the emission energy of the surface and bulk excitons transitions does not change with time, for all temperatures. We have analyzed the dynamics of the bound exciton emission, fitting the decaying part of the PL intensity with a single exponential function, extracting a decay time. We find that this decay time increases with increasing temperature, evidencing an enhancement of the non-radiative recombination mechanisms.

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 We-23p

Optical spin control in spherical charged semiconductor nanocrystals

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One of the most common techniques of the spin coherence generation, detection and manipulation in semiconductors is the pump-probe method. In this method two optical pulses, one circularly and one linearly polarized, are used to orient charge carriers spins and to detect their spin polarization via magneto-optical Faraday, Kerr or ellipticity effect, respectively. Additional linearly or circularly polarized control pulse is used to control the electron spin state [1,2].

An extremely convenient object for the spin dynamics studying is an array of singly-charged quantum dots [1] due to very long spin coherence time of the resident carriers. The present work describes theoretically the processes of spin coherence generation, control and detection by means of short optical pulses for spherical singly charged nanocrystals (NCs) with allowance for the complex valence band structure. Under the pump pulse the singlet trion (a pair of the electrons with antiparallel spins and a hole) can be formed in the NC. Consequently the spin orientation in the crystal is defined by the hole state, and the effects of the complex valence band structure, namely, four-fold ($\square_8$) spin degeneracy of the trion state are crucial.

We show that the direction of the electron spin generated by a single pump pulse depends not only on the radiation helicity and the light propagation axis but also on the pump pulse power. This is a result of interference of different optical transitions in the case of the complex valence band. The possibilities of the spin rotation by means of the detuned circularly polarized control pulse are discussed.

Periodic train of pump pulses are described theoretically. We show that the electron can be completely spin polarized by means of a sufficiently long train of pump pulses with appropriate power. We demonstrate that the mode-locking of electron spin precession can be observed in the inhomogeneous arrays of NCs, similarly to the case of self-organized quantum dots with simple valence band structure [3].

The theoretical description of probing of the spin polarization is also developed. The weak probe pulse was described in the framework of perturbation theory in the first order. The spectral dependence of spin Faraday, Kerr and ellipticity signals is discussed, and the different temporal behavior of Faraday and ellipticity signals in inhomogeneous NC ensembles is predicted.

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Magnetic polarons in (Cd,Mn)Te magnetic quantum dots

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0D diluted magnetic semiconductor nanostructures have recently renewed the interest for magnetic polarons - a local magnetic order induced by the coupling between localized spins and confined carriers [1, 2]. II-VI's are particularly interesting because: *(i)* isoelectronic Mn atoms can be used to introduce localized spins in well controlled 0D nanostructures, *(ii)* 0D carrier can be independently injected optically or by doping, *(iii)* single objects can be studied by micro-photoluminescence (PL).

Self-organized (Cd,Mn)Te/ZnTe magnetic quantum dots (QDs) have been fabricated by depositing and desorbing in situ amorphous Te on a CdMnTe layer with Mn concentrations comprised between 4% and 10%, grown by molecular beam epitaxy. We investigated the magnetic polaron formation during the lifetime of an electron-hole pair optically injected in the QD. Micro-PL spectra of single QD have been recorded under magnetic field at temperatures between 5°K and 100□‹K. In the samples with nominal Mn concentrations larger than 6%, the formation of magnetic polarons is revealed by a characteristic non monotonic variation of the PL line versus temperature. We analyzed consistently all the experimental data using a muffin-tin model and by taking into account Gaussian spin fluctuations. All the experimental parameters (polaron energy, Zeeman shift and circular polarization) can be reproduced by assuming a reduced Mn concentration in the dots. This result suggests that Mn atoms diffuse less than Cd during the QD formation obtained by a Te surface treatment of the CdMnTe layer.

As revealed recently [1], more stable magnetic polarons can be obtained by increasing the 0D confinement of the holes. We started to study a new geometry based on magnetic QDs inserted in nanowires in order to investigate the possibilities and limits related to this geometry. CdTe QDs inserted in ZnTe nanowires have been grown by molecular beam epitaxy using gold as a catalyst [3]. Micro-PL studies of single nanowires have been performed with nanowires dispersed on a patterned Si substrate. Excitonic lines characteristic of electron-hole pairs confined in the QD [4] have been identified. The growth of magnetic quantum dots and micro-PL under magnetic field and are presently under progress.

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Magnetorefractive effect in manganites

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We studied a magnetic-field-induced change in reflectivity (magnetoreflection) and transmission (magnetotransmission) of natural light in optimally doped manganites $La,Nd_{1-x}A_xMnO_3$ (A=Ca,Sr,K,Ag) possessed the colossal magnetoresistance effect (CMR)[1-3]. It was showed the magnetoreflection and magnetotransmission in manganites are an optical response to the CMR in the IR-region. Effects can reach tens of percents in the field of 0.3 T near the magnetic phase transition temperature. The observed phenomena are connected with the change of ratio between the localized and delocalized charge carriers under the magnetic field applied [2]. At the same time, there is no strict correlation between these effects and CMR in the visible range. The nature of effects can be explained by the alteration of the optical density under the magnetic field in the range of interband transitions [3]. Magnitude of the observed effects is as one order more as that for the traditional linear magneto-optical effects. The results of study of magnetoreflection and magnetotransmission in manganites may be proposed for creation of different magnetic and electronic sensors and light modulators.

Supported by the program of DPS RAS "Physics of new materials and structures", program of UD-FED of the RAS, Russian Federation President Grant MK-1048.2012.2 and RFBR № 10-02-00038.

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Polariton-like Excitations and Classical Rotons in Weak Light-Matter Interactions in Cold Atomic Traps

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In large magneto-optical traps (MOTs), the effect of multiple scattering of photons is quite important and has been identified to be in the root of long-range interactions, which allows for the system to be treated as a one-component plasma. Additionally, if the system is optically dense, the dynamics of the multiple scattered light can be diffusive, which leads to interesting optical features. By investigating the elementary excitations of the system, we show that the combination of these two effects can result on a mode spectrum containing a “roton” minimum.

We consider that the dynamics of cold atoms in MOTs is described by the Vlasov equation, accounting for the collective forces due to multiple scattering . Such collective force can be described by a Poisson equation [1, 2], which strength is connected to an "effective charge" for the neutral atoms [2]. The latter, in its turn, is a function of the light intensity [3, 4, 5]. A light-matter coupling can therefore take place if the light intensity is allowed to fluctuate, similarly to what happens with density.

In optical thick magneto-optical traps, the dynamics of the light intensity can be described with the help of a diffusion equation [6]. The diffusion coefficient is a function of the density of the system, what actually loses the system. As a consequence, the linearization of the relevant equations (Vlasov, Poisson and diffusion equations), yields a kinetic dispersion relation for the coupled light-matter excitations. The latter can then be seen as a polariton-like dispersion. Moreover, for a proper combination of the relevant parameters, one can observe the emergence of a minimum in the mode dispersion, which is a classical manifestation of the roton minimum. Such interpretation, although possibly misleading, is possible because of the long range order associated to it. Such long-range order parameter can be computed by using the fluctuation-dissipation theorem [7, 8], which allows us to explicitly relate the dispersion relation to the static structure factor of the system [9]. The physical origin of this 'roton' minimum is a consequence of the dynamical competition between the long-range forces, due to multiple scattering of the atoms, and the short-range forces sue to the diffusive dispersion of light inside the trap.

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 We-27p

Single-photon III-V quantum dot emitters and photonic crystal cavities monolithically grown on a Si substrate

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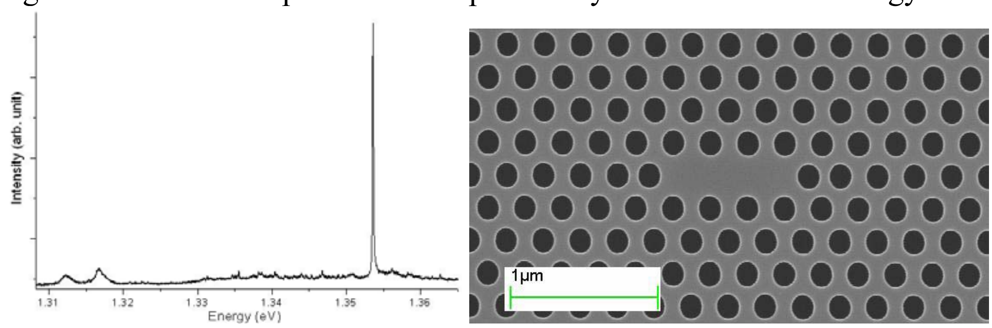
Utilization of quantum light in photonic applications allows functionalities beyond what is possible using classical light [1]. For example, carrying information with single photons provides a means to test the secrecy of optical communications. For these applications, light sources, which generate pure single-photon states 'on demand' in response to an external trigger signal, are of key importance. Here we report fabrication of III-V QDs embedded in photonic crystal cavities monolithically grown on Si substrates. Incorporating photonic components into Si microelectronics has been the impetus behind the development of Si photonics for the last twenty years. Here we achieve a first major step towards fabrication of monolithic optically and electrically pumped quantum light sources on a Si platform.

GaAs/AlGaAs layers were grown on 3-inch Si substrates using molecular beam epitaxy. Strain filters comprising multiple InAlAs/GaAs quantum wells were used to compensate for the lattice constant mismatch between GaAs and Si and to capture dislocations. At the top of the structure a layer sequence allowing fabrication of suspended GaAs membranes comprising InAs quantum dots was realised. We first studied unprocessed wafers using micro-photoluminescence (μ-PL) at low temperatures below 20K. Bright emission of single dot lines in the region 1.30 to 1.42 eV was observed exhibiting average linewidth of 35 μeV (see inset on the left in the figure below). Photon correlation measurements showed clear anti-bunching confirming single-photon emission from the III-V dots grown on Si substrates.

Different types of photonic crystal cavities were fabricated on the sample including L3 (right panel in the figure), H1 and microdisks. L3 cavities measured at 8K showed bright photonic mode emission all across the InAs dot spectral region with mode quality factors up to 13000 and the average Q-factor of 9000 (main plot in the left panel below). H1 cavities exhibited Q-factors between 4000 and 6000.

The quality of both QDs and photonic crystals in these samples does not differ from similar structures grown on GaAs substrates. Especially promising are the large Q-factors as they reflect the high quality of the III-V material on a more macroscopic scale than single QDs. This is a promising first step towards integration of III-V quantum light emitters with Si photonics and potentially with CMOS technology.



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Multistability of cavity exciton-polaritons affected by the thermally generated exciton reservoir

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Cavity polaritons are quasiparticles formed by strong coupling between excitons in quantum wells and light confined in microcavity [1]. Because of their bosonic nature they can form a macrooccupied coherent state. Interaction between polaritons comes from their excitonic fraction and is related to exciton-exciton exchange interaction. This leads to strong non-linear optical response of microcavities and gives rise to many significant optical effects. One of them, the low-threshold bistability, has been experimentally observed and described in 2004 [2]. Considering the facts that polaritons possess two spin projections and polariton-polariton interaction shows spin anisotropy the multistability effect was proposed [3]. This effect was observed and described in [4] but, surprisingly, a strong effective repulsion between the polaritons of opposite spins was suggested in this work to explain the data, while previous experiments have shown that this interaction should be slightly attractive [5].

In our work we develop the idea of exciton reservoir proposed phenomenologically in [6]. We consider resonant pumping in the ground state and polariton-acoustic phonon scattering processes. Solving exact Boltzmann equations we show that in the case of small Rabi splitting and positive detunings between photonic and excitonic dispersion branches it is possible to obtain significant densities of reservoir excitons in the system. This fact results in strong renormalization of the interaction constants and can give rise to effective repulsion between opposite spins. Finally, we solve Gross-Pitaevskii equation where reservoir density is taken as a parameter and by this we reproduce the hysteresis curves observed in [4], while keeping attractive interactions between the particles of opposite spins.

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