

International School on

Physics of Indirect Excitons

Ettore Majorana Center, Erice (IT) | July 26—August 1, 2014

Marie Curie ITN INDEX Summer School

Book of Abstracts

art work: Luisa Neri

ORGANIZED BY

ETTORE MAJORANA FOUNDATION AND CENTRE FOR SCIENTIFIC CULTURE

TO PAY A PERMANENT TRIBUTE TO GALILEO GALILEI, FOUNDER OF MODERN SCIENCE AND TO ENRICO FERMI, "THE ITALIAN NAVIGATOR", FATHER OF THE WEAK FORCES

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SCUOLA NORMALE SUPERIORE PISA

ITN INDEX

MARIE CURIE ACTIONS

INTERNATIONAL SCHOOL ON THE PHYSICS OF INDIRECT EXCITONS | 66TH COURSE ON SOLID STATE PHYSICS

ETTORE MAJORANA FOUNDATION AND CENTER FOR SCIENTIFIC CULTURE | FP7 MARIE CURIE ITN ñINDEX: INDIRECT EXCITONS ï FUNDAMENTALS PHYSICS AND APPLICATIONSò

26 JULY ï 1 AUGUST 2014

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PRESENTATION

We are glad to welcome you to the International School on the Physics of Indirect Excitons & 65th Course On Solid State Physics organized by the Ettore Majorana Foundation and Center For Scientific Culture and by the FP7 Marie Curie ITN ñINDEX: Indirect Excitons ï Fundamentals Physics And Applicationsò with the support of the Nanoscience Institute Cnr, Modena, and the Scuola Normale Superiore, Pisa.

This school brings together scientists and students active in research on indirect excitons.
This school will address the fundamental physics of cold bosons in solid state materials, the novel principles for optoelectronic devices, and the new systems with indirect excitons. Moreover we wish that it will represent an opportunity for discussing/sharing ideas possibly paving the way to novel collaborations.

We are really happy to host you in the wonderful frame of Erice. We are certain that you will greatly enjoy this major scientific event as well as the Sicilian and Italian culture, cuisine and hospitality.

Leonid Butov, Aron Pinczuk, Vittorio Pellegrini, and Massimo Rontani
Erice, July 26, 2014

COMMITTEES

BOARD OF DIRECTORS: LEONID BUTOV, VITTORIO PELLEGRINI, ARON PINCZUK, MASSIMO RONTANI.
ORGANIZING COMMITTEE @CNR NANO: LUISA NERI, ROBERTA DE DONATIS, ANNA GRAZIA STEFANI.

PROGRAM

	Saturday July 26, 2014
	Arrival, no lectures
	Sunday July 27, 2014
09:00-09:15	Opening remarks
09:15-10:45	**J. Baumberg**: Polaritons (lecture)
10:45-11:15	Coffee Break
11:15-12:00	**G. Christmann**: Direct-indirect exciton coupling and tunnelling effects in strongly coupled microcavities
12:00-12:45	**J. Baumberg**: Exercise / Discussion
	Lunch
15:00-16:30	**E. Molinari**: Fundamentals of excitons (lecture)
16:30-17:00	Coffee Break
17:00-17:45	**A. Holleitner**: Few-exciton Physics
17:45-18:30	**E. Molinari**: Exercise / Discussion
	Monday July 28, 2014
09:00-10:30	**A. Pinczuk**: Optics of two-dimensional electron gases and quantum Hall bilayers (lecture)
10:30-11:00	Coffee Break
11:00-11:45	**L. Pfeiffer**: Semiconductor bilayers
11:45-12:30	**A. Pinczuk**: Exercise / Discussion
	Lunch
15:00-16:30	**L. Butov**: Indirect excitons (lecture)
16:30-17:00	Coffee Break
17:00-17:45	**F. Dubin**: Bose-Einstein condensation of excitons: the key role of dark states
17:45-18:30	**L. Butov**: Exercise / Discussion
18:30-20:00	INDEX Network Meeting 1st session (only for network participants)
	Tuesday July 29, 2014
09:00-10:30	**M. Dyakonov**: Spin physics of electrons, holes, and excitons in quantum wells (lecture)
10:30-11:00	Coffee Break
11:00-11:45	**M. Dyakonov**: Exercise / Discussion
	Excursion to Selinunte

19:00-20:00	INDEX Network Meeting 2nd session (only for network participants)
	Wednesday July 30, 2014
09:00-10:30	**L. Levitov**: Long-range valley currents, plasmons and energy waves in graphene
10:30-11:00	Coffee Break
11:00-11:45	**V. Pellegrini**: Exploring electron-hole pairing in graphene -GaAs heterostructures
11:45-12:30	**M. Vladimirova**: Spin dynamics in coupled quantum wells
	Lunch
15:00-15:45	**M. Polini**: Transport anomalies in separately-contacted bilayer exciton condensates
15:45-17:00	Short presentations given by students
17:00-19:00	Poster session with wine & other goodies
	Thursday July 31, 2014
09:30-10:15	**L. Ponomarenko**: Transport in bilayer graphene
10:15-10:45	Coffee Break
10:45-11:30	**L. Levitov**: Exercise / Discussion
11:30-12:15	**C. Tejedor**: Exciton-plasmon-polaritons
	Lunch
15:00-15:45	**K. Bolotin**: Excitons in two-dimensional semiconductors
15:45-16:15	Coffee break
16:15-17:00	**M. Rontani**: Anomalous magnetization of carbon nanotubes as excitonic insulators
17:00-17:15	Closing remarks
	Friday August 1, 2014
	Departure

POSTER SESSION

Nonlinear optical spectroscopy of indirect excitons in biased coupled quantum wells.
P. Andreakou, S. Cronenberger, D. Scalbert, A. Nalitov, N. A. Gippius, A. V. Kavokin, M. Nawrocki, J. R. Leonard, L. V. Butov, K. L. Campman, A. C. Gossard, and M. Vladimirova.

Momentum and real space tomography of exciton-polariton gap solitons in two-dimensional lattices.
J. Buller, E. A. Cerda-Mendez, R. Balderas, K. Biermann, D. Sarkar, D. N. Krizhanovskii, and P. V. Santos.

Spin currents in indirect excitons in high magnetic fields.
Y. Y. Kuznetsova, E. V. Calman, J. R. Leonard, L. V. Butov, K. L. Campman, and A. C. Gossard.

Exciton Correlations.
M. Remeika, J. R. Leonard, C. J. Dorow, M. M. Fogler, L. V. Butov, M. Hanson, and A. C. Gossard.

Transport of indirect excitons in polar GaN/AlGaN quantum wells
F. Fedichkin, B. Jouault, P. Andreakou, P. Valvin, M. Vladimirova, T. Guillet, T. Bretagnon, A. Dussaigne, N. Grandjean, and P. Lefebvre.

Indirect optical excitations of hybrid nanosystems.
G. Gil, A. Delgado, A. Bertoni, G. Goldoni, and S. Corni.

Time-Dependent Quantum Dynamics of 1D Spatially Indirect Excitons.
F. Grasselli, A. Bertoni, and G. Goldoni.

Two-dimensional trap and stirring potential for indirect excitons.
M. W. Hasling, Y. Y. Kuznetsova, P. Andreakou, J. R. Leonard, E. V. Calman, C. J. Dorow, L. V. Butov, M. Hanson, and A. C. Gossard.

Indirect excitons in high magnetic fields.
Y. Y. Kuznetsova, E. V. Calman, L. V. Butov, K. L. Campman, and A. C. Gossard.

Optically Controlled Excitonic Transistor.
S. V. Poltavtsev, P. Andreakou, J. R. Leonard, E. V. Calman, M. Remeika, Y. Y. Kuznetsova, L. V. Butov, J. Wilkes, M. Hanson, and A. C. Gossard.

Zero-point energy of bosonic collective excitations in the BCS-BEC crossover.
L. Salasnich.

Magneto-luminescence study of the inter-layer interactions of electron bilayer.
T. Satzoukidis, I. Aliaj, A. Gamucci, V. Pellegrini, B. Karmakar, L. Pfeiffer, and A. Pinczuk.

Bias controlled bistability in dipole oriented polariton system.
P. K Sharma, S. I. Tsintzos, G. Christmann, A. Tzimis, Z. Hatzopoulos, J. J Baumberg, and P. G Savvidis.

Towards the optical study of electrically generated electron-hole bilayer systems.
U. Siciliani de Cumis, A. F. Croxall, H. E. Beere, I. Farrer, D. A. Ritchie, I. Aliaj, T. Satzoukidis, D. Spirito, A. Gamucci, and V. Pellegrini.

Exciton spin noise in quantum wells.
D. S. Smirnov and M. M. Glazov.

Strong exciton-photon coupling in organic microcavities.
L. Tropf, E. Rezende Martins, C. P. Dietrich, I. D. W. Samuel, and S. Höfling.

Spin transfer torque with excitons.
K. L. Vendelbjerg, L. J. Sham, and M. Rontani.

ABSTRACTS OF TALKS

DIRECT-INDIRECT EXCITON COUPLING AND TUNNELLING EFFECTS IN STRONGLY COUPLED MICROCAVITIES

G. Christmann

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Semiconductor microcavities in the strong coupling regime are very promising candidates for the realization of integrated on chip optical circuits. Polaritons, the half-light half-matter quasiparticules resulting from the strong light matter interaction between a quantum well (QW) exciton and a cavity photon, offer very interesting properties. Owing to their bosonic character they can form a Bose-Einstein condensate which allows the realization of ultralow threshold coherent light emitters [1,2]. Furthermore, their strong dipole moment leads to very strong polariton-polariton interactions. This allows the realization of several optical processing devices such as transistors, switches or bistable systems [3,4]. It is therefore highly desirable to combine these effects with an electrical control. Up to now electrical control on QW excitons and thus polaritons is mostly done by quantum confined Stark effect (QCSE), which leads to an energy redshift and a decrease in oscillator strength. We propose here a scheme using tunnel coupled double QWs inside microcavities in order to go beyond the limitation of single QW QCSE.

By using carefully designed weakly tunnel coupled double QW structures it is possible to control the charging the structure by quantum tunnelling. This will have a dramatic effect on the polariton properties due to their interaction with these free charges. Control of polariton parametric amplification using this technique will be presented [5]. A structure designed for very strong charging, and showing tuning opposite to the conventional QCSE [6], will also be discussed.

Instead of using weakly tunnel coupled double QW structures, it is also very useful to study strongly coupled ones. In that case the wavefunctions will be delocalized over the two quantum wells. A carefully designed asymmetric double QW structure can have its electron wavefunction delocalized over two wells while its hole wavefunction will remain strongly confined in one well [7]. This will result in a strong exciton static dipole moment and results on the insertion of such active region in a microcavity will be presented.

This new direction for interfacing cavity polaritons with electrical control is promising for the realization of devices combining optical circuits and conventional electronics.

[1] Kasprzak *et. al.*, Nature **443**, 409 (2006).
[2] Schneider *et al.*, Nature **497**, 348 (2013).
[3] Gao *et al.*, Phys. Rev. B **85**, 235102 (2012).
[4] Liew *et al.*, Physica E **43**, 1543 (2011).
[5] Christmann *et al.*, PRB **82**, 113308 (2010).
[6] Tsotsis *et al.*, Phys. Rev. Appl. **2**, 014002 (2014).
[7] Cristofolini *et al.*, Science **336**, 704 (2012).

SINGLE INDIRECT EXCITONS IN GATE-DEFINED QUANTUM TRAPS

A. W. Holleitner

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

In coupled double quantum wells (CDQW) photogenerated and spatially indirect excitons can be efficiently manipulated via gate-voltage-induced control of the quantum confined Stark Effect (QCSE). On an InGaAs-GaAs CDQW heterostructure we have realized electrostatically widely tunable trapping devices for dipolar indirect excitons. Utilizing the QCSE resonantly excited direct excitons transform into indirect excitons and are collected via electrostatically shaped energy landscapes. With their electron and hole confined to two different quantum wells, these indirect excitons exhibit a large dipole moment and long lifetimes of about 100 ns. Employing a 3He-cooled confocal microscope with two objectives that can be independently positioned we generate indirect excitons at a location outside the trap and measure their photoluminescence from the trap center after they have been cooled to lattice temperatures and transferred into the trap. The scheme also allows exploring the photoluminescence of spatially indirect Mahan excitons, consisting of individual holes in one of the quantum wells interacting with a degenerate two-dimensional electron system confined in the other quantum well.

In this lecture, I report on photoluminescence measurements on circular traps allowing the control of single indirect excitons. The electrostatic traps can be voltage-tuned to generate a parabolic confinement potential for the dipolar indirect excitons with effective confinement diameters down to about 100 nm. At low temperature of 250 mK, we are able to study the transition to the few exciton regime of down to a single indirect exciton. We observe up to three discrete spectral lines which are explained by successive occupation of the trap with individual excitons and reflect molecular-like spatial arrangements of excitons caused by their strong dipolar repulsion. These discrete excitonic transitions are tunable by gate voltages and magnetic fields and are well reproduced by a straightforward model of interacting dipoles confined in a parabolic trap. Further filling the trap by increasing the power of the laser generating excitons we are able to observe the transition from discrete lines in the photoluminescence spectrum to an increasingly asymmetric line shape with an edge-like singularity on its blue side. The asymmetry we also interpret as reflecting a correlated ground state of the indirect excitons caused by the interplay of dipolar repulsion and spatial confinement at low temperatures.

Acknowledgement: I thank the very fruitful collaboration with J. Repp, S. Dietl, U. Wurstbauer, G. J. Schinner, K. Kowalik-Seidl, E. Schubert, A. K. Rai, D. Reuter, A. D. Wieck, A. O. Govorov, and J. P. Kotthaus, and I acknowledge the financial support by the ñDeutsche Forschungsgemeinschaftò (DFG) via project KO416/17 and the excellence cluster ñNanosystems Initiative Munichò (NIM).

INDIRECT MAGNETOEXCITONS IN QUANTUM HALL FLUIDSÀ

Aron Pinczuk*

Dept. of Appl. Physics & Appl. Math. and Dept. of Physics, Columbia University, New York, NY, USA.

Magnetorotons are the lowest spin-conserving excitations of quantum fluids of two-dimensional electron systems embedded in large perpendicular magnetic fields B. The modes are indirect excitons in a high magnetic field that are built from quasiparticle-quasihole pairs with a separation of the order of a magnetic length (k̆c/eB)$^{1/2}$. In quantum Hall fluids magnetorotons are characteristic low-energy excitation modes that manifest underlying fundamental interactions and key physics of quasiparticles.

Inelastic light scattering methods at very low temperatures (reaching below 50 milliKelvin degrees) are experimental methods to study excitations of electron fluids in the low dimensional systems. While magneto-transport experiments probe the quantum Hall fluids through current-carrying edge states, the light scattering experiments access directly low-lying ñquasiparticleò excitation modes that take the óbulkô 2D electron fluids above ground states. These quasiparticle excitations express key properties of emergent quantum phases of the 2D electron system.

This lecture considers optics studies of magnetoroton modes of quantum Hall phases in that reside in superior quality GaAs quantum wells.

The presentation starts with an introduction that describes inelastic light scattering methods for studies of quantum Hall phases in single electron layers and in electron bilayers. In this introduction results at Landau level filling factor of з=1/3 in single layers and for filling factors near з=1 in bilayers demonstrate how light scattering methods uncover key features of magnetoroton modes. Following the introduction the presentation considers recent results that explore low-lying excitations of the quantum Hall fluids that reside in the second Landau level of single electron layers. The fascinating fractional quantum Hall states at even-denominator з=2+1/2=5/2 and at odd-denominator з=2+1/3=7/3 are of particular interest.

(À) Supported by NSF.
(*) The research of quantum phases in electron bilayers is in collaboration with V. Pellegrini, B. Karmakar, S. Luin and L. N. Pfeiffer.
The recent research on quantum Hall phases in single electron layers is in collaboration with U. Wurstabauer, A. L. Levy, L. N. Pfeiffer and M. J. Manfra.

BOSE-EINSTEIN CONDENSATION OF EXCITONS: THE KEY ROLE OF DARK STATES

François Dubin

ICFO - The Institute for Photonic Sciences, http://www.icfo.eu
INSP - Institute for NanoSciences of Paris, University of Paris VI, http://www.insp.jussieu.fr.

Semiconductor excitons are very attractive candidates in order to study Bose-Einstein condensation (BEC), a unique quantum phase transition across which elementary bosonic particles are all collapsed in the ground-state of the system. In particular, dipolar (electrically polarized) excitons receive growing interest: they fulfill all the requirements to enter the regime where quantum statistical effects can be dominant. However, dipolar excitons have an optically inactive, i.e. dark, ground-state where BEC has to occur [1]. This considerably hardens experimental studies to reveal BEC.

In this presentation, I report experiments highlighting the formation of a Bose-Einstein condensate of dipolar excitons [2]. The condensate is signaled by its quantum statistical distribution with a dominant (90-95%) fraction of dark excitons at sub-Kelvin temperatures. The weak photoluminescence that it emits exhibits macroscopic spatial coherence and significant linear polarization. These two last observations reveal that in our experiments bright and dark excitons are coherently coupled in the condensed state, as theoretically expected [3].

[1] M. Combescot, O. Betbeder-Matibet, and R. Combescot, Phys. Rev. Lett. **99**, 176403 (2007).
[2] M. Alloing *et al.*, EuroPhys. Lett. **107**, 10012 (2014).
[3] R. Combesco and M. Combescot, Phys. Rev. Lett. **109**, 026401 (2012).

SEMICONDUCTOR BILAYERS

Loren Pfeiffer

Princeton University, Princeton NJ, USA.

Measuring the long-range diffusion of aligned indirect excitons, with David Snoke at the University of Pittsburg. For 140A-wide double quantum wells we find exciton lifetimes in excess of 30 μsec, and diffusion lengths in excess of 240 μm.

Localizing indirect excitons within an exciton trap, David Snoke has pioneered strain traps, and Ronen Rapaport at Hebrew University, has pioneered electrostatic traps for excitons. We show evidence for the diffusion of excitons within an electrostatic trap over times of several hundred nsec.

Measuring local density variations in 2D electron systems using the exciton/trion decay ratio, with Hidefumi Akiyama at the University of Tokyo, and Jerry Lee at Princeton. We will show images of the local electron density variations within a high mobility quantum well obtained using this exciton/trion technique.

EXPLORING ELECTRON-HOLE PAIRING IN GRAPHENE ï GAAS HETEROSTRUCTURES

Vittorio Pellegrini

Istituto Italiano di Tecnologia, Graphene labs, Via Morego 30 I-16163 Genova and NEST, Istituto Nanoscienze-Consiglio Nazionale delle Ricerche and Scuola Normale Superiore, I-56126 Pisa, Italy.

Vertical heterostructures combining different layered materials offer novel opportunities for applications and fundamental studies of collective behavior driven by inter-layer Coulomb coupling. In this talk I shall discuss a new class of heterostructures comprising a single-layer (or bilayer) graphene carrying a fluid of massless (massive) chiral carriers and a quantum well created in GaAs, supporting a high-mobility two-dimensional electron gas. These represent new architectures of double-layer devices composed of spatially-separated electron and hole fluids. We find that the Coulomb drag resistivity significantly increases for temperatures below 5-10K, following a logarithmic law. This anomalous behavior is suggestive of the onset of strong inter-layer correlations, compatible with the formation of a condensate of permanent excitons. The ability to induce strongly-correlated electron-hole states paves the way for the realization of coherent circuits with minimal dissipation and nanodevices including analog-to-digital converters and topologically protected quantum bits..

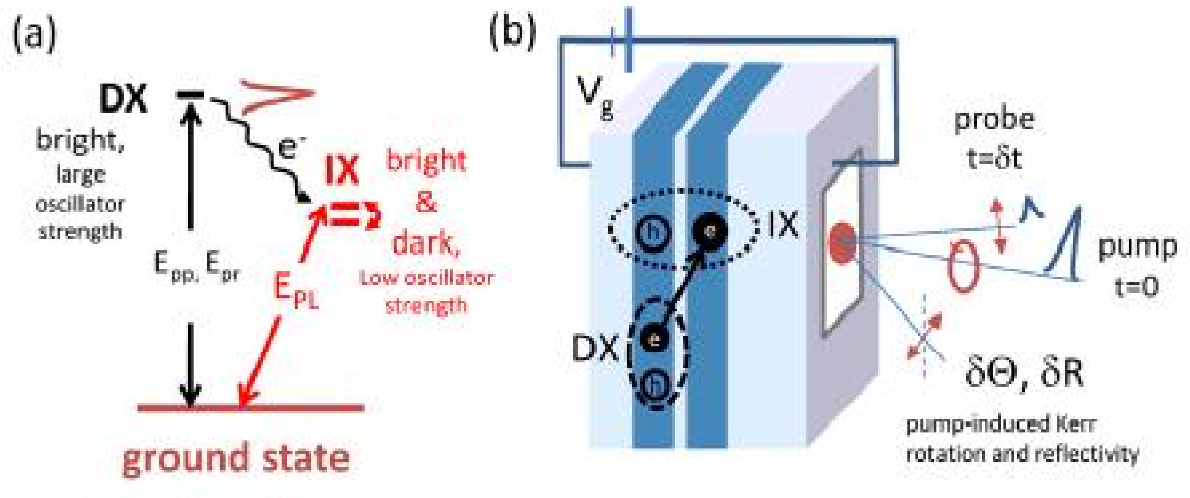
Work done in collaboration with: A. Gamucci, D. Spirito, M. Carrega, B. Karmakar, A. Lombardo, M. Bruna, A. C. Ferrari, L. N. Pfeiffer, K. W. West, M. Polini.

SPIN DYNAMICS IN COUPLED QUANTUM WELLS

Masha Vladimirova

Laboratoire Charles Coulomb, UMR 5221 CNRS/ University Montpellier 2, France.

Semiconductor coupled quantum wells (CQWs) offer an excellent laboratory for studying both intra-well direct excitons (DX) and inter-well indirect excitons (IX), as well as their interactions and spin dynamics. The presentation will focus on the pump-probe spectroscopy, a powerful tool of nonlinear optics, that we have applied to biased CQW. We will show how DX and IX spin and population dynamics, as well as the spin polarization of residual electrons may be detected via the modulation of reflectivity and Kerr rotation spectra [1]. In particular, the origin of the nonlinearities related to the low oscillator strength IXs will be addressed. Finally, a brief discussion of the spin relaxation mechanisms for DX, IX and electron gas will be presented.



(a) Three-levels scheme of the pump-probe experiment with relevant excitonic states in a biased CQWs. Low oscillator strength IX states are pumped and probed via DX transition, through their common ground state. (b) Sketch of CQWs and pump-probe experiment.

[1] P. Andreakou, S. Cronenberger, D. Scalbert, A. Nalitov, N. A. Gippius, A. V. Kavokin, J. R. Leonard, L. V. Butov, K. L. Campman, A. C. Gossard, and M. Vladimirova, arXiv:1407.5500.

EXCITON-PLASMON-POLARITONS

Carlos Tejedor

Departamento de Fisica Teorica Materia Condensada,
Universidad Autonoma de Madrid, Madrid, 28049 Spain.

This talk starts with a tutorial introduction to the field of plasmonics in nanostructures. Plasmon-polaritons are produced by the coupling of longitudinal plasmons in metallic nanostructures to transverse electromagnetic fields which decay out of the metallic interfaces. Molecules, quantum dots, defect centers or other semiconductor nanostructures with a discrete electronic spectrum behave as independent qubits in the low-density regime while in the high density limit they become an effective medium supporting extended excitons. When close to each other, excitons and plasmon-polaritons become coupled giving rise to exciton-plasmon-polaritons. We present here a study of the quantum properties of such a system.

We start by using 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 excitons and plasmons is in a strong- or in a weak-coupling regime.

Firstly we present, in the 2D geometry, the theoretical foundation of the phenomenon of strong-coupling between excitons and plasmon-polaritons observed in 2D metal surfaces. We study an ensemble of N quantum emitters and incorporate the presence of dephasing and excitation mechanisms into the theoretical framework in order to be as close as possible to the experimental situation. The experiments required to determine the quantum character of these phenomena are discussed.

Finally, the case of a single quantum emitter is analyzed exploring the range of parameters (lifetime, distance to the surface,é) in which, contrarily to intuition, the strong-coupling regime could emerge.

Work in collaboration with A. Gonzalez-Tudela, P. A. Huidobro, L. Martín-Moreno, and F. J. García-Vidal.

ANOMALOUS MAGNETIZATION OF A CARBON NANOTUBE AS AN EXCITONIC INSULATOR

Massimo Rontani

CNR-NANO Research Center S3, via Campi 213a, 41125 Modena, Italy.

We show theoretically [1] that an undoped carbon nanotube might be an excitonic insulator - the long-sought phase of matter proposed by Keldysh, Kohn and others fifty years ago. We predict that the condensation of triplet excitons, driven by intervalley exchange interaction, spontaneously occurs at equilibrium if the tube radius is sufficiently small. The signatures of exciton condensation are its sizeable contributions to both the energy gap and the magnetic moment per electron. The increase of the gap might have already been measured, albeit with a different explanation [Deshpande *et al.*, Science **323**, 106 (2009)]. The enhancement of the quasiparticle magnetic moment is a pair-breaking effect that counteracts the weak paramagnetism of the ground-state condensate of excitons. This property could rationalize the anomalous magnitude of magnetic moments recently observed in different devices close to charge neutrality (see discussion in [2]).

Work supported by EU-FP7 Marie Curie ITN INDEX and MIUR-PRIN2012 MEMO.

[1] M. Rontani, arXiv:1405.3108.
[2] E. A. Laird *et al.*, arXiv:1403.6133.

ABSTRACTS OF POSTERS

NONLINEAR OPTICAL SPECTROSCOPY OF INDIRECT EXCITONS IN BIASED COUPLED QUANTUM WELLS

P. Andreakou[1], S. Cronenberger[1], D. Scalbert[1], A. Nalitov[2], N. A. Gippius[3], A. V. Kavokin[4], M. Nawrocki[5], J. R. Leonard[6], L. V. Butov[6], K. L. Campman[7], A. C. Gossard[7], and M. Vladimirova[1]

[1]*Laboratoire Charles Coulomb, UMR 5221 CNRS/ University Montpellier 2, France.*
[2]*Institut Pascal, PHOTON-N2, Blaise Pascal University, CNRS, France.*
[3]*Russian Quantum Center, 100, Novaya, Skolkovo, Moscow Region, 143025, Russia.*
[4]*Spin Optics Laboratory, St-Petersburg State University, Russia.*
[5]*Institute of Experimental Physics, University of Warsaw, Poland.*
[6]*Department of Physics, University of California at San Diego, USA.*
[7]*Materials Department, University of California at Santa Barbara, USA.*

A spatially indirect exciton (IX) can be formed when an electron and a hole are confined in two different spatially separated coupled quantum wells (CQWs). The spatial separation of an electron and a hole wavefunctions can be engineered to control the spin lifetimes of IXs. In GaAs/AlGaAs CQWs, IX spin relaxation time up to tens of nanoseconds have been recently reported [1,2]. However, the measurements of IX spin dynamics by nonlinear spectroscopy are challenging, due to low oscillator strength of the IX state.

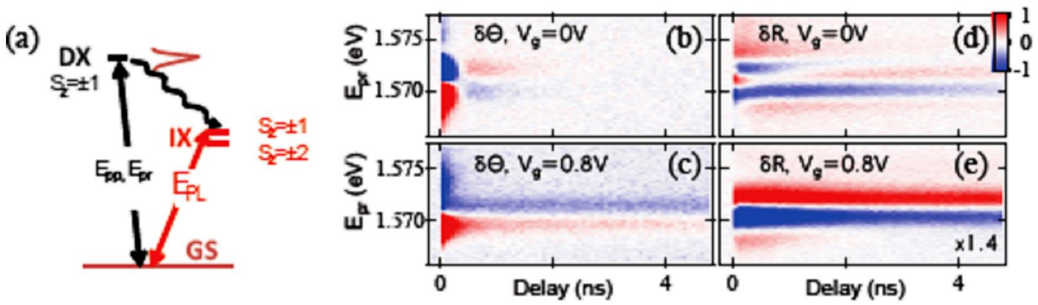


FIG.1: Three-levels scheme of the pump-probe experiment with relevant excitonic states in a biased CQWs (a). Photoinduced Kerr rotation ŏŪ (b, c) and reflectivity ŏR (d, e) measured as a function of pump-probe delay and probe energy (E_{pr}) for unbiased structure (Vg = 0) (b, d) and Vg = 0.8V (c, e).

We demonstrate a proof-of-concept for time-resolved pump-probe spectroscopy of IXs in CQWs. Pump and probe light pulses are resonant with optically active direct exciton (DX) transition, and IXs are probed via their common ground state with DXs (Fig.1a). Photoinduced reflectivity measurements show that the IX lifetime time in biased CQWs is of order of 30 ns at Vg=0.8 V, consistent with the PL kinetics measurments [3]. Pump-probe experiments allow unraveling DX, IX and electron spin dynamics (Fig.1 (b-d)). It appears that not only DX, but also bare electron spin relaxation is much faster ($\simeq$ 200 ps) than one of IXs (up to 10 ns), Fig.2.

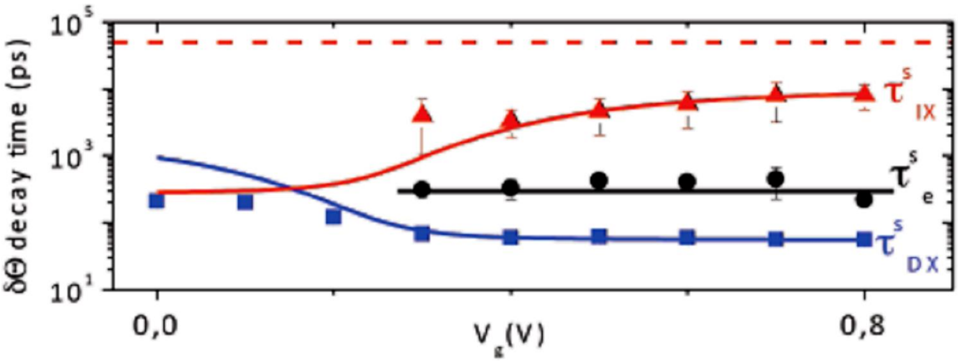


FIG.2: Spin lifetimes extracted from Kerr rotation decay as a function of gate voltage (symbols). Solid lines: coupled oscillators model for DX and IX, estimation from Dyakonov-Perel mechanism for electrons. Dashed line: theoretical limit for IX spin relaxation time.

We fit the probe spectra measured at a given excitation energy to the phenomenological model, in order to identify the DX-IX interaction mechanisms, responsible for the nonlinear signals [2]. We show that the photoinduced reflectivity signal is dominated by the narrowing of the DX resonance, which does not depends on the IX spin. The blue shift of the DX resonance due to the presence of IX appears to be strongly spin-dependent and gives the main contribution to Kerr rotation signal. The proposed technique opens the way for measuring the density and polarization state of both dark and bright components of the IX gas, and therefore, can address one of the main challenges in the physics of IXs Bose-Einstein condensation.

[1] J.R. Leonard, Y.Y. Kuznetsova, S. Yang, L. V. Butov, T. Ostatnicky, A. Kavokin, and A. C. Gossard, Nano Lett. **9**, 4204 (2009).
[2] K. Kowalik-Seidl, X. P. Vögele, B. N. Rimpfl, S. Manus, J. P. Kotthaus, D. Schuh, W. Wegscheider, and A. W. Holleitner, APL **97**, 011104 (2010).
[3] L. V. Butov, A. Imamoglu, A. V. Mintsev, K. L. Campman, and A. C. Gossard, Phys. Rev. B **59**, 1625 (1999).
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MOMENTUM AND REAL SPACE TOMOGRAPHY OF EXCITON-POLARITON GAP SOLITONS IN TWO-DIMENSIONAL LATTICES

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Exciton-polaritons are bosonic light-matter quasiparticles that result from the strong coupling of photon modes and quantum well (QW) excitons in a semiconductor microcavity (MC). Due to their photonic component, exciton-polaritons have very low effective masses, while their interexcitonic component provides strong non-linear interactions. In a MC with a periodic spatial modulation, where an artificial band structure with energy gaps and anomalous dispersion is created, exciton-polaritons may form self-localised states within the energy gaps. These states are known as exciton-polariton gap solitons (GS)[1] and form when the interparticle repulsion is compensated by the negative effective masses of the exciton-polaritons. However, a complete and detailed description of both real and momentum space is still missing.

In this work, we present experimental results on the tomography in momentum and real space of exciton-polariton GS in tunable 2D lattices introduced by surface acoustic waves (SAW). The tomographic results give insight into spatial distribution of exciton-polariton GS within the non-equilibrium condensate both in real and in momentum space. Our results will further enhance the fundamental understanding of the exciton-polariton GS.

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SPIN CURRENTS IN INDIRECT EXCITONS IN HIGH MAGNETIC FIELDS

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We report on spin currents and polarization patterns in indirect excitons in high magnetic fields. Indirect excitons in coupled quantum wells (CQW) can travel over large distances before recombining, cool down below the temperature of quantum degeneracy, and form a coherent Bose gas. Condensation of indirect excitons causes suppression of exciton scattering [1] and spin relaxation [2], facilitating long-range spin currents. The formation of a coherent exciton gas [1] and long-range spin currents [2] were measured in the regions of external rings and localized bright spot (LBS) rings in the exciton emission pattern. These features form in boundaries between electron-rich and hole-rich regions.

Here, we present polarization-, spatially-, and spectrally-resolved measurements of the emission of indirect excitons in the excitation spot region at temperature Tbath = 40 mK and magnetic fields B = 0 ī 10 T perpendicular to the CQW plane. We observed a ring of linear polarization around the excitation spot in the region where the exciton temperature is high (Fig.1a). When excitons move further away from the excitation spot and cool down further, a helical exciton polarization texture that winds by 2´ around the origin emerges around the excitation spot. We observed that the divergent momentum distribution of excitons produces a vortex of linear polarization with polarization oriented perpendicular to exciton momentum. The observed radial exciton polarization currents are associated with spin currents carried by electrons and holes bound into excitons.

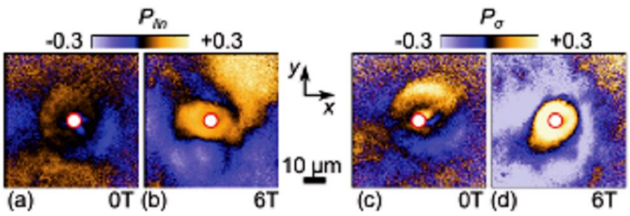

Fig.1: Linear (a,b) and circular (c,d) polarization of the emission of indirect excitons at B = 0 (a,c) and 6 T (b,d) around the laser excitation spot (red)

We observed that applied magnetic fields bend the spin current trajectories, creating spiral patterns of linear polarization around the origin (Fig. 1b). The spiral direction of the exciton polarization current clearly deviates from the radial direction of the exciton density current, presenting the spin-Hall effect in excitons. Spin currents are also observed in the circular polarization (Fig. 1c,d).

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EXCITON CORRELATIONS

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Understanding the interaction between particles is a fundamental problem. Excitons in semiconductors are neutral composite particles and their interaction forms an important case that has been intensively studied for decades [1,2,3]. An indirect exciton is a bound state of an electron and a hole confined to different quantum well layers. Indirect excitons have a built-in dipole moment ~ ed and form a dipolar matter with repulsive dipole-dipole interaction (d is the separation of electron and hole layers). The interaction leads to the enhancement of the energy of indirect excitons with increasing density [4]. In two-dimensional systems, the dipole interaction $\propto 1/r^3$ is short-range and, therefore, the relation between the energy shift ŭE and exciton density n can be estimated using the formula ***ŭ****E* = [1ï *C*(*n*)]Å4´ de^2n /***Ů*** where *C*(*n*) is a dimensionless correlation parameter ***Ů***and is the dielectric constant.

In this contribution, we present a method to measure the exciton correlations. We also present the measurements of the correlation parameter *C* as a function of density. The method is based on using tunable electrostatic lattices.

Because indirect excitons are oriented dipoles, potential landscapes for excitons $Eex(x,y) = edF_z(x,y)$ can be created by laterally modulated electric field $F_z(x,y)$ perpendicular to the quantum well plane. Earlier works [6,7] demonstrated the implementation of linear and two-dimensional electrostatic lattices for indirect excitons. Voltages applied to interdigitated electrodes create in-plane lattice potentials for excitons. The lattice depth is controlled by voltage.

Our method determines ***ŭ****E* and the correlation parameter *C* using the measurement of the exciton energy shift and energy modulation. Indirect excitons partially screen the lattice potential due to the repulsive interaction. The degree of screening is revealed by the spatial modulation of exciton energy. We present a theoretical model that relates the exciton density *n* and correlation parameter *C* to the measured exciton energy shift and energy modulation in a lattice potential. Using this model, we determined the exciton correlations for a wide range of parameters. We measured the exciton-exciton interaction as a function of the lattice depth (controlled by voltage), and exciton density and temperature (controlled by laser excitation power and bath temperature). We found strong correlations in the dipolar system of indirect excitons.

This work is supported by DOE.

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TRANSPORT OF INDIRECT EXCITONS IN POLAR GaN/AlGaN QUANTUM WELLS

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GaN/AlGaN polar single quantum wells have attracted particular attention due to their large binding energies and the presence of strong internal electric fields that naturally induce long-lived excitons. In this case, the exciton transport is driven by the potential landscape caused by the local alteration of the built-in electric field, which results from the exciton accumulation at the same point.

We study by spatially- and time-resolved PL experiments AlGaN/GaN coupled quantum wells (QW). The active zone of studied sample consists of a 30 nm thick Al0.20Ga0.80N barrier, a 4.4 nm (17 atomic monolayers) GaN QW followed by 1 monolayer of Al0.20Ga0.80N and a 1.6 nm (6 atomic monolayers) GaN QW and 30 nm thick Al0.20Ga0.80N cap layer. The sample structure is shown in Figure 1a.

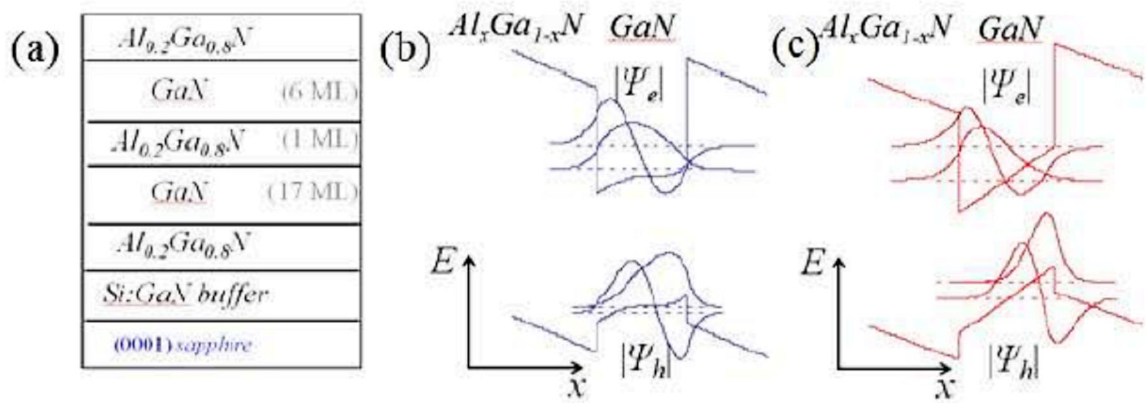

Fig.1. (a) Sample structure. Electronic band structures showing changes of wave functions of electron and hole in a single quantum well in case of blue shift (b) and red shift (c).

By solving Schroedinger-Poisson equation, we illustrate the two regimes of strongly screened electric field (blue-shift, left of figure 1b) and the totally un-screened QW system (redshift, right figure 1c). We show that the screening of the build-in electric field enhances the electron-hole wave-function overlap and increases the optical recombination energy. In other words, dipole-dipole repulsion between excitons raises their potential energy and drastically increases their radiative recombination rate.

A blue-shift of 0.3 eV under continues wave, localized excitation and a quasi-continuous red-shift of the emission as excitons are drifted away from the excitation spot up to distances of 90 εm are observed experimentally. Strong LO-phonon replica are also noticed, as a result of the strongly dipolar character of excitons [1]. These replicas follow the same position dependence as the zero-phonon line. Using our Schroedinger-Poisson equation solver, we can extract from the measured blue-shift the position-dependent exciton density.

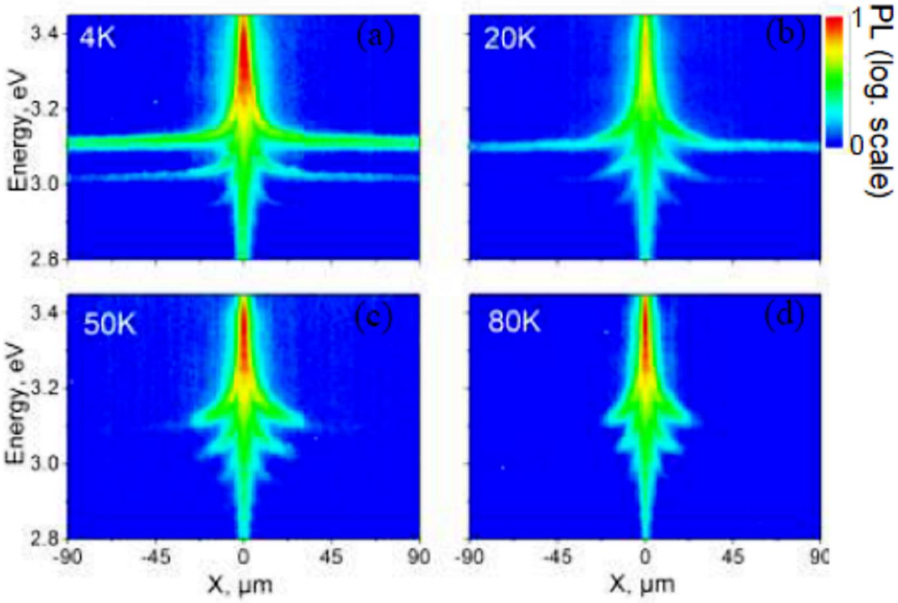

Fig.2. Spatially-resolved PL images taken on a 24ML-wide *GaN/Al0.20Ga0.80N* SQW containing 1ML AlGaN barrier at 4 (a), 20 (b), 50 (c) and 80 K (d). Sample was excited with the excitation power 10 mW by using excitation spot diameter of 0,75 εm.

Last, we present simulations of the observed transport features, namely the exciton densities and luminescence intensities by solving the nonlinear drift-diffusion equation. We establish that the long-range excitonic transport is mainly dominated by drift caused by repulsive dipole-dipole interaction between excitons in combination with their long lifetimes.

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INDIRECT OPTICAL EXCITATIONS OF HYBRID NANOSYSTEMS

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We introduce a novel numerical approach to treat the electronic excitations of an hybrid nanosystem composed by an organic molecule and a semiconductor nanoparticle, starting from the correct physical descriptions of both scenarios. The states and spectra of the subsystems will be computed by state-of-the-art Configuration Interaction approaches, either atomistic (for the molecule) or envelope-function based (for the nanoparticle), while the Coulomb coupling will be represented and diagonalized in the space generated by the correlated states of the separated fragments, so as to obtain the eigenstates of the hybrid system.

This method, called Hybrid Configuration Interaction, will allow us to study the direct and indirect (or charge-transfer) optical excitations taking into account correlation effects in both subsystems, as well as electrostatic interaction with the environment. Foreseen applications are in the field of light response of dye sensitized solar cells.

TIME-DEPENDENT QUANTUM DYNAMICS OF 1D SPATIALLY INDIRECT EXCITONS

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We simulate the coherent dynamics of a single spatially indirect exciton (SIX) in prototypical potential landscapes. SIXs can be generated in coupled quantum wells and accelerated or guided through potential gates.[1] This opens the way to quantum coherent electro-optical single-SIX devices.[2] Here, we use the Split-Step method to perform the exact two-body Schrödinger propagation[3] of a 1D SIX model, which fully takes into account the electron-hole internal degrees of freedom. Several energy scales come into play: i) electron-hole interaction, which may be experimentally controlled by proper heterostructure engineering; ii) kinetic energy of the SIX wavepacket, which can be modulated by acceleration ramps; iii) electron and hole potential energies, which can also be independently modulated by a proper gating of the structure. We expose the complex phenomenology arising in the scattering of a single SIX against in-plane stationary electrostatic potentials, e.g. potential steps/downhills and barriers/wells for the electron and the hole, which may occur in layered gated heterostructures.

In addition to reflection or partial transmission, SIXs may undergo ionization or excitation to higher internal states, under suitable conditions. A periodic emission of the SIX probability density in small periodic wavepackets, due to dwelling of one particle of the pair nearby the potential edges, can also be observed, both in the transmitted and in the reflected part. An example in shown in Fig.1.

The external potential parameter space has been explored in order to identify prominent experimental situations.

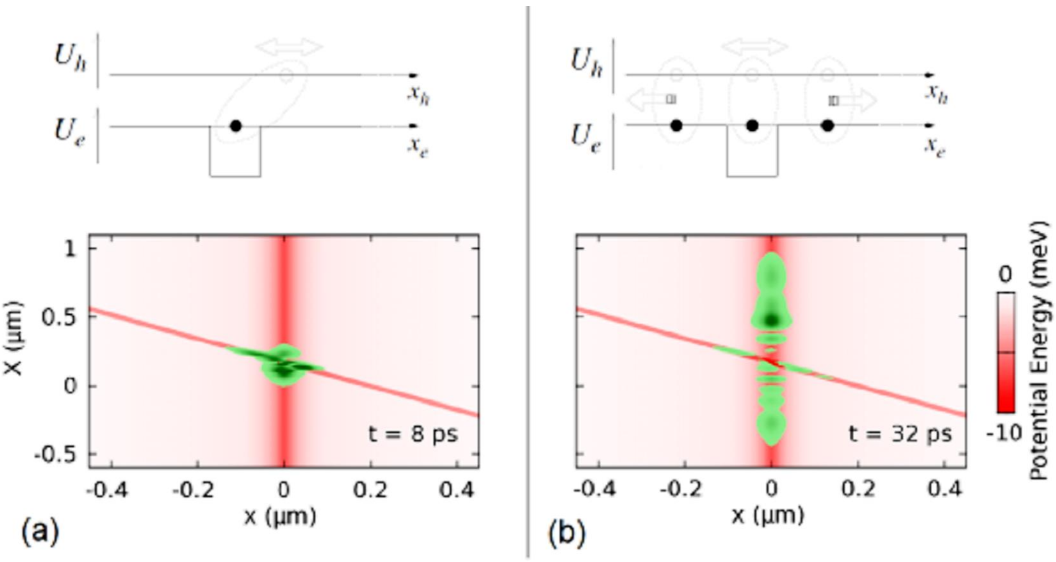

Fig.1: Potential pro_le and wavepacket in the relative (x) and center-of-mass (X) coordinates of the electron-hole pair scattering against an electron potential well (dark slanted stripe). The vertical dark stripe is the Coulomb interaction. In this particular simulation, a wavepacket initialized with a central kinetic energy of 0:5 meV and in the ground internal state of the SIX, undergoes exact Schrödinger evolution. After some ps (a), the hole starts oscillating around the electron well position, due to the Coulomb interaction. This dwelling of the wavepacket around the electron well implies a periodic emission of SIX probability density at later times (b). These phenomena are sketched above the relative simulation plots.

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TWO-DIMENSIONAL TRAP AND STIRRING POTENTIAL FOR INDIRECT EXCITONS

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We present experimental proof of principle for a two-dimensional snowflke trap for collecting a large number of indirect excitons at the trap center and experimental proof of principle for a stirring potential for indirect excitons.

Indirect excitons in coupled quantum wells (CQW) have a built-in dipole moment and are thus electronically controllable. Snowflake traps [1] produce two-dimensional confining potentials for indirect excitons on a large area and provide an opportunity to study condensates with a large number of excitons compared to the previously implemented diamond traps [2]. Snowflake traps (Fig.1) explore the principle of exciton energy control by electrode density: Decreasing electrode density toward the trap edges reduces the electric field perpendicular to the CQW plane, resulting in a confining potential for indirect excitons with the exciton energy gradually reducing toward the trap center from any direction. Figure 1 shows proof of principle for the snowflake trap: For any position of the laser excitation spot, the generated excitons are collected to the trap center by the trap potential.

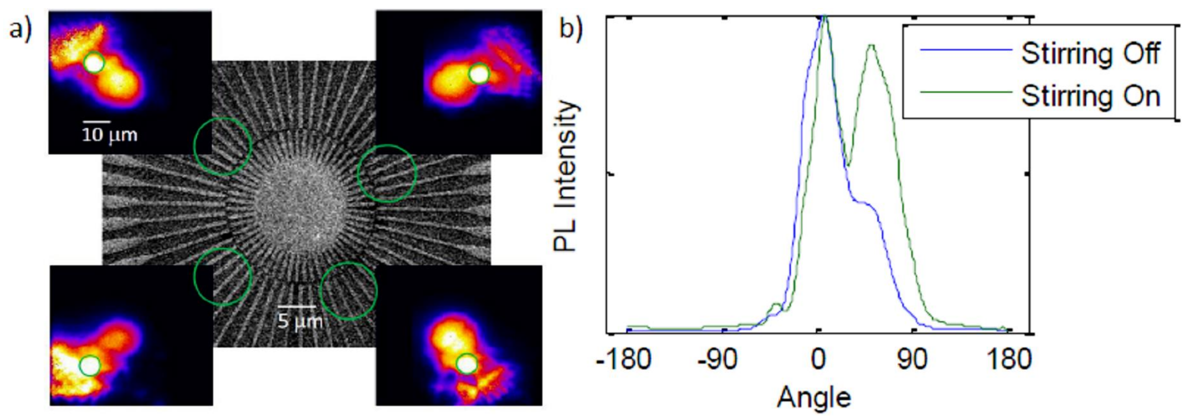

Fig.1: Experimental proof of principle for snowflake trap (a) and stirring potential (b). (a) SEM image of the electrode forming a snowflake trap for indirect excitons. Four side images present the exciton emission for four different positions of the laser excitation spot. The excitation spot positions are given by green circles. The circle size corresponds to the excitation spot size. (b) Profiles of exciton emission along the rotation angle for stirring off and on. The excitation spot is centered at zero angle, 13μm from the trap center. The stirring potential drives the excitons to higher angles.

The presented device can also provide stirring potentials for indirect excitons. The principle is based on the earlier developed moving lattices - conveyers - for indirect excitons [3]. AC voltages are applied to the electrodes spreading from the center (Fig.1a), creating a rotating potential for indirect excitons. The azimuthal wavelength of this stirring potential is set by the electrode periodicity, the amplitude is controlled by applied voltage, and the angular velocity by AC frequency. Stirring potentials can be used to probe vortices of cold excitons. A proof of principle demonstration of the stirring of indirect excitons is shown in Fig.1b.

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INDIRECT EXCITONS IN HIGH MAGNETIC FIELDS

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Transport, relaxation, and correlation effects are observed for indirect excitons in high magnetic fields.
Neutral electron-hole (e-h) systems in high magnetic fields were studied in single quantum wells (QWs) [1]. However, the short exciton lifetimes did not allow achieving low exciton temperatures. An indirect exciton in a coupled QW structure is composed of an electron and a hole in separate wells, resulting in long enough lifetimes for the indirect excitons to cool below the temperature of quantum degeneracy. This gives an opportunity to experimentally probe cold composite bosons and e-h systems in high magnetic fields.
Here, we present spatially- and spectrally-resolved measurements of indirect excitons at temperature *T*bath = 40 mK and magnetic fields *B* = 0ī 10 T perpendicular to the CQW plane. The density of e-h system is controlled by the laser excitation, which allows realizing virtually any Landau level filling factor, ranging from fractional **з** < 1 to high **з**, when several electron and hole Landau levels are occupied, even at fixed magnetic field. We probed indirect excitons formed from electrons and holes at zeroth, first, and second Landau level: 0_eī 0_h, 1_eī 1_h, and 2_eī 2_h indirect magnetoexcitons.

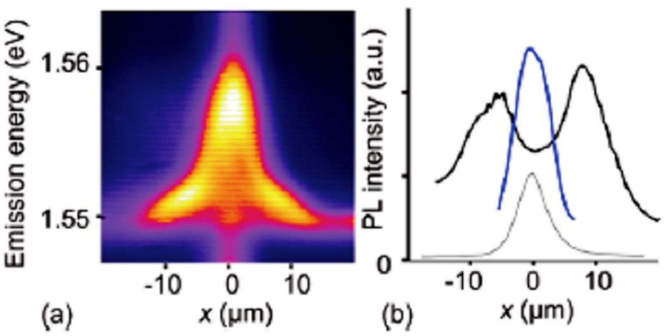

Fig.1: (a) *x*ī energy emission pattern of indirect magnetoexcitons. (b) Emission intensity of 0_eī 0_h (black) and 1_eī 1_h (blue) Landau level transitions. Excitation spot is shown in grey. T_{bath}=40 mK, *B* = 3 T.

Figure 1 presents a measured *x*ī energy emission pattern (a). The highand low-energy lines correspond to the 1_eī 1_h and 0_eī 0_h transitions, respectively. Indirect magnetoexcitons travel from the area of laser excitation (x = 0): The emission extends well beyond the excitation spot. The 0_eī 0_h emission shows a ring structure around the excitation spot (Fig.1b) similar to the inner ring [2]. In contrast, the spatial profile of 1_eī 1_h emission has a bell-like shape with the spatial width slightly larger than that of the laser excitation profile (Fig.1b), showing that the high-energy 1_eī 1_h states are filled near the excitation spot region where the temperature and density are maximum. Magnetoexcitons in single QWs are essentially noninteracting particles, and their energy practically does not depend on density [1]. In contrast, indirect magnetoexcitons have a built-in dipole moment ~ *ed* (*d* is the separation between the QW centers) and are characterized by repulsive dipole-dipole interaction. We observed correlations for indirect excitons in high magnetic fields revealed in the magnetoexciton energy variations.

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OPTICALLY CONTROLLED EXCITONIC TRANSISTOR

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Indirect exciton transport in coupled semiconductor quantum wells (CQW) is appealing for potential applications as alternative approach of charged particles transport in semiconductors. In spite of the fact that excitons are bosons, they repel each other since their dipole moments are aligned along the structure growth axis, which allows one to manipulate their propagation along the quantum well layers by means of optical excitation of the sample in different spots with subsequent formation of potential hills. The more powerful method of manipulation of the indirect exciton transport is using so called potential ramps, which are, in simplest case, the electrodes placed on the sample surface in shape of a stripe narrowing with the coordinate along the stripe with a constant potential applied to the electrode.

In this report, we present experimental implementation of the idea of optically controllable crossed-ramp excitonic device. This excitonic device demonstrates experimental proof of principle for all-optical excitonic transistors with a high ratio between the excitonic signal at the optical drain and the excitonic signal due to the optical gate [1]. The device also demonstrates experimental proof of principle for all-optical excitonic routers.

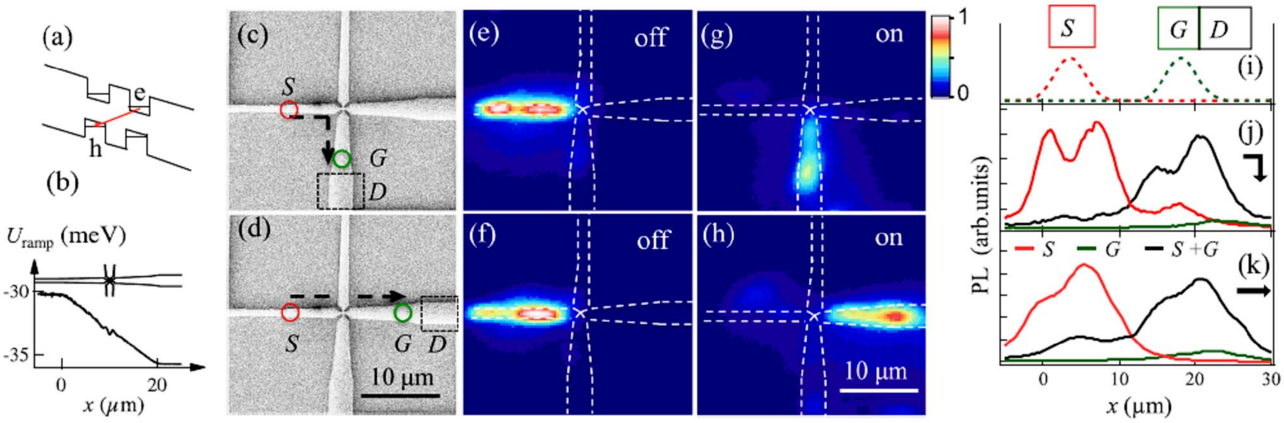

Figure. The principle and demonstration of working excitonic transistor.

The Figure represents the principle of excitonic transistor work. Scheme (a) shows the formation of indirect exciton in CQW structure at application of a bias voltage. Graph (b) reflects the calculated potential distribution along the ramp region. Figures (c) and (d) are the SEM images of the device with schematic indication of Source (*S*), Gate (*G*) and Drain (*D*) regions as well as two directions of indirect exciton flow. Figures (e)-(h) are spatial micro-PL intensity graphs demonstrating the functioning of transistor in two regimes with different flow directions. Graphs (i)-(k) are measured PL intensity profiles along the exciton flow paths for different sequences of Source and Gate optical signals.

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ZERO-POINT ENERGY OF BOSONIC COLLECTIVE EXCITATIONS IN THE BCS-BEC CROSSOVER

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We study zero-temperature quantum fluctuations of a three-dimensional superfluid made of ultracold alkali-metal atoms in the BCS-BEC crossover [1]. In particular, we analyze the zero-pointenergy of bosonic collective excitations, which is crucial to obtain a reliable equation of state in the BEC regime. These bosonic elementary excitations are obtained with a low-momentum expansion up to the forth order of the quadratic (Gaussian) action of the fluctuating pairing field [2]. By performing a meaningful cutoff regularization [3] we find that the scattering length a_B of composite bosons, bound states of fermionic pairs, is given by a_B=(2/3)a_F, where a_F is the scattering length of fermions.

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MAGNETO-LUMINESCENCE STUDY OF THE INTER-LAYER INTERACTIONS OF ELECTRON BILAYER

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The aim of this poster is to present our recent magneto-luminescence results in electron bilayers made of GaAs/AlGaAs in the quantum hall regime To this end, two samples with and without a tunneling gap were tested under low power illumination with a tunable near-infrared laser beam (Ti/Sa). In a sample with a small tunneling gap, the magneto-optical emission from the lowest asymmetric subband, which is not populated in a single electron picture, displays maxima at filling factor 1 and 2/3. These findings reveal a loss of pseudospin polarization that indicates an anomalous population of the antisymmetric level due to excitonic correlations. In addition, the emission from the sample without tunneling gap under simultaneous illumination with a Tis/Sa and an He/Ne beam reveald an additional line which becomes predominant by increasing the He/Ne laser power and has a quadratic dependence on the magnetic field implying an excitonic behavior.The results demonstrate a new realm to probe the impact of inter-layer Coulomb interaction in quantum hall bilayers.

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BIAS CONTROLLED BISTABILITY IN DIPOLE ORIENTED POLARITON SYSTEM

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We introduce nonlinear properties of dipole oriented polaritons through bias controlled bistability measurements in specially prepared microcavity structures fabricated to allow transmission measurements while biased. This electrically induced bistability is a very promising candidate for switching applications [1]. Also we observed effect of the degree of polariton dipole orientation on the strength of nonlinearities observed in bistability measurements as well as their spin dependent properties. The p-i-n microcavity diode structure consists of two DBRs forming a cavity and 4 sets of InGaAs asymmetric double quantum wells with 4nm barrier layer positioned at the antinodes of the electric field inside the cavity. When we apply the electric field on such type of structure, the electrons levels of neighbouring QWs can come into resonance [2]. Under these condition the spatially direct and indirect exciton become coupled sharing oscillator strength and providing strong dipole moment in the growth direction. The energies of the transmission maxima as functions of exciton-photon detuning on varying the temperature have been shown in figure (a). To map out polariton dispersions, transmission measurements using white light are performed at 170K. Figure (b) shows clear anti-crossing behaviour between DX, IX and cavity modes when tuning the bias. In Figure (c) bistability measurements are performed when pumping at 1.3908eV with near resonant laser under application of electric bias. Strong dependence of bistable behaviour on the degree of dipole orientation as well as pump polarization is found indicating that nonlinearities can be tuned on demand in this system.

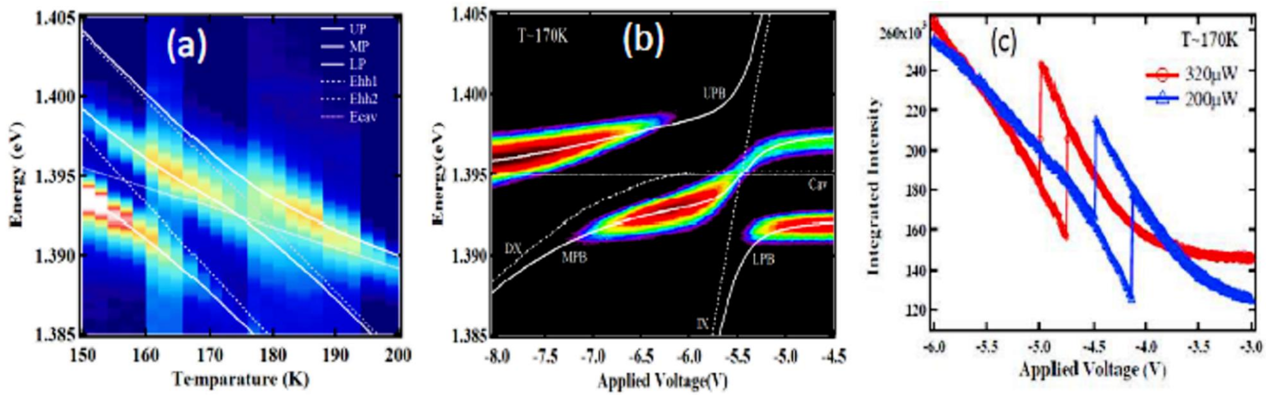

Fig.: (a) Transmission vs temperature (b) Polariton branches under application of bias close to the resonance in transmission configuration for a mesa with 4nm barrier layer showing clear anticrossing at 170K. (c) Bias controlled bistability at different power shown in figure.

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TOWARDS THE OPTICAL STUDY OF ELECTRICALLY GENERATED ELECTRON-HOLE BILAYER SYSTEMS

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The sustained improvement in semiconductor growth techniques over the past 30 years has allowed electrons and holes to be confined in spaces so thin that they can be considered to be quasi two-dimensional systems.

An interesting and more complex possibility arises when electrons and holes are confined in two adjacent GaAs /AlGaAs quantum wells kept apart by distance of few nanometres so that particle recombination is hindered by the presence of a potential barrier. These systems are commonly known as electron-hole bilayers.

The behaviour of the particles in such systems is the product of the relative contributions of inter-layer and intra-layer Coulomb interactions. In particular, when the distance between the layers is comparable to the average separation between particles in the same layer, intriguing phenomena have been predicted to emerge that cannot be observed in an isolated layer, like a supersolid Wigner crystal [1], an excitonic superfluid phase of indirect excitons [2] with a BEC to BCS crossover [3].

Electrically generated and independently contacted electron-hole bilayers have been intensively studied in the recent past, with a particular focus on electron transport measurements, as the Coulomb drag technique, used to directly probe the inter-layer interactions [3,4].

Here, a novel approach is presented: electron-hole bilayers that are electrically generated by means of optically semi-transparent inducing gates: the light is allowed to access the bilayer for characterising optical measurements like photoluminescence and inelastic scattering. Initial results and the future perspectives are presented.

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EXCITON SPIN NOISE IN QUANTUM WELLS

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Spin noise spectroscopy was suggested in 1980s to study magnetic resonance in atomic gases by all-optical means, namely by measuring fluctuation spectra of Faraday/Kerr rotation of weak non-resonant probe beam. The later studies demonstrated that this technique allows one to determine the parameters of spin dynamics such as g-factors, spin relaxation rates and nuclear fields distribution in solids. By now the rapid development of experimental techniques of optical spin detection in semiconductors and semiconductor nanostructures has made the spin noise spectroscopy one of the most popular and promising methods of spin dynamics studies [1,2].

Nowadays the studies of spin dynamics in non-equilibrium conditions attracts the special interest of both experimentalists and theorists. In this regard, the spin noise spectra of excitons can be especially interesting because these particles do not exist without pumping, while their spin dynamics are quite rich, particularly, owing to an interplay of optically active and inactive states [3]. The goal of this work is to develop a microscopic theory of direct and indirect exciton spin fluctuations taking into account short range exchange interaction between electrons and holes in quantum wells and the strong external magnetic field applied in the Voigt geometry.

We have shown that the spin noise spectrum consists of three contributions: electron spin noise, hole spin noise and the correlation noise of electron and hole in the exciton. The interplay of exchange splitting between dark and bright excitonic states and the Zeeman splitting of electron spin levels in the magnetic field determines the shape of the spin noise spectrum. In general case the spectrum consists (for positive frequencies) of two peaks. One of them is centred at zero frequency and gets suppressed with the increase of magnetic field. The second peak gradually appears at the frequency corresponding to the bright-dark excitonic splitting and then shifts towards the Larmor precession frequency in relatively strong magnetic fields. For the spatially indirect excitons, the spin noise spectrum has the similar two peaks structure, but in this case the crosscorrelation between electron and hole spins can be neglected. The peak at zero frequency is related with the hole spin fluctuations, while the other one corresponds to the electron spin precession in transverse magnetic field. The numerical calculations of the spin noise spectra are well described by simple analytical asymptotics. Strong sensitivity of the spin noise to the exchange interaction, magnetic field and relaxation times in the system is demonstrated, enabling one to obtain these parameters from the excitonic spin noise spectra.

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STRONG EXCITON-PHOTON COUPLING IN ORGANIC MICROCAVITIES

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The study of the strong coupling regime between excitons and cavity photons is both of fundamental and applied interest. Due to the low mass of the exciton-polaritons (~10^{-5} m_e) [1], the observation of Bose-Einstein condensation (BEC) [2] becomes possible at temperatures which can be obtained by standard cryogenic techniques. They are thermally limited in common inorganics by the low Wannier-Mott exciton binding energy which causes them to break up at elevated temperatures. In organics, in contrast, the excitons are more localized and form Frenkel excitons with strong binding energies leading to a persistence of the BEC up to room temperature [3]. Polariton lasers have great potential on the photonic market due to their very low lasing thresholds. Organic polariton lasers [4] are in this regard of considerable interest as they combine simple and low cost fabrication with ambient operation temperatures. However, a crucial requirement for commercial use is the possibility to pump the polariton devices electrically, which has so far only been achieved in InGaAs quantum wells [5], but not yet in organic microcavities.

Our aim is to take steps in that direction. For that, we are studying the strong coupling regime in different organic materials with high quantum yields, dioctyl-substituted polyfluorene (PF8) and poly[2,5-bis(2N,5N-bis(2n-ethyl-hexyloxy)phenyl)-p-phenylene vinylene] (BBEHP-PPV). Both materials emit in the blue spectral region. The microcavities are formed by dielectric (SiO2/HfO2) as well as thermally evaporated Al mirrors. While the dielectric mirrors lead to higher finesse of the cavities, the Al mirrors could simultaneously be used as a contact [6]. Since the organic materials are sensitive to heat and thus to each fabrication process after spin-coating the organic films, investigations on the lamination of microcavities are carried out. The different cavities and fabrication processes are analyzed by reflectometry and photoluminescence measurements. The results of the characterization are then compared to transfer matrix calculations. This enables on the one hand the screening of the fabricated samples, on the other hand a theoretical estimation of optimized cavities.

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SPIN TRANSFER TORQUE WITH EXCITONS

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The phenomenon of spin transfer torque (STT) between a small ferromagnetic (FM) domain and a spin-polarized current plays a crucial role in spintronics. In this work we investigate theoretically the effect of STT induced by a flow of spin-polarized quasiparticles though a thin ferromagnetic layer when the ground state is a Bose-Einstein condensate of excitons.

We consider a one dimensional scattering model with mirror symmetry which consists of a thin ferromagnetic layer sandwiched between two semiconductors (SC). The semiconductors are treated within a two-band model in the effective mass approximation. The thin ferromagnetic layer acts as a spin-dependent scattering center for the quasiparticles, which are the elementary excitations of the excitonic ground state. Excitons are indeed continuously created through irradiation by an external laser in a steady state regime.

By considering elastic scattering at equilibrium and matching the wave functions across the SC-FM junction, we work out the scattering matrix and compute the STT. We find a sharp dependence of the STT on the quasiparticle energy, which is a peculiar coherence effect of the exciton condensate. This behavior could be useful for spintronics applications.

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