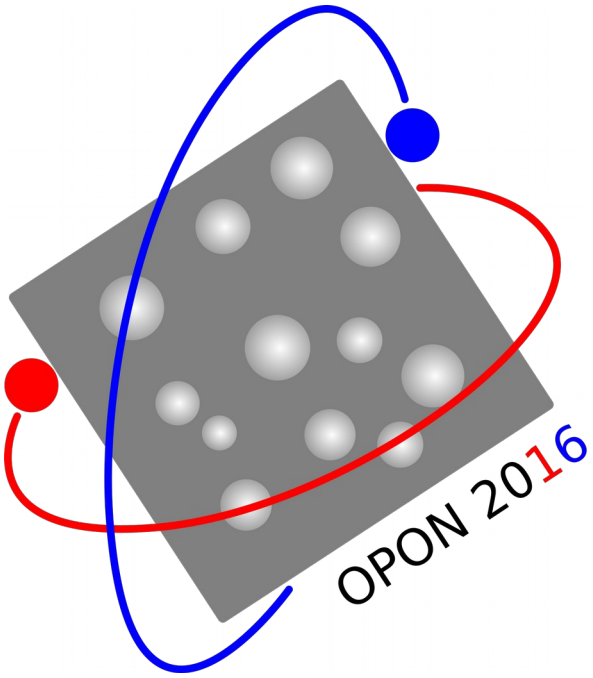
4TH INTERNATIONAL WORKSHOP

ON THE

OPTICAL PROPERTIES OF NANOSTRUCTURES

Wrocław, 17-19.02.2016



Program and abstracts

Dear Colleagues,

In 2011 we initiated a series of workshops on the optical properties of nanostructures. The first three events (initially under the name of *Polish-German Workshops*) were organized in Wrocław, Münster (2012) and Bayreuth (2013). From the beginning, the idea behind these topically focused workshops was to provide a forum for the exchange of ideas related to theoretical and experimental work in the field of optical properties of nanostructures and related solid state systems. The workshops have provided an opportunity to discuss and analyze current probems in nanostructure research, to strengthen existing collaborations and create new scientific links, and to help researchers (and students) to keep track of current developments in a relatively narrow field of solid state physics.

All three previous workshops were extremely successful, with nearly 100% acceptance rate by the invited speakers and with very high participation of students and young scientists. This has convinced us that there is high demand for such a topically focused, short scientific event, where senior researchers can exchange ideas and look for collaboration opportunities, while students and post-docs can hear a series of excellent talks given by leading researchers in the field. At the same time, the group leaders would have an opportunity to assess and appreciate the potential of young researchers. In light of this, we decided to revive the series after some years of break and venture into organization of the 4th workshop on the same topic.

The detailed scope of the workshop has evolved, following the research interests of our community. For instance, the growing number of presentations on photonic structures and the broad coverage of plasmonics-related topics show the technological and experimental progress achieved since our previous workshops and the corresponding shift of theoretical interests. Nonetheless, the idea of the workshop remains the same: a topically focused, compact, two-and-a-half-day event with a good balance of invited and contributed talks and an opportunity to present the whole scope of activities of each research group in the form of posters, in most cases presented by PhD and MSc students.

We would like to thank you for your participation in the workshop and wish you a good time in Wrocław and many fruitful discussions during the workshop.

The Program Committee:
Vollrath Martin Axt,
Tilmann Kuhn,
Paweł Machnikowski,
Jan Misiewicz.

The Workshop is co-organized by the Departments of Theoretical and Experimental Physics and the Centre for Advanced Materials and Nanotechnology of Wrocław University of Technology in collaboration with the Institute for Solid State Theory, University of Münster, and Institute for Theoretical Physics III, University of Bayreuth.

PRACTICAL INFORMATION

The workshop will take place at the Conference Centre of Wrocław University of Technology (building D-20).

The poster session will be held on Thursday afternoon. The poster space is located directly outside the conference hall. We invite presenting authors to display posters on the first day of the conference in the morning. We kindly ask participants displaying posters to remove them at the end of the conference on Friday.

Lunches and coffee breaks are provided free of charge during the three days for all the participants of the workshop. Lunches will be served at the university canteen in the "Students' Culture Zone" (*Strefa Kultury Studenckiej*, building C-18). Coffee breaks will be organized in the space adjacent to the conference hall (near the poster space).

A bus will be provided to take participants from the Tumski Hotel to the University each morning and back to the hotel after the last session of the day (and after lunch on Friday).

The members of the local groups will be happy to help you if you encounter any problem. Those particularly responsible for the organization of the workshop can be recognized by the color of their conference badges.

The Organizing Committee:
Paweł Machnikowski,
Katarzyna Roszak,
Krzysztof Ryczko.

WORKSHOP PROGRAM

Wednesday, February 17th

9:00-9:15 Opening

Session We-1: Two-dimensional systems and the quantum Hall effect

9:15-9:45 R. Bratschitsch,
Atomically thin semiconductors light up

9:45-10:00 J. Jadczak, D. Dumcenco, Y. S. Huang, Y. C. Lin, K. Suenaga, J. Kutrowska, A. Wójs, P. Sitarek, L. Bryja,
Composition dependence of lattice dynamics and photoluminescence emission in two dimensional $MoS_{2x}Se_{2(1-x)}$ alloys

10:00-10:30 A. Wójs, A. C. Balram, U. Wurstbauer, A. Pinczuk, J. K. Jain,
Detection of fractional skyrmions in Raman studies of quantum Hall systems

10:30-11:00 B. Szafran, S. Heun, K. Kolasiński, A. Mreńca-Kolasińska,
Aharonov–Bohm interferometers: scanning probe microscopy and magnetic forces

11:00-11:30 Coffee break

Session We-2: Harnessing light-matter coupling: plasmons

11:30-12:00 X. Wu, P. Jiang, H. Zhang, M. Pfeiffer, K. Lindfors, M. Lippitz, A. Rastelli, O. G. Schmidt,
Single quantum emitters for plasmonics

12:00-12:30 O. Hess,
Ultrafast and quantum dynamics of plasmonic stopped–light nanolasing

12:30-13:00 A. Vagov, I. A. Larkin, M. D. Croitoru, K. Keil, V. M. Axt,
Impact of spatial non–locality and Landau damping on the dynamics of a quantum dot coupled to surface plasmons

13:00-13:15 D. Knebl, A. Hörl, A. Trügler, J. Kern, J. R. Krenn, P. Puschnig, U. Hohenester,
Gap plasmonics of metallic nanoparticle dimers

13:15-15:00 Lunch

Session We-3: Harnessing light-matter coupling: plasmons and polaritons

15:00-15:30 U. Hohenester,
Probing particle plasmons with electrons

15:30-15:45 J. Kern, A. Trügler, I. Niehues, J. Ewering, R. Schmidt, R. Schneider, S. Najmaei, A. George, J. Zhang, J. Lou, U. Hohenester, S. Michaelis de Vasconcellos, R. Bratschitsch,
Nanoantenna–enhanced photoluminescence of atomically thin WS_2

15:45-16:00 J.-G. Rousset, M. Król, R. Mirek, K. Lekenta, J. Szczytko, M. Nawrocki, B. Piętka, W. Pacuski,
Semimagnetic microcavity polaritons

16:00-16:15 M. Pieczarka, M. Syperek, Ł. Dusanowski, J. Misiewicz, F. Langer, M. Kamp, Ch. Schneider, S. Höfling, A. V. Kavokin, G. Sęk,
Collective excitations of a polariton condensate under incoherent pumping

16:15-16:45 Coffee break

Session We-4: Carrier states in quantum dots and dashes

16:45-17:15 J. Finley,
Electron spin and orbital dynamics in individual quantum dots and molecules

17:15-17:45 G. Sęk,
Exploring the application–relevant properties of InAs–InP epitaxial nanostructures

17:45-18:00 C. Dicken, C. Wolpert, K. Lindfors, H. Schweizer, M. Lippitz, L. Wang, P. A. Atkinson, A. Rastelli, O. G. Schmidt, R. Singh, G. Bester,
Ultrafast DC Stark switching of a single quantum dot

18:00-18:15 I. D'Amico,
Introduction to COST Action MP1403 NANOSCALE QUANTUM OPTICS

Thursday, February 18th

Session Thu-1: Excitons (large and small) in various dimensions

9:00-9:30 M. Bayer,
Rydberg excitons in cuprous oxide

9:30-10:00 D. E. Reiter,
Optical control of the dark exciton in a semiconductor quantum dot

10:00-10:15 M. Syperek, Ł. Dusanowski, J. Misiewicz, A. Somers, J. P. Reithmaier, S. Höfling, G. Sęk,
Exciton spin relaxation in InAs/InP(001) quantum dashes emitting at 1.55 μm

10:15-10:30 D. Wigger, Q. Mermillod, V. Delmonte, D. E. Reiter, C. Schneider, M. Kamp, S. Höfling, W. Langbein, T. Kuhn, G. Nogues, J. Kasprzak,
Dynamics of four–wave mixing signals from excitons in single quantum dots

10:30-10:45 L. Bryja, J. Jadczak, K. Ryczko, M. Kubisa, A. Wójs, M. Potemski, F. Liu, D. R. Yakovlev, M. Bayer, C. A. Nicoll, I. Farrer, D. A. Ritchie,
Investigations of charged exciton localization in magneto-photoluminescence experiments in $GaAs/Al_xGa_{1-x}As$ quantum wells

10:45-11:00 K. Gawarecki, P. Machnikowski,
Modeling of exciton states in double quantum dots in magnetic field

11:00-11:30 Coffee break

Session Thu-2: Spin dynamics

11:30-12:00 P. Kossacki, T. Smoleński, J. Kobak, M. Goryca, A. Bogucki, M. Koperski, J.-G. Rousset, J. Suffczyński, M. Nawrocki, A. Golnik, W. Pacuski,
Spin manipulation of a single magnetic ion in a quantum dot

12:00-12:30 M. P. Estarellas, I. D'Amico, T. P. Spiller,
Topologically protected localised states in spin chains

12:30-12:45 T. Smoleński, T. Kazimierczuk, J. Kobak, M. Goryca, A. Golnik, P. Kossacki, W. Pacuski,
Magnetic ground state of an individual Fe^{2+} ion in a strained semiconductor nanostructure

12:45-13:00 J. Debus, T. S. Shamirzaev, D. Dunker, V. F. Sapega, D. R. Yakovlev, M. Bayer,
Spin properties of the indirect exciton in indirect band–gap (In,Al)As/AlAs quantum dot ensembles

13:00-13:15 M. Cygorek, F. Ungar, P. I. Tamborenea, V. M. Axt,
Quantum kinetic spin dynamics in intrinsic diluted magnetic semiconductors

13:15-15:00 Lunch

Session Thu-3: Harnessing light-matter coupling: quantum dots and photonic structures

15:00-15:30 V. Savona,
Automated optimization of photonic crystals for broadband slow light and ultra–high–Q cavities

15:30-16:00 J. Kasprzak,
Coherence of individual emitters in photonic nanostructures

16:00-16:15 A. Pusch, M. Yoshida, N. P. Hylton, A. Steiner-Vaquero, O. J. Curtin, C. C. Phillips, N. J. Ekins-Daukes, O. Hess,
The photon ratchet intermediate band solar cell: using nanostructures to improve efficiency

16:15-16:30 A. Musiał, C. Hopfmann, M. Strauß, A. M. Barth, M. Glässl, A. Vagov, M. Strauß, C. Schneider, S. Höfling, M. Kamp, V. M. Axt, S. Reitzenstein,
Temperature–stable strong light–matter coupling in the solid state with quantum dot–micropillars

16:30-16:45 M. Holtkemper, D. E. Reiter, G. F. Quinteiro, T. Kuhn,
The role of Coulomb interaction and band mixing on twisted light absorption in semiconductor quantum dots

16:45-17:00 Coffee break

17:00-19:00 Poster session

Friday, February 19th

Session Fri-1: Harnessing light-matter coupling: photonic structures

9:00-9:30 S. Unsleber, Y.-M. He, S. Maier, S. Gerhardt, X. Ding, C.-Y. Lu, J.-W. Pan, M. Kamp, C. Schneider, S. Höfling,
On–demand indistinguishable photons generated by pulsed fluorescence from quantum dot–micropillar systems

9:30-10:00 M. Gschrey, A. Thoma, P. Schnauber, A. Kaganskiy, R. Schmidt, B. Wohlfeil, M. Seifried, J.-H. Schulze, S. Burger, F. Schmidt, A. Carmele, A. Knorr, A. Strittmatter, T. Heindel, S. Rodt, S. Reitzenstein,
Quantum dot microlenses: building blocks for quantum communication networks

10:00-10:15 P. Stepanov, A. Delga, N. Gregersen, E. Peinke, M. Munsch, J. Tessier, J. Mork, M. Richard, J. Bleuse, J.-M. Gérard, J. Claudon,
Gaussian and directive emission of giant photonic trumpets

10:15-10:45 Coffee break

Session Fri-2: Fundamental quantum physics and quantum information

10:45-11:15 P. Horodecki,
From broadcasting of information to emergence of objectivity from quanta

11:15-11:30 K. Roszak, Ł. Cywiński,
Characterization and measurement of qubit–environment entanglement generation during pure dephasing

11:30-11:45 K. Korzekwa, M. Lostaglio, D. Jennings, T. Rudolph,
Quantum coherence, time–translation symmetry and thermodynamics

11:45-12:00 P. Szańkowski, M. Trippenbach, Ł. Cywiński,
Spectroscopy of cross–correlations of environmental noises with two qubits

12:00-12:15 J. Tuziemski, J. Korbicz,
Emergence of classical features in Quantum Brownian Motion

12:15-12:30 Closing

12:30-14:15 Lunch

Poster Session (Thursday)

P01 S. Lüker, D. E. Reiter, T. Kuhn,
Phonon–impact on the preparation of dark excitons in a quantum dot

P02 T. Smoleński, T. Kazimierczuk, M. Goryca, M. Koperski, P. Wojnar, A. Golnik, P. Kossacki,
P–shell exciton complexes with neutral–exciton–like exchange interaction in CdTe/ZnTe quantum dots

P03 T. Smoleński, M. Goryca, T. Kazimierczuk, P. Wojnar, P. Kossacki,
Mechanism and dynamics of biexciton formation from a long–lived dark exciton in a CdTe quantum dot

P04 M. Ściesiek, J. Suffczyński, W. Pacuski, J.-G. Rousset, M. Parlińska-Wojtan, A. Golnik,
Design, growth and spectroscopy of coupled ZnTe planar optical microcavities

P05 A. Musiał, B. Wohlfeil, S. Burger, T. Heuser, A. Kaganskiy, E. Y. Tauscher, R. Schmidt, S. Rodt, S. Reitzenstein,
Circular Bragg grating cavity design for efficient sources of single photons fabricated within a deterministic technology platform

P06 A. Henrykowski, W. Jacak,
Size dependence and spatial range of plasmon effect in photovoltaics – theory and experiment

P07 K. Kluczyk, W. Jacak,
Surface plasmon resonance in metallic nano–particles: comparison of RPA, FEM calculations and Mie theory

P08 R. Kerber, J. Fitzgerald, S. S. Oh, O. Hess, T. Kuhn, D. E. Reiter,
Simulation of electric field patterns modified by metallic nanoantennas

P09 K. Gwóźdź, E. Płaczek-Popko, Z. Gumienny, E. Zielony, R. Pietruszka, B. S. Witkowski, K. Kopalko, M. Godlewski,
Recombination losses in n–ZnO nanorods/p–Si plasmonic solar cells

P10 S. Guazzotti, A. Pusch, D. E. Reiter, O. Hess,
Intensity dependence of the third harmonic generation from a semiconductor quantum well

P11 J. Rautert, J. Debus, D. Braukmann, V. Yu. Ivanov, D. R. Yakovlev, G. Karczewski, T. Wojtowicz, M. Bayer,
Impact of the dynamically tuned 2DEG density on the photoluminescence of CdTe and CdMnTe quantum wells

P12 M. P. Polak, P. Scharoch, R. Kudrawiec,
Bismuth diluted III–V semiconductor materials for quantum well based optoelectronic devices

P13 A. Bogucki, M. Goryca, K. Oreszczuk, T. Smoleński, J. Kobak, W. Pacuski, P. Kossacki,
Spin relaxation studies of an individual Co^{2+} ion in a CdTe/ZnTe quantum dot

P14 A. Mielnik–Pyszczorski, K. Gawarecki, P. Machnikowski,
Charge and spin injection in a quantum well–quantum dot system

P15 M. Gawełczyk, P. Machnikowski,
Spin dynamics and magneto–optical response in charge-neutral tunnel–coupled quantum dots

P16 F. Ungar, M. Cygorek, P. I. Tamborenea, V. M. Axt,
Competition between exchange interaction and spin–orbit coupling in the spin dynamics of paramagnetic II–VI diluted magnetic semiconductors

P17 M. Krzykowski, M. Gawełczyk, P. Machnikowski,
Hole spin dynamics in coupled quantum dots

P18 I. Bragar, Ł. Cywiński,
Dynamics of entanglement between two singlet–triplet qubits: role of nuclear spin baths and charge noise

P19 J. Kutrowska, J. Jadczak, E. Zdanowicz, P. Sitarek, Y. S. Huang, L. Bryja,
Optical control of charge carrier density in monolayer MoS_2 and WS_2

P20 M. Bieniek, T. Woźniak, P. Potasz, A. Wójs,
Electronic properties of 2–dimensional bilayer bismuth topological insulator

P21 M. Brzezińska, P. Potasz, A. Wójs,
Entanglement spectrum of a Chern insulator on the Lieb lattice

P22 P. Bugajny, P. Potasz, A. Wójs,
Analysis of symmetry in the graphene quantum dots

P23 B. Kuśmierz, A. Wójs,
Natural and reverse lexicographic order of partitions and fractional quantum Hall effect

P24 T. Woźniak, M. Bieniek, J. Jadczak, P. Scharoch, A. Wójs,
Ab initio studies of structural, electronic and dynamical properties of chosen group VI–B transition metal dichalcogenides systems

P25 A. Sitek, G. Thorgilsson, V. Gudmundsson, A. Manolescu,
Controllable properties of polygonal quantum rings

P26 P. Podemski, A. Maryński, M. Pieczarka, J. Misiewicz, A. Löffler, S. Höfling, S. Reitzenstein, G. Sęk,
Microphotolumienscence excitation spectroscopy on single $In_{0.3}Ga_{0.7}As/GaAs$ quantum dots

P27 A. Maryński, M. Syperek, J. Misiewicz, V. Liverini, M. Beck, J. Faist, G. Sęk,
Barrier layer dependence of the carrier dynamics in InAs/InP quantum dot structures

P28 P. Mrowiński, K. Tarnowski, J. Olszewski, W. Urbańczyk, P. Machnikowski, J. Misiewicz, A. Somers, J. P. Reithmaier, S. Höfling, G. Sęk,
Tailoring the polarization anisotropy of exciton emission from InAs/InGaAlAs quantum dashes

P29 Ł. Dusanowski, M. Syperek, J. Misiewicz, A. Somers, J. P. Reithmaier, S. Höfling, G. Sęk,
Temperature dependence of photon emission statistics and dynamics of a charged exciton in an InAs/InP quantum dash

P30 A. Crai, A. Pusch, D. E. Reiter, O. Hess,
Microscopic model of hot electron generation in a metal nanosphere

P31 A. M. Barth, S. Lüker, F. Ungar, S. Wolf, A. Vagov, V. M. Axt, D. E. Reiter, T. Kuhn,
The role of adiabatic undressing for fast phonon–assisted quantum dot state preparation

P32 S. Holzinger, E. Schlottmann, B. Lingnau, K. Lüdge, C. Schneider, M. Kamp, S. Höfling, J. Wolters, S. Reitzenstein,
Injection Locking in the Quantum Regime

P33 A. Vagov, A. A. Shanenko, S. Wolf, J. A. Aguiar, V. M. Axt,
Inter–type superconductivity in multi–band materials

P34 S. Wolf, A. Vagov, A. A. Shanenko, J. A. Aguiar, V. M. Axt,
Exotic vortex configurations in superconductors with deep and shallow bands

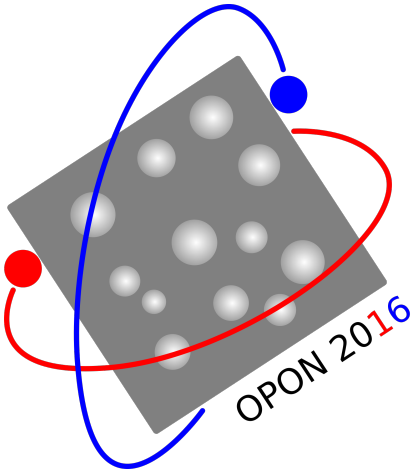
P35 K. Wittek, H. Mączko, M. P. Polak, M. Gładysiewicz, P. Scharoch,
Ab initio vs $k \cdot p$ $Ge_{(1-x)}Sn_{(x)}$ electronic structure for QW modelling

P36 P. Karwat, D. E. Reiter, T. Kuhn, O. Hess,
Thermal lasing in nanoscopic quantum systems

P37 D. Kwiatkowski, Ł. Cywiński,
Decoherence of an NV center coupled to a bath of ^{13}C nuclear spins

P38 E. Zielony, M. Morawski, E. Płaczek-Popko, Z. Gumienny, S. Chusnutdinow, G. Karczewski,
Investigation of recombination centers in CdTe–based photodiodes

P39 K. M. Paradowska, E. Płaczek-Popko, M. A. Pietrzyk, A. Kozanecki,
Optical and electrical properties of ZnO–based structures for ultraviolet detection



WEDNESDAY

Atomically thin semiconductors light up

R. Bratschitsch

Institute of Physics and Center for Nanotechnology, University of Münster, 48149 Münster, Germany

Graphene is known as a prototypical two-dimensional material with unique physical properties. However, the difficulty of creating an optical band gap stimulated the search for other monolayer materials. In my talk I will show that atomically thin transition metal dichalcogenides serve as a promising new material class for opto-electronics [1,2] and quantum optics [3].

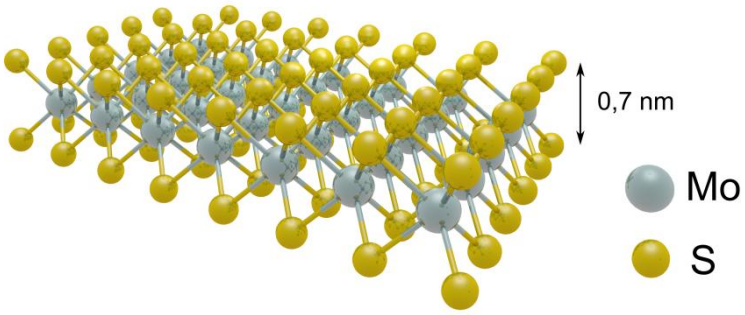


Fig. 1: Schematic drawing of a MoS_2 monolayer

[1] P. Tonndorf, R. Schmidt, P. Böttger, X. Zhang, J. Börner, A. Liebig, M. Albrecht, C. Kloc, O. Gordan, D. R. T. Zahn, S. Michaelis de Vasconcellos, and R. Bratschitsch, Opt. Expr. **21**, 4908 (2013).
[2] R. Bratschitsch, Nature Nanotech. **9**, 247 (2014).
[3] P. Tonndorf, R. Schmidt, R. Schneider, J. Kern, M. Buscema, G. A. Steele, A. Castellanos-Gomez, H. S. J. van der Zant, S. Michaelis de Vasconcellos, and R. Bratschitsch, Optica **2**, 347 (2015).

Composition dependence of lattice dynamics and photoluminescence emission in two dimensional $MoS_{2x}Se_{2(1–x)}$ alloys

J. Jadczak [1], D. Dumcenco [2,3], Y. S. Huang [2], Y. C. Lin [4], K. Suenaga [4], J. Kutrowska [1], A. Wójs [5], P. Sitarek [1], L. Bryja [1]

[1] *Department of Experimental Physics, Wrocław University of Technology, Wrocław, Poland*
[2] *Department of Electronic Engineering, NTUS&T, Taipei, Taiwan*
[3] *Electrical Engineering Institute, EPFL, CH-1015 Lausanne, Switzerland*
[4] *National Institute of Advanced Industrial Science and Technology, Tsukuba, Japan*
[5] *Department of Theoretical Physics, Wrocław University of Technology, Wrocław, Poland*

The mixed layered crystals allow continuous tunability of the optical band gap, rendering 2D transition metal dichalcogenide alloys appealing materials for electronic and optoelectronic device applications. Hence, characterization of these systems including understanding of the arrangement of substituting atoms in one or more layers has become fundamentally important.

We report on comparative Raman scattering studies of monolayer and bulk $MoS_{2x}Se_{2(1–x)}$. The single- and few-layer flakes of $MoS_{2x}Se_{2(1–x)}$ were obtained by mechanical exfoliation from bulk crystals grown by chemical vapor transport (CVT). Flakes with single-layer regions were identified using optical microscopy, atomic force microscopy (AFM) and subsequently by observation of strong photoluminescence (PL) in the broad range of temperatures from 6 K to 300 K.

The Raman spectra for bulk $MoS_{2x}Se_{2(1–x)}$ reveal two distinct sets of features related to the E^1_{2g} and A_{1g} modes of pure members of series [1]. As composition x changes, the in-plane E^1_{2g} mode shows a two-mode behavior, whereas the out-of-plane A_{1g} mode presents more complex evolution. When x slightly increases we can identify four Raman peaks in the range 200-280 cm^{-1}. They evolve in different manner as composition changes, and we divided them into two types related to different distribution of the chalcogenide atoms within the $MoS_{2x}Se_{2(1–x)}$ layers. The first type corresponds to the Se-Se case and originates at the frequency of $MoSe_2$-like A_{1g} mode. The second type at higher frequencies with regard to A_{1g} mode is related to the Se-S case. Among these we can identify at least three components, shifting to higher frequency upon increasing x. They are well resolved for $0.1 < x < 0.2$, when the $2Se_2$ + 1SeS, $2Se_2$ + $1S_2$ or $2Se_2$ +2SeS arrangements are the most probable. The frequencies of two modes corresponding to Se-S type are not significantly affected by reducing thickness down to a monolayer, suggesting that series of the Se-S modes are related to intralayer (rather than interlayer) interaction. The frequency of the Se-Se A_{1g} peak increases with increasing layer number by about 1.5 cm^{-1}.

At low temperatures the PL spectra consists of two peaks, well resolved for smaller sulfur composition (x). We attribute them to the exciton (X) and the trion (T). For $MoSe_2$, the PL spectrum is dominated by trion at low temperatures, which is quenched with increasing temperatures and becomes negligible compared to the exciton for T>120 K. When x slightly increases ($0.1 < x < 0.3$) the PL spectra start to be dominated by trion's contribution for wider range of temperatures up to 200 K.

[1] J. Jadczak et al., J. Appl. Phys. **116**, 193505 (2014).

Detection of fractional skyrmions in Raman studies of quantum Hall systems

Arkadiusz Wójs [1], A. C. Balram [2], U. Wurstbauer [3], A. Pinczuk [4], J. K. Jain [2]

[1] *Department of Theoretical Physics, Wrocław Univ. of Technology, 50-370 Wrocław, Poland*
[2] *Department of Physics, Pennsylvania State University, Pennsylvania 16802, USA*
[3] *Walter Schottky Institut, Technische Universität München, D-85748 Garching, Germany*
[4] *Department of Physics, Columbia University, New York 10027, USA*

We have combined resonant inelastic light scattering (RILS) experiments with the large-scale exact and composite-fermion diagonalization calculations to detect fractional skyrmions in the excitation spectrum of the $\nu=1/3$ ferromagnetic ground state of fractional quantum Hall effect (FQHE).

Understanding of FQHE involves variety of exotic emergent topological particles, such as fractionally charged Laughlin quasiparticles, composite fermions (CFs), nonabelian anyons, or Majorana fermions. In particular, formation of essentially free CFs from strongly correlated electrons (through binding of an even number of quantized vortices of the many-electron wave-function) underlies the incompressibility and the nature of excitation spectrum of all many known FQH ground states.

Skyrmions are remarkable topological vortex-like spin structures in the two-dimensional ferromagnets, connected through a stereographic projection with the hedgehog spin configuration on a sphere. Long known in the $\nu=1$ integer quantum Hall state of electrons, they have also been anticipated [1,2] in the same $\nu^*=1$ state of CFs, realized as the $\nu=1/3$ state of FQHE. However, while most of FQHE relies on the mere formation of CFs, the skyrmion dynamics crucially depends on the residual CF-CF interaction, which is different from e-e interaction and hence cannot guarantee stable FQH skyrmions based on the simple CF-electron mapping. Indeed, compared to electron skyrmions at $\nu=1$, fractionally charged CF skyrmions at $\nu=1/3$ were predicted to be much more fragile and suppressed by very small Zeeman energies.

We find theoretically/numerically that the minimal fractional skyrmions should exist in the excitation spectrum for a wide range of Zeeman energies slightly away from $\nu=1/3$, and present qualitative and quantitative evidence that the resonances we have detected in Raman scattering experiments just below the long wave length spin wave mode are precisely these fractional skyrmions [3]. The spectroscopy of these exotic bound states is a sensitive probe of the residual interaction between CFs, which is responsible for delicate new FQH states at nearby $\nu=3/8$, 4/11, or 5/13, and also contains information about the spin polarization of the ground state.

[1] R. Kamilla, X. Wu, J. Jain, Solid State Commun. **99**, 289 (1996).
[2] A. Wójs, J. J. Quinn, Phys. Rev. B **66**, 045323 (2002).
[3] A. C. Balram, U. Wurstbauer, A. Wójs, A. Pinczuk, J. K. Jain, Nature Commun. **6**, 8981 (2015)

Aharonov-Bohm interferometers: scanning probe microscopy and magnetic forces

B. Szafran[1], S. Heun[2], K. Kolasiński[1], A. Mreńca-Kolasińska[1,2]

[1]*Faculty of Physics and Applied Computer Science, AGH University of Science and Technology, al. Mickiewicza 30, 30-059 Kraków, Poland*
[2]*NEST, Istituto Nanoscienze-CNR and Scuola Normale Superiore, Piazza San Silvestro 12, 56127 Pisa, Italy*

Quantum rings as solid-state electron interferometers has been studied since the eighties, with new variants which are still being produced. The talk presents results of numerical simulations of the electron transport in ring-like structures and of the scanning gate microscopy. The role of the classical Lorentz force [1,2] in two-dimensional electron gas in GaAs as well as in n-p junctions defined in graphene will be discussed. The simulation results to be presented cover the magnetic deflection [1,2], evaluation of the effective tip potential [3], and conductance mapping of Aharonov-Bohm interferometers (etched rings [3], and quantum Hall islands [4] within quantum point contact constrictions). A proposal of electron interferometers induced by an external perturbation to a graphene nanoribbon with circular n-p junction electron waveguides in quantum Hall conditions will be presented [5].

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Single quantum emitters for plasmonics

Xiaofei Wu[1,2], Ping Jiang[1], Hongyi Zhang[2], Markus Pfeiffer[2,3], Klas Lindfors[2,3], Markus Lippitz[1,2], Armando Rastelli[4], Oliver G. Schmidt[4]

[1] *Experimental Physics III, University of Bayreuth, Germany*
[2] *Max Planck Institute for Solid State Research, Stuttgart, Germany*
[3] *Physical Chemistry, University of Cologne, Germany*
[4] *Institute for Integrative Nanosciences, IFW Dresden, Germany*

Plasmonics offers the opportunity of tailoring the interaction of light with single quantum emitters. However, the strong field localization of plasmons requires spatial fabrication accuracy far beyond what is required for other nanophotonic technologies. Furthermore, this accuracy has to be achieved across different fabrication processes to combine quantum emitters and plasmonics. We demonstrate [1] a solution to this critical problem by controlled positioning of plasmonic nanoantennas with an accuracy of 11 nm next to single self-assembled GaAs semiconductor quantum dots, whose position can be determined with nanometer precision. These dots do not suffer from blinking or bleaching or from random orientation of the transition dipole moment as colloidal nanocrystals do. Our method introduces flexible fabrication of arbitrary nanostructures coupled to single-photon sources in a controllable and scalable fashion.

We also demonstrate [2] efficient coupling of excitons in near-surface GaAs quantum dots (QDs) to surface-plasmon polaritons. We observe distinct changes in the photoluminescence of the emitters as the distance between the QDs and the gold interface decreases. Based on an electric point-dipole model, we identify the surface plasmon launching rates for different QD-surface distances. While in conventional far-field experiments only a few percent of the emitted photons can be collected due to the high refractive index semiconductor substrate, already for distances around 30 nm the plasmon launching-rate becomes comparable to the emission rate into bulk photon modes, thus much larger than the photon collection rate. For even smaller distances, the degrading optical properties of the emitter counterweight the increasing coupling efficiency to plasmonic modes

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Ultrafast and Quantum Dynamics of Plasmonic Stopped-Light Nanolasing

Ortwin Hess

The Blackett Laboratory, Department of Physics, Imperial College London,
Prince Consort Road, London SW7 2AZ, United Kingdom
E-mail: o.hess@imperial.ac.uk

In recent years lasers have become smaller and smaller, reaching with the demonstration of plasmonic nanolasing scales much smaller than the wavelength of the light they emit [1-4]. Such plasmonic nanolasers employ plasmonic resonances for feedback, allowing them to concentrate light into mode volumes that are no longer limited by diffraction. The use of localised surface plasmon resonances as cold-cavity modes, however, is only one route to lasing on subwavelength scales. Providing feedback by stopped-light singularities in the density of states we have recently been shown that stopped-light lasing that does no longer require a traditional cavity can be realised on subwavelength (nano-) scales [5].

Here, extending these stopped-light principles to surface plasmons, we demonstrate cavity-free surface-plasmon polariton amplification. Extensive full-time domain Maxwell–Bloch Langevin simulations in combination with (semi-) analytic theory show that in the absence of cavity-induced feedback a phase-locked superposition of quasi dispersion-free waveguide mode promotes the dynamic formation of a subwavelength lasing/spasing mode with a remarkably high in-coupling of (amplified) spontaneous emission. This demonstrates that applying the nanoplasmonic stopped-light lasing principle [5] to surface-plasmon polaritons (SPP) allows the realization of trapped/condensed nonequilibrium surface-plasmon polaritons at stopped-light singularities, providing an entry point to SPP-condensation [6], quantum gain in quantum plasmonics and quantum fluids of light. The talk will also show that this principle opens up a new platform for cavity-free ‘stopped-light’-quantum electro-dynamics with novel features such as bound states without geometrical confinement, linking free-space and ideal cavity QED.

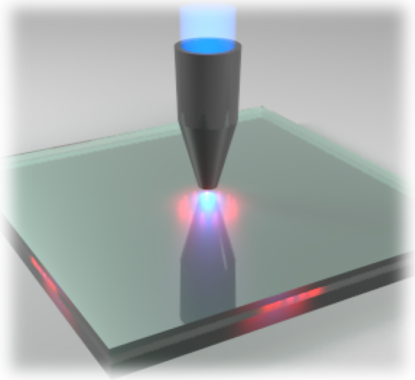

Figure: Subwavelength localised vortex-lasing in a gain-enhanced nano-plasmonic metal-dielectric-metal (MIM) heterostructure. Localised optical pumping excites in-plane sub-wavelength cavity-modes that self-localise at singularities of the density of states forming an optical near-field energy vortex as revealed by the Poynting vectors.

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Impact of spatial non-locality and Landau damping on the dynamics of a quantum dot coupled to surface plasmons

A. Vagov[1], I. A. Larkin[2,3], M. D. Croitoru[4], K. Keil[1], and V.M. Axt[1]

[1] *Institut für Theoretische Physik III, Universität Bayreuth, 95440 Bayreuth, Germany*
[2] *Department of Physics, Minho University, 4710-057, Braga, Portugal*
[3] *Institute of Microelectronics Technology Russian Academy of Sciences, 142432 Chernogolovka, Russia*
[4] *Departement Fysica, Universiteit Antwerpen, B-2020 Antwerpen, Belgium*

Unique properties of surface plasmon-polariton (SPP) excitations can be used in a variety of applications. Many of them utilize the possibility of a precise manipulation of the electromagnetic fields associated with SPP modes [1], which unlike conventional light waves resolve scales below the diffraction limit achieving both a considerable enhancement of the field intensity and a better control of its spatial distribution. The Achilles heel of such techniques is the weak coupling between SPP modes and external light. This can be remedied by introducing additional scatterers, for example strongly confined quantum dots. The analysis of the SPP modes in such systems and of the corresponding dynamics of quantum scatterers traditionally neglects the spatial dispersion of the dielectric permittivity of the metallic samples. This simplification is reasonable when the characteristic lengths of the system are much larger than the mean free path of the charge carriers in the metal. However, it fails in the most interesting case when the dot is placed very close to the metallic surface to achieve a strong coupling to the SPP modes [2,3].

We present a study of the dynamics of a quantum dot in the vicinity of a flat metallic surface. To describe SPP modes we use the non-local Lindhard dielectric response model modified for the half-space. This approach takes into account the Landau damping which is known to be an important relaxation mechanism in such systems [2,3]. The non-locality leads to strong modifications of the SPP modes. Particularly strong affected is the frequency dispersion. SPP excitations with large wave vectors have a linear dispersion with a finite group velocity and exhibit Landau-type damping. Both features lead to notable changes in the dynamics of the quantum dot which are characterized by two damping rates. The larger rate describes a fast decay of Rabi oscillations and the smaller one corresponds to a much slower monotonic relaxation. The time evolution is strongly dependent on the dot-SPP coupling controlled by the dot-surface distance. Within a certain range of parameters the decay of the Rabi oscillations slows down reflecting qualitative changes in the time evolution. The role of the non-locality for SPP modes is even more important when a metallic sample has finite dimensions. In order to illustrate this we consider a metallic slab of several nanometer width. The system has two types of SPP modes one of which reveals a negative group velocity in a finite interval of wave vectors that grows wider for thinner slabs. This leads to a number of interesting features in the propagation of SPP wave packets. The non-locality also leads to qualitative changes in the long-distance asymptote of the spatial decay of the electric field inside a metal further increasing the role of non-local interactions in finite samples.

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Gap plasmonics of metallic nanoparticle dimers

Dario Knebl[1], Anton Hörl[1], Andreas Trügler[1], Johannes Kern[2], Joachim R. Krenn[1], Peter Puschnig[1], and Ulrich Hohenester[1]

[1] *Institute of Physics, University of Graz, Universitätsplatz 5, 8010 Graz, Austria*
[2] *Institute of Physics and Center for Nanotechnology, University of Münster, 48149 Münster, Germany*

Gap plasmonics deals with surface plasmons (SPs) in narrow gap regions of coupled metallic nanoparticles. For sufficiently narrow gaps, electrons can tunnel directly from one nanoparticle to the other one, leading to the emergence of new charge transfer plasmons (CTPs). Molecular tunnel junctions enable tunneling over larger gap distances in the nanometer regime [1], and thus establish a novel platform for hybrid structures reconciling molecular electronics with plasmonics.

In this paper we theoretically investigate gap plasmons for two silver nanocubes coupled through a molecular tunnel junction, similar to the experiment of Ref. [1], using classical and quantum-corrected electrodynamic simulations. We find that in absence of tunneling, the red-shift of the bonding mode saturates with decreasing gap distance. Tunneling at small gap distances leads to a damping and slight blue-shift of the bonding mode, but no low-energy charge transfer plasmon mode appears in the spectra. This finding is in stark contrast to recent work of Tan et al [1]. We will argue why we believe that our results are valid within the model under consideration, and why a re-interpretation of the experiments might be needed [2].

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Probing particle plasmons with electrons

Ulrich Hohenester [1]

[1] *Institute of Physics, University of Graz, Universitätsplatz 5, 8010 Graz, Austria*

Electron energy loss spectroscopy (EELS) and microscopy allow probing of the evanescent fields of particle plasmons with nanometer resolution. In this talk I will first show how to efficiently simulate EELS signals with our recently developed MNPBEM toolbox [1], and will present results for the prototypical system of a silver nanodisk [2] as well as for a silver nanocube dimer whose geometry has been extracted using electron tomography [3].

I will then address the interpretation of EELS maps, which has led to some controversy in the literature. I will show how EELS can be rephrased in terms of a tomography problem [4] and how to extract the three-dimensional plasmon fields from a sinogram of EELS maps. I will discuss how the tomography scheme can be generalized for larger nanoparticles, where the quasistatic approximation fails, as well as for more complex particle geometries, and will demonstrate the applicability of our tomography scheme [4].

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Nanoantenna-enhanced photoluminescence of atomically thin WS_2

J. Kern[1], A. Trügler[2], I. Niehues[1], J. Ewering[1], R. Schmidt[1], R. Schneider[1], S. Najmaei[3], A. George[3], J. Zhang[3], J. Lou[3], U. Hohenester[2], S. Michaelis de Vasconcellos,[1] and R. Bratschitsch[1]

[1] Institute of Physics and Center for Nanotechnology, University of Münster, Germany
[2] Institute of Physics, University of Graz, Austria
[3] Department of Mechanical Engineering and Material Science, Rice University, Houston, USA

Atomically thin transition metal dichalcogenides (TMDCs) are promising two-dimensional materials for opto-electronic devices [1]. They absorb more than 10% of the light at their excitonic resonances and exhibit photoluminescence (PL) [2]. However, the PL quantum yield of ~10^{-3} is relatively low. Therefore, strategies are needed to optimize the light-matter interaction.

We present a hybrid system consisting of a single-crystalline plasmonic gold nanoantenna and an atomically thin tungsten disulphide (WS_2) layer [3] (Fig. 1a). In the electron micrograph (Fig. 1b) WS_2 monolayers appear dark. A bright horizontally/vertically aligned rod is marked by a dashed/solid white circle.

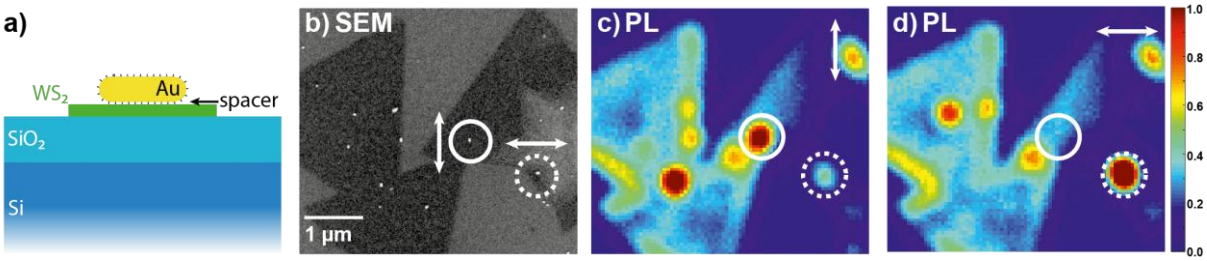

Fig 1. Nanoantenna-monolayer hybrid. a) Schematic drawing of the sample. b) Electron micrograph of monolayer WS_2 (dark) with gold nanoantennas on top (bright). c), d) Photoluminescence intensity maps of the region shown in b) with emission polarization indicated by arrows.

In Figure 1c and d PL intensity maps for excitation with circularly polarized light at a wavelength of 588 nm are presented, where the emission polarization is selected along the vertical or horizontal direction. Whereas the PL emission from the WS_2 monolayer alone shows no polarization dependence, a clear enhancement is observed at position of the metal nanoantennas. By matching both excitation and emission polarization an overall PL enhancement of up to 11 is observed. The fact that the PL intensity strongly depends on the excitation as well as the emission polarization indicates that both absorption and emission are increased. The enhancement is due to the optical near-field created by the longitudinal plasmon resonance of the nanoantenna.

The presented tailored hybrid nanoantenna-monolayer system lights the way to efficient photodetectors and conceptually new valleytronic devices based on 2D materials.

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Semimagnetic microcavity polaritons

J-G. Rousset, M. Król, R. Mirek, K. Lekenta, J. Szczytko, M. Nawrocki, B. Piętka, W. Pacuski

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, ul. Pasteura 5, PL-02-093 Warsaw, Poland

There is growing interest in investigation of magneto-optical and spin-related phenomena of microcavity polaritons [1-4]. However observation of such effects is limited due to small Zeeman splitting of non-magnetic semiconductors. Motivation of our work was to enhance magnetic effects by exploiting *s,p-d* exchange interaction between magnetic ions and exciton-polaritons in quantum well embedded in microcavity.

We designed and grew new Te based microcavities made of nonmagnetic DBRs and cavity embedding Mn doped quantum wells (QWs). All the layers of the structure are made of (Cd,Zn,Mg)Te lattice matched to MgTe, with various concentration of Mg allowing for a precise control of the optical properties and band gap of each layer (Fig. 1). The (Cd,Zn,Mn)Te QWs contain ≈1% Mn are lattice matched to the whole structure. In such a microcavity, we observe strong coupling and polariton lasing [5]. Application of magnetic field result in the giant Zeeman splitting of the cavity polaritons (Fig. 2), even larger than 5 meV which justifies the denomination of semimagnetic cavity polaritons. Owing to the dependence of the Hopfield coefficient, and hence the excitonic weight in the lower polariton, the amplitude of the giant Zeeman splitting depends on the detuning and the in-plane wave vector. This splitting is more than one order of magnitude larger than what is observed in III-V based structures (about 100 μeV, which is comparable to the linewidth of the polaritons).

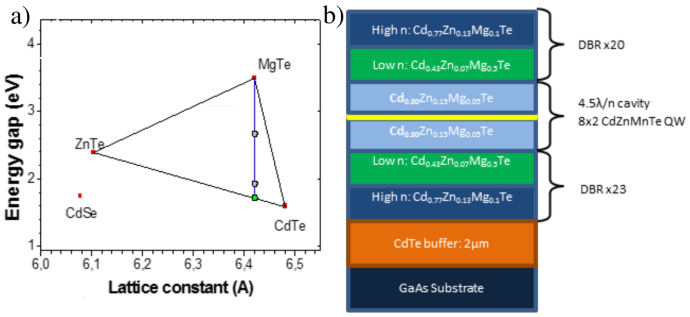

Fig. 1: Map showing the energy gap as a function of the lattice constant for chosen tellurides. Blue line: compounds lattice matched to MgTe. Grey points: (Cd,Zn,Mg)Te layers of the DBRs. Green point: (Cd,Zn,Mn)Te quantum well lattice matched to the whole structure. b) Example of a microcavity structure.

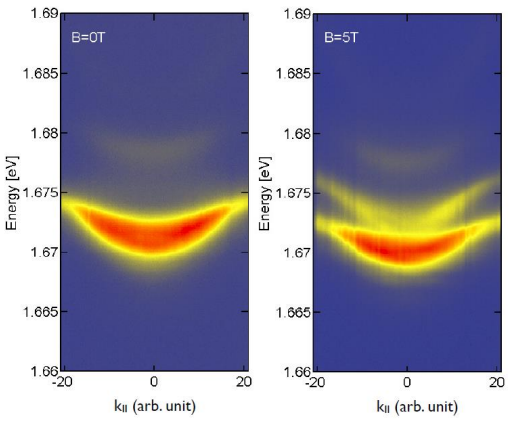

Fig. 2: Polariton dispersion in magnetic field (T=5K). For B=5T, the giant Zeeman splitting of the lower polariton is clearly visible.

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Collective excitations of a polariton condensate under incoherent pumping

M. Pieczarka [1], M. Syperek [1], Ł. Dusanowski [1], J. Misiewicz [1], F. Langer [2], M. Kamp [2], Ch. Schneider [2], S. Höfling [2,3], A. V. Kavokin [4,5], G. Sęk [1]

[1] *Laboratory for Optical Spectroscopy of Nanostructures, Department of Experimental Physics, Wrocław University of Technology, Wrocław, Poland*
[2] *Technische Physik, University of Würzburg and Wilhelm-Conrad-Röntgen-Research Center for Complex Material Systems (RCCM), Würzburg, Germany*
[3] *SUPA, School of Physics and Astronomy, University of St. Andrews, St. Andrews, UK*
[4] *Spin Optics Laboratory, Saint Petersburg State University, St Petersburg, Russia*
[5] *Physics and Astronomy School, University of Southampton, Southampton, UK*

Exciton-polaritons are composite bosonic quasiparticles arising from exciton-photon strong coupling in a semiconductor microcavity system. In a polariton condensate interactions between particles can result in parametric scattering processes, which occur to non-parabolic scattering bands, including normal branches (NB) and ghost branches (GBs), where the latter ones are populated by the virtual off-branch exciton-polaritons. The GB has been evidenced in a resonant excitation scheme in a complex geometry of four wave mixing [1]. However, since the work of Utsunomiya et al. [2], where the Bogoliubov-like dispersion of excitations in polariton condensates was detected in absence of signal from the GB, there were no further reports on full formation of two coupled Bogoliubov branches in a nonresonant photoluminescence (PL) experiment.

We present the observation of a PL signal of a spontaneously formed NB and GB in a polariton condensate [3]. We investigate the luminescence of a polariton gas excited nonresonantly with a pulsed laser focused to a diffraction limited spot. The studied sample is a GaAs-based microcavity containing low indium content quantum wells ($In_{0.3}Ga_{0.7}As$/GaAs), emitting in the near infra-red spectral range. Our excitation scheme provided a repulsive potential, forming a ballistic flow of polaritonic wave packets propagating outside the pump spot. Under a sufficient pump fluence we observe a distinct renormalization of a polariton momentum dispersion and record strong signal of virtual off-branch states, comparable in intensity to the signal originating from the thermally populated NB. This observation is verified in polarization-resolved measurements, were we explore the peculiar polarization nature of the two coupled branches, according to polarization selection rules in polariton-polariton scattering processes. Further insight is given in time-resolved measurements of full dispersion evolution after a pump pulse, where we resolve signal from the NB and GB and observe dynamical transition from weakly coupled lasing to polariton condensation. Discussion of the observed features is given in terms of spontaneous multiple scattering processes of polaritonic waves on intrinsic disorder potential pattern of the sample.

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Electron spin and orbital dynamics in individual quantum dots and molecules

Jonathan Finley

Walter Schottky Institut and Physik Department, Technische Universität München, Am Coulombwall 4, 85748 Garching, Germany

For spin qubits in optically active quantum dots the hyperfine coupling to the nuclear spin bath gives rise to a local effective hyperfine field (B_n) in which the spin evolves coherently over nanosecond timescales [1]. Phenomenological models of electron spin decoherence in such systems generally include two basic types of spin relaxation: fast dephasing due to static but randomly distributed hyperfine fields (~2 ns) and a much slower process ($>$ 1 µs) of irreversible monotonic relaxation due either to nuclear spin co-flips or other complex many-body interaction effects [1-3]. I will present results that show that this is an oversimplification; the electron spin qubit relaxation is determined by three rather than two distinct stages. The additional stage corresponds to the effect of coherent precession processes that occur in the nuclear spin bath itself, leading to a relatively fast but incomplete non-monotonic relaxation at intermediate timescales (750 ns). Electron spin coherence timescales are also measured using spin echo techniques, revealing complex oscillatory dependencies of T_2 on the applied magnetic field. This behaviour is shown to reflect the interplay between dynamics dominated by the externally applied B-field to one where the quadrupolar interaction within the nuclear spin bath dominates the coherent spin dynamics [4,5]. Finally, we show that the methods we apply are capable of probing the correlations in stochastic outputs of time-distributed weak optical measurements of a single spin via measurement of higher order quantum correlations (g^3 (τ_1, τ_2)) [6]. We show that such correlators are sensitive to pure quantum effects that cannot be explained within the classical framework, and which allow direct determination of ensemble and quantum dephasing times, T_2^* and T_2 using only repeated projective measurements *without* coherent spin control.

In related work, we will explore Coulomb mediated hybridization of excitonic states in quantum dot molecules [7]. By probing the optical response of the quantum dot molecule as a function of the static electric field applied along the molecular axis, we observe entirely unexpected avoided level crossings that do not arise from the dominant single particle tunnel coupling. We identify a new few-particle coupling mechanism stemming from Coulomb interactions between different neutral exciton states. Such Coulomb resonances hybridize the exciton wave function over four different electron and hole single-particle orbitals. Comparisons of experimental observations with microscopic 8-band $\boldsymbol{k}\cdot\boldsymbol{p}$ calculations taking into account a realistic quantum dot geometry show good agreement and reveal that the Coulomb resonances arise from broken symmetry in the quantum dot molecule.

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Exploring the application-relevant properties of InAs-InP epitaxial nanostructures

Grzegorz Sęk

Laboratory for Optical Spectroscopy of Nanostructures, Department of Experimental Physics, Faculty of Fundamental Problems of Technology, Wroclaw University of Technology, Wybrzeze Wyspianskiego 27, 50-370 Wroclaw, Poland

Optical properties of semiconductor nanostructures have recently been explored mainly with respect to applications in optoelectronics, as in lasers or amplifiers, and in nanophotonics as in single photon sources, nanolasers up to the ultimate single-dot thresholdless laser, or emitters of entangled photon pairs. For that purpose, epitaxially-grown nanostructures on InP substrate, can potentially be considered, mainly due to their easily tunable emission wavelength covering well the range of the 2nd and 3rd telecommunication windows and the tunability of their shapes and geometry, and the resulting control of the electronic structure and polarization properties.

There will be reported the results of a spectroscopic study of molecular-beam-epitaxy-grown InAs/InGaAlAs/InP quantum-dot-like structures emitting in the application-relevant range of 1.3 - 1.55 μm, properties of which are tailored via changes in the morphology or the surrounding of the structure. Based on high resolution microphotoluminescence experiment many of single dot properties could be explored. Emission of various exciton complexes has been identified from the excitation power dependent spectra combined with the polarization-resolved photoluminescence allowing to determine the binding energy of various excitonic complexes and revealing the exciton fine structure, all supported by the photon correlation measurements employed to confirm the origin of the lines. The carrier/exciton dynamics on a single dot level has been investigated giving the respective lifetimes. Further, efficient single photon emission from such nanostructures has been detected at the telecommunication windows from both a neutral exciton state and a charged exciton – a trion. Eventually, magnetic field control of the exciton bright states splitting has been proposed making possible its reduction down to zero, which appeared to be specific for nanostructures of that kind with large in-plane anisotropy and due to the certain spin-split states configuration. These results open up a new route for quantum nanostructures on InP and other anisotropic structures to be applied in sources of entangled photon pairs from the biexciton-exciton cascade or in spin-based quantum memories suitable for fiber-based telecommunication and data transmission technologies.

Ultrafast DC Stark switching of a single quantum dot

Christian Dicken[1,2], **Christian Wolpert**[2], **Klas Lindfors**[2], **Heinz Schweizer**[3], **Markus Lippitz**[1,2], **Lijuan Wang**[4], **Paola Atkinson**[4], **Armando Rastelli**[4], **Oliver G. Schmidt**[4], **Ranber Singh**[2], **Gabriel Bester**[2]

[1] *Experimental Physics III, University of Bayreuth, Germany*
[2] *Max Planck Institute for Solid State Research, Stuttgart, Germany*
[3] *4th Physics Institute, University of Stuttgart, Germany*
[4] *Institute for Integrative Nanosciences, IFW Dresden, Germany*

The controlled interaction of different optical building blocks such as quantum dots, color centers, optical cavities or waveguides is a key to the realization of new technologies using nanoscale optical systems. Fast and selective tuning of single quantum emitters is required.

We perform ultrafast manipulation of the optical transition of a single GaAs/AlGaAs quantum dot using the photo-Dember effect. A 500 fs laser pulse is absorbed in the GaAs substrate (see left figure) and creates free photo carriers. As a consequence of different velocities of electrons and holes, separated negative and positive charge clouds form when the photo carriers are reflected from the GaAs/AlGaAs interface. A DC-electric field of several 10 kV/cm is induced on a picosecond timescale that Stark-shifts the nearby quantum dot. We investigate the shift of the resonance energy and reduction of the transition dipole moment of the neutral exciton transition by far-field transient reflection spectroscopy [1]. Redshifts up to 100 μeV with a rise time below 1 ps and a decay time of 50 ps are observed. Additionally we observe power induced spectral diffusion due to fluctuations of the electric field.

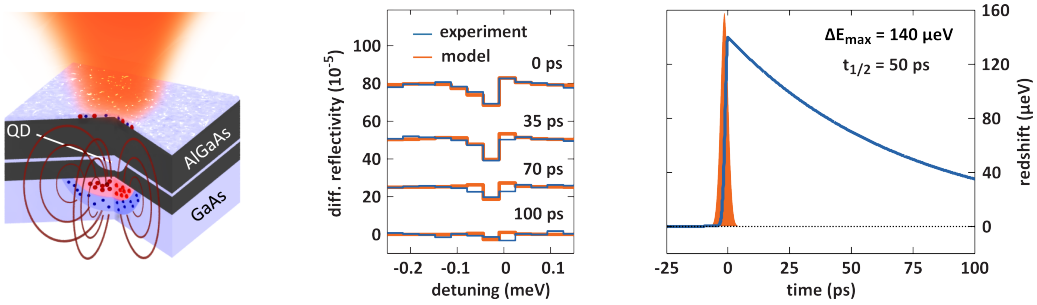

Figure 1: Expanding clouds of carriers produce an electric field at the position of the quantum dot (left). This leads via the DC Stark effect to a shift of the optical transition and a reduction of the oscillator strength that can be measured in a transient reflection experiment (middle). Fitting a simple model based on ab-initio calculations reveals the ultrafast response of the quantum dot (right).

Our results show that optically induced electric fields allow for fast and selective manipulation of the optical properties of single quantum dots. They provide a new approach to control the interaction between emitters and their nanostructured environment.

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Introduction to COST Action MP1403 NANOSCALE QUANTUM OPTICS

I. D'Amico

Department of Physics and York Center for Quantum Technologies, University of York, York, UK

At the core of the COST Action MP1403 NANOSCALE QUANTUM OPTICS is the idea that the investigation of quantum phenomena in nanophotonics systems may lead to new scales of quantum complexity and constitutes the starting point for developing photonic technologies that deliver quantum-enhanced performances in real-world situations. The key aim of this COST Action is to proactively increase the interaction among the communities of nanophotonics, quantum optics and materials science and to support them towards common objectives.

The COST Action Nanoscale Quantum Optics has indeed very quickly built a very large network of scientists spanning more than 20 Countries. They discuss results and challenges, define research priorities and initiate new collaborations as well as consortia that will apply for funding research projects. The Action is a vector to organize thematic workshops; it funds Short-Term Scientific Missions (STSMs) to further collaborative research among the Action members and encourage the mobility of ESRs; it organizes and funds training Schools and ESR Workshops to promote the education and training of young scientists in academia and industry. Female scientists and ESR participation is proactively encouraged.

The COST Action Nanoscale Quantum Optics includes four working groups: the first on generation, detection & storage of quantum states of light at the nanoscale with emphasis on efficiency, fidelity and rate; the second focuses on nonlinearities and ultrafast processes in nanostructured media; the third on nanoscale quantum coherence; and the fourth concentrates on cooperative effects, correlations and many-body physics tailored by strongly confined optical fields.

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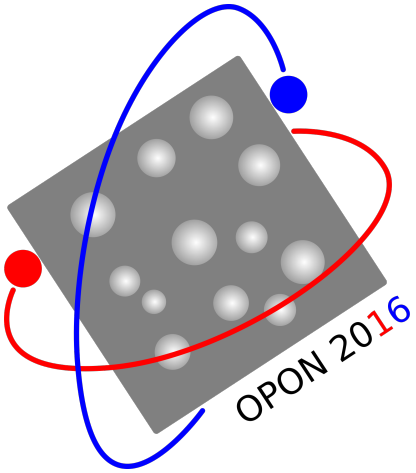

THURSDAY

Rydberg excitons in cuprous oxide

Manfred Bayer

Experimentelle Physik 2, TU Dortmund, D-44221 Dortmund, Germany

Excitons are decisive for the description of the optical properties of semiconductors. Their description of excitons as hydrogen atom-like complexes has turned out to be extremely useful. In Rydberg atoms an electron is promoted into a state with high principal quantum number. Thereby the atom becomes a mesoscopic object with dimensions in the micrometer-range, with which for example the transition from quantum to classical dynamics can be studied. Recently it has been shown that also an exciton can be highly excited by observing states with principal quantum number up to n=25 in high-quality natural cuprous oxide crystals [1]. This corresponds to an average radius of more than 1 m so that the exciton wave function is extended over more than 10 billion crystal unit cells. In this contribution I will address similarities and differences of these Rydberg excitons compared to atoms.

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Optical control of the dark exciton in a semiconductor quantum dot

Doris E. Reiter

Institut für Festkörpertheorie, Universität Münster, 48149 Münster, GERMANY
Doris.Reiter@uni-muenster.de

The optical control of excitons in semiconductor quantum dots (QDs) is a crucial step towards their usage in quantum information technology. The combination of electron and hole spin determines the optical activity of the exciton: For antiparallel spins of electron and hole the exciton is optically accessible or bright, while for parallel spins the exciton is optically inactive or dark. Due to its optical inactivity the dark exciton cannot be prepared by typical optical schemes used for the preparation of the bright exciton and is much more difficult to access. For the same reason, the lifetime of the dark exciton exceeds the one of the bright by far and could possibly be used for photon memory. This makes the dark exciton interesting for applications in the field of quantum information.

In our proposal we present a new method to optically access the dark exciton using the combination of a chirped laser pulse and a tilted magnetic field [1]. Because of the in-plane component of the magnetic field, bright and dark exciton are coupled, but the coupling is weak enough such that the distinction into bright and dark exciton still holds. When the QD is excited with a chirped laser pulse, the adiabatic passage effect allows for a population inversion between ground and exciton states [2]. Simultaneously bright and dark exciton are coupled, which can lead to a population of the dark exciton. Thus, by a single pulse, the dark exciton can be directly prepared.

In this contribution, I will discuss a theoretical study on the dependence of this mechanism on the excitation conditions and show that this excitation scheme sensitively depends on the sign of the chirp. For positive chirps a high fidelity preparation of the dark exciton is possible, while for negative chirps the dark exciton is not excited at all. Further, the influence of phonons on the preparation scheme is discussed, showing that for low temperatures the proposed mechanism is almost unaffected by phonons, such that a controlled preparation of the dark exciton in a QD should be possible.

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Exciton spin relaxation in InAs/InP(001) quantum dashes emitting at 1.55 μm

M. Syperek [1], Ł. Dusanowski[1], J. Misiewicz[1], A. Somers[2], J. P. Reithmaier[3] S. Höfling[2,4], G. Sęk[1]

[1] *Laboratory for Optical Spectroscopy of Nanostructures, Dep. of Exp. Physics, Wrocław Univ. of Technology, Wyb. Wyspiańskiego 27, 50-370 Wrocław, Poland*
[2] *Technische Physik, Univ. of Würzburg and Wilhelm-Conrad-Röntgen-Research Center for Complex Material Systems, Am Hubland, D-97074 Würzburg, Germany*
[3] *Institute of Nanostructure Technologies and Analytics, Univ. of Kassel, Heinrich-Plett-Str. 40, 34132 Kassel, Germany*
[4] *SUPA, School of Physics and Astronomy, University of St. Andrews, North Haugh, KY16 9SS St. Andrews, United Kingdom*

Recently, the InAs/InP(001) QDash-based non-classical single photon emitter operating at 1.55 μm has been demonstrated [1] along with the possibility to diminish the confined exciton fine structure splitting [2]. While the former clearly shows QDash capabilities to generate single photons at a time, the latter can lead soon to demonstration of polarization-entangled photons at telecom wavelengths, essential for e.g. quantum repeater technology. Since QDashes can be considered as a bridge platform between the solid-state quantum information storage/operation and the quantum state of light, it is crucial to investigate properties of the confined spin state that can mediate the exchange process of quantum information.

We demonstrate an impact of different spin-injection scenarios on the possibility to read out the written exciton spin state confined in a QDash. The spin initialization as well as the read-out processes are realized by all-optical means. Linearly polarized train of laser pulses creates the spin excitation in an ensemble of QDashes whereas analysis of the photoluminescence signal (as a function of time or averaged in time) provides information about the confined spin state.

In the case of a spin injection into the QDash barrier the resultant ground state emission is strongly linearly polarized. The degree of linear polarization (DOP) is ~27%, that defines the "background" DOP. The DOP is related to intrinsic properties of a QDash ground state and is not connected to accumulation of a spin population. In the case of a spin injection into the wetting layer the DOP is increased by ~15% in respect to the "background" one. This result indicates that the injected spin state is partially preserved during the exciton relaxation process down to the QDash ground state, and can be recovered in the emission. Finally, the quasi-resonant spin injection that utilizes a single longitudinal optical phonon-mediated process led to the increased contrast between the "background" DOP and the actual one up to 35%, i.e. indicates on easy recovery of the spin memory state. However, this value is much lower than expected. Moreover, the measured spin relaxation time reaches 1.7 ns, which is comparable to the exciton decay time. Therefore, the obtained results rise the question about possible spin relaxation mechanisms for such types of quantum structures. A high "background" DOP suggests that strong heavy-light hole mixing might be responsible for efficient relaxation channel of the spin state injected to such large nanostructures made of InAs on InP(001).

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Dynamics of four-wave mixing signals from excitons in single quantum dots

D. Wigger[1], Q. Mermillod[2,3], V. Delmonte[2,3], D. E. Reiter[1], C. Schneider[4], M. Kamp[4], S. Höfling[4,5], W. Langbein[6], T. Kuhn[1], G. Nogues[2,3], J. Kasprzak[2,3]

[1] *Institut für Festkörpertheorie, Universität Münster, Germany*
[2] *Univ. Grenoble Alpes, France*
[3] *CNRS, Institut Néel, "Nanophysique et semiconducteurs" group, France*
[4] *Technische Physik and Wilhelm Conrad Röntgen Research Center for Complex Material Systems, Universität Würzburg, Germany*
[5] *SUPA, School of Physics and Astronomy, University of St Andrews, United Kingdom*
[6] *Cardiff University School of Physics and Astronomy, United Kingdom*

In a combined experimental and theoretical study on excitons in single semiconductor quantum dots (QDs) we reveal a detailed picture of the dynamics in the four level system consisting of ground state, two excitons and the biexciton [1] as depicted in Fig. 1 (A). Two pulse excitations are employed to probe the coherence dynamics, while in three pulse excitations populations and typically hidden coherences are accessible. The oscillatory dynamics of the four-wave mixing (FWM) signals in the system is governed by the fine-structure splitting δ and the biexciton binding energy Δ. The analysis of the excitation conditions displays a dependence of the dynamics on the specific choice of polarization configuration, pulse areas and temporal ordering of driving fields in an excellent quantitative agreement between theoretical prediction and experimental data. As seen in Fig.1 (B) and (C) the occurrence of quantum beats strongly depends on the polarization angle α with respect to the QD axis. For $\alpha = 0°$ the system reduces to three levels (GXB) and no oscillation is present. For $\alpha = 45°$ the two single excitons $|X\rangle$ and $|Y\rangle$ are equally excited yielding a strong quantum beat. Using two-dimensional FWM spectroscopy we shed light on the exciton-biexciton coupling and distinguish between neutral and charged exciton complexes in a single QD.

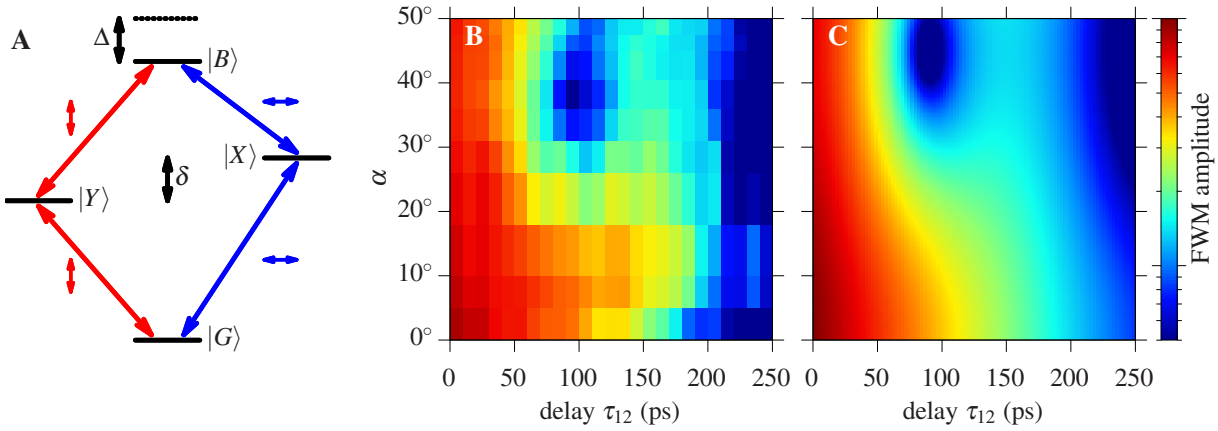

Figure 1: (A) Sketch of four level system. (B,C) Contour plot of FWM signal after two pulse excitation. (B) Experimental data. (C) Simulation.

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Investigations of charged exciton localization in magneto-photoluminescence experiments in GaAs/$Al_xGa_{1-x}As$ quantum wells

L. Bryja[1], J. Jadczak[1], K. Ryczko[1], M. Kubisa[1], A. Wójs[2], M. Potemski[3], F. Liu[4], D. R. Yakovlev[4,5], M. Bayer[4,5], C. A Nicoll[6], I. Farrer[6], and D. A Ritchie[6]

[1] *Department of Experimental Physics, Wroclaw University of Technology, Wroclaw, Poland*
[2] *Department of Theoretical Physics, Wroclaw University of Technology, Wroclaw, Poland*
[3] *Laboratoire National des Champs Magnetiques Intenses, CNRS-UJF-UPS-INSA, Grenoble, France*
[4] *Experimentelle Physik 2, Technische Universitat Dortmund, D-44221 Dortmund, Germany*
[4] *Ioffe Physical-Technical Institute, Russian Academy of Sciences, St. Petersburg, Russia*
[6] *Cavendish Laboratory, University of Cambridge, Cambridge, CB3 OHE, United Kingdom*

Since the very first observation of charged excitons (trions) in quasi-two-dimensional structures there has been considerable controversy about trion localization. In many papers trions were considered as mobile, free particles [1]. However it was also suggested that being charged and massive, trions (both negative and positive: X^- and X^+) are necessarily localized by ionized donors (D^+) or acceptors (A^-), always present in the barriers of the quantum well.

We report on extensive experimental and theoretical studies of the degree of localization of different excitonic complexes confined in high-mobility asymmetric GaAs quantum wells.

In low-temperature, polarization-resolved, high-magnetic-field (up to 23T) photoluminescence experiments we have detected two strong emission lines of the neutral and positively charged exciton (X and X+) and a series of weaker lines identified as the excitonic complexes bound to ionized acceptors (AX^-). From the Zeeman splitting of emission lines detected in σ^+ and σ^- polarizations we have determined the hole g-factor (g_h) of different complexes (Fig. 1).

For X and X^+, g_h initially grows with the increase of magnetic field and then saturates at g_h=0.88 and 1.55, respectively. For the AX^- complexes g_h begins from a high value (between 6 and 11 at zero field) and decreases with field growth. This contrasting behavior is traced to the structure of valence band Landau levels, calculated numerically within the Luttinger model (beyond axial approximation). We realize the fact that in all asymmetric structures, electrons and holes are separated by a built-in electric field. The field-induced band bending shifts heavy holes closer to the interface than light holes. We found that g-factors of heavy and light holes reveals similar behavior as the experimentally detected g_h of X and X^+. They both grow in low magnetic fields and saturate at higher fields at values g_h=0.82 and 2.65 for light and heavy holes, respectively. This indicates that g_h of X comes predominately from the light hole levels, g_h of X^+ reveals balanced occupation of light- and heavy-hole levels, and g_h of AX^- comes mainly from the heavy-hole states.

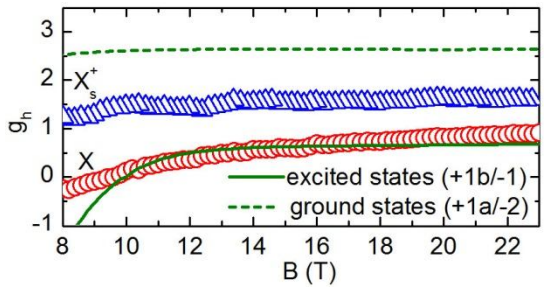

Fig.1 Measured hole g-factors of X and X+ (symbols) compared with the values calculated theoretically for two lowest eigenstates of a free hole (from [3]).

These results allow unambiguous identification of X and X^+ as nearly free objects, and the multiple AX^- states as excitons bound by Coulomb interaction to ionized acceptors placed on subsequent crystallographic planes in the doped barrier [1].

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Modeling of exciton states in double quantum dots in magnetic field

Krzysztof Gawarecki, Paweł Machnikowski

Department of Theoretical Physics, Faculty of Fundamental Problems of Technology, Wrocław University of Technology, Wybrzeże Wyspiańskiego 27, 50-370 Wrocław, Poland

Systems composed of vertically stacked quantum dots (QDs) can be used for constructing quantum-coherent devices, including spin-based quantum bits. From this point of view, understanding of carrier states and their response to external fields is crucial.

In this contribution, we present the results of modeling of coupled QD structures based on the combination of several methods: the electron and hole states ale calculated within 8-band and 14-band kp methods in the presence of strain and piezoelectric field in the 2nd order in strain tensor elements [1]. We take into account non-uniform InGaAs distribution in the dots according to the trumpet-shape composition [2]. Magnetic field is incorporated via gauge invariance theory [3] and preserving correct operator ordering [4]. Then, the exciton states are calculated using the configuration interaction method.

We calculate exciton energy levels of two vertically stacked QDs as a function of external axial magnetic field and electric field. We take into account the effects related to the geometrical axial-symmetry breaking, which allows us to describe couplings that do not appear in the case of axially symmetric system. We also investigate the Coulomb mediated hybridization mechanism [5] that leads to the appearance of new resonances in the energy spectra. Such resonances, recently observed in an experiment [6], involve two particles and cannot be assigned to the single-particle tunneling. Their structure is well reproduced by our modeling [6].

We compare the spectrum of exciton states (including its magnetic field dependence) with that of single particle states. While the latter is not directly accessible by optical spectroscopy, the former can be inferred from the observed coupling between bright direct exciton and nominally dark excited indirect exciton states. We show that the excited single-particle hole states are reflected in the spectrum of excited indirect exciton states that is measurable via Coulomb resonances with direct states. Our numerical analysis reveals the spin structure of excited hole states, resulting from the interplay between spin-orbit coupling and axial anisotropy.

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Spin manipulation of a single magnetic ion in a quantum dot

P. Kossacki, T. Smoleński, J. Kobak, M. Goryca, A. Bogucki,
M. Koperski, J.-G. Rousset, J. Suffczyński, M. Nawrocki, A. Golnik, W. Pacuski

*Institute of Experimental Physics, Faculty of Physics, University of Warsaw,
ul. Pasteura 5, 02-093 Warsaw, Poland*

The ability to detect and manipulate a single spin in a semiconductor quantum dot has recently attracted a lot of interest. Particularly II-VI quantum dots give unique opportunity to incorporate a single isoelectronic impurity of transition metal. This is a very promising model system for studying building blocks of future information storage and processing devices. Recent experiments have shown the possibilities to read and manipulate the electronic spin state of several ions such as Mn^{2+}, Co^{2+} [1-3] and Fe^{2+} [4].

In this talk I will summarize spectroscopic studies of new systems of quantum dots with single magnetic ions. I will discuss the optical observation of individual magnetic ions in a systems such as a CdTe/ZnTe quantum dot with Co^{2+} and CdSe/ZnSe dot with individual manganese ion [1]. The observed phenomena will be compared to magneto-photoluminescence results obtained for canonical system of CdTe/ZnTe quantum dot with single Mn^{2+} ion. Particular attention will be paid to mechanisms of optical spin orientation, limitations of the single spin relaxation and a direct observation of coherent dynamics of an individual magnetic impurity.

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Topologically protected localised states in spin chains

M. P. Estarellas, I. D'Amico, and T. P. Spiller

Department of Physics and York Center for Quantum Technologies, University of York, York, UK

The topological confinement of quantum states has engaged the condensed matter community for a few decades. Now this field is receiving increasing interest due to its potential applications for topological quantum computation, quantum state transfer and quantum memories.

Here we consider spin chain systems analogous to the Su, Schrieffer and Hegger (SSH) model, which was first presented to describe soliton formation in polyacetylene [1]. Recently, an analogy of this model has been implemented with a set of identical, coupled dielectric resonators placed in a microwave cavity [2], inducing spatially confined states. Here we present a model inspired by these systems and explore the presence of topological localisation in finite one-dimensional spin chains. Spin chains are of particular interest due to their versatility to be engineered. By tuning the couplings, we can construct our chains to be topologically analogous to the SSH model. Experimentally, this can be done for any system where it is possible to engineer the couplings between the sites, e.g. using electrons and excitons trapped in nanostructures.

We demonstrate explicitly the topologically induced spatial localisation of quantum states, and present detailed investigations of the effects of random noise, showing that these topologically protected states are very robust against this type of perturbation. Systems with such topological robustness are good candidates for quantum information tasks.

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Magnetic Ground State of an Individual Fe^{2+} Ion in a Strained Semiconductor Nanostructure

T. Smoleński, T. Kazimierczuk, J. Kobak, M. Goryca, A. Golnik, P. Kossacki, W. Pacuski

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, ul. Pasteura 5, 02-093 Warsaw, Poland

Spin manipulation of individual impurities has attracted a lot of research attention over the last years [1-3]. Important contribution to this field can be done using quantum dots (QDs) containing various single transition metal ions, as was recently shown by the measurements of Mn^{2+} and Co^{2+} spin relaxation dynamics in different QD systems [2] or by the observation of coherent precession of a single Mn^{2+} spin [3]. One of the strongest motivations for the research in this area is a possibility to obtain long spin coherence time of a single magnetic moment. From that perspective the nuclear-spin-free Fe^{2+} ion in a QD seems a promising system. However, it was not considered as a candidate for quantum information applications, since the Fe^{2+} ion in bulk host semiconductors was found to inherently exhibit a single non-degenerate ground state and thus regarded as not able to store any quantum information.

In this work we demonstrate that by using the strain of a semiconductor QD it is possible to tailor the energy spectrum of the Fe^{2+} ion to exhibit doubly degenerate (i.e., magnetic) ground state [4]. Moreover, this ground state is composed of states corresponding to the ion spin projections $S_z = \pm 2$, which makes those two states less prone to decoherence, e.g., by residual in-plane magnetic field. Our concept is evidenced both theoretically and experimentally. From the theoretical side, we find that strong structural strain of the QD alters the spectrum of the ion orbital states, which in turn induces a distinctive changes in the ordering of the ion spin levels due to the spin-orbit coupling. The experimental proof is based on the results of photoluminescence (PL) studies of a novel QD system: self-assembled CdSe/ZnSe quantum dots doped with individual Fe^{2+} ions. A direct fingerprint of a nonzero spin of the Fe^{2+} ion ground state is a pronounced twofold splitting of the emission lines visible in a QD PL spectrum, which is observed for all three excitonic complexes (Fig. 1). In each case, the splitting originates from the *s,p-d* exchange interaction between the ion and confined carriers, which leads to two different energies of the optical transitions depending on the spin projection of the Fe^{2+} ion. Our analysis is complemented by the measurements of a QD PL spectrum evolution in magnetic field, which allow us to determine the character and strength of the *s,p-d* exchange and to obtain the ion *g*-factor of 2.0, exactly as expected for the Fe^{2+}.

Finally, we demonstrate that the Fe^{2+} spin can be optically oriented by spin-polarized excitons. Altogether, our findings evidence that the Fe^{2+} ion in a CdSe/ZnSe QD is a robust, optically-controllable two-level system free of any nuclear spin fluctuations, thus a perfect candidate for quantum information processing.

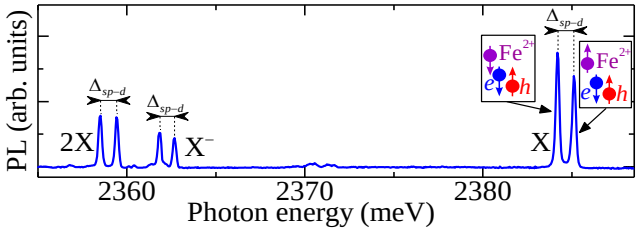

Fig 1. PL spectrum of a CdSe/ZnSe QD with a single Fe^{2+} ion ($\Delta_{sp\text{-}d}$ represents the *s,p-d* exchange splitting visible for all excitonic complexes).

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[3] M. Goryca *et al.*, Physical Review Letters **113**, 227202 (2014).
[4] T. Smoleński *et al.*, Nature Communications, in press (2016).

Spin properties of the indirect exciton in indirect band-gap (In,Al)As/AlAs quantum dot ensembles

J. Debus [1], T. S. Shamirzaev [2], D. Dunker [1], V. F. Sapega [3], D. R. Yakovlev [1,3], and M. Bayer [1,3]

[1] *Experimental Physics 2, TU Dortmund University, Dortmund, Germany*
[2] *Rzhanov Institute of Semiconductor Physics, Siberian Branch of Russian Academy of Sciences, Novosibirsk, Russia*
[3] *Ioffe Institute, Russian Academy of Sciences, St. Petersburg, Russia*

While semiconductor quantum dots (QDs) have been established as efficient light emitters and detectors in optoelectronics, other applications are only prospective so far. Particular examples are implementations in spin electronics and quantum information technologies. For these purposes, the QDs are typically loaded with resident carriers whose spins are well protected from relaxation by the three-dimensional confinement. In this context, exciton complexes are often used for spin manipulation, but are considered less promising as information carriers. This reservation is primarily related to the limited exciton lifetime of about a nanosecond, which is too short to provide sufficient coherent manipulation. This situation may change if the exciton lifetime could be extended significantly.

An appealing possibility is the realization of QDs with a band gap that is indirect in real or momentum space. We focus on self-assembled (In,Al)As/AlAs QDs with type-I band alignment, in which a crossover of the lowest conduction-band states between the Γ- and X-valley occurs, depending on the dot size. This crossover is reflected by the lifetime of the corresponding exciton, which is formed by a Γ-valley heavy-hole and a Γ- or an X-valley electron. Due to the valley mixing, the lifetime of that exciton can be as long as hundreds of µs [1]; the longitudinal spin relaxation time lies within the same time range [2].

We report on spin properties of the indirect exciton in undoped (In,Al)As/AlAs quantum dots. Resonant spin-flip Raman scattering is used to initialize and orient the spins of the electron, heavy hole, and, in particular, indirect exciton with coherent manipulation efficiencies of up to 20% [3]. It is also used to characterize the Γ-X-state mixing and gives comprehensive insight into the electron and hole spin-flip mechanisms and exciton spin-level structure. A sign change in the temporal evolution of the circular polarization degree of the photoluminescence (in the high µs-range) moreover indicates the competing spin dynamics of the dark and bright indirect excitons. Besides, at low magnetic fields of a few mT a high optical orientation degree reaching 80% is surprisingly found for the indirect exciton. It sensitively responds to the optical excitation density as well as weak variations in the magnetic field strength.

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Quantum kinetic spin dynamics in intrinsic diluted magnetic semiconductors

M. Cygorek[1], F. Ungar[1], P.I. Tamborenea[1,2] and V.M. Axt[1]

[1] *Theoretische Physik III, Universität Bayreuth, 95440 Bayreuth, Germany*
[2] *Departamento de Física and IFIBA, FCEN, Universidad de Buenos Aires, Ciudad Universitaria, Pabellón I, 1428 Ciudad de Buenos Aires, Argentina*

The spin dynamics in intrinsic diluted magnetic semiconductors (DMS) is studied in the framework of a quantum kinetic theory [1,2,3]. Besides the *s-d* interaction between the carrier and magnetic impurity spins also an external magnetic field as well as **k**-dependent effective magnetic fields [4] for the carrier spins are taken into account on a quantum kinetic level [5].

We show that genuine (non-Markovian) quantum kinetic effects in the carrier spin dynamics can be caused by the excitation of electrons in proximity to the band edge [6].

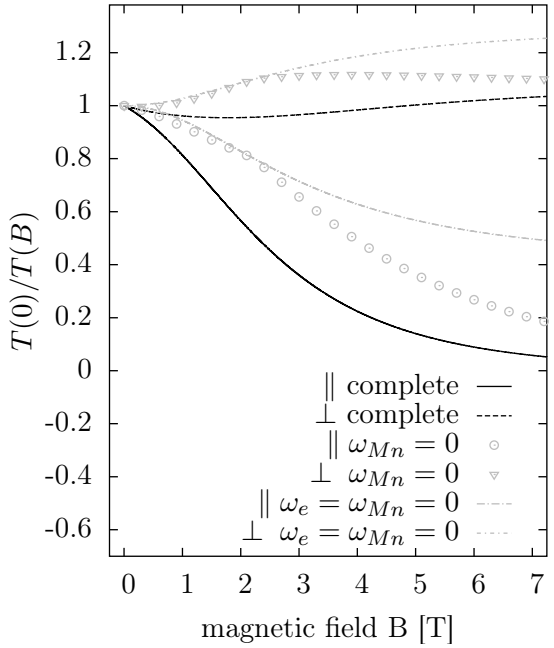

Figure 1: Magnetic field dependence of the parallel (∥) and perpendicular (⊥) carrier spin transfer rate with respect to the direction of the impurity magnetization in an 8 nm wide $Cd_{0.9983}Mn_{0.0017}Te$ quantum well [5].

Even when the Markovian approximation is valid, the quantum kinetic approach is favorable, as it allows us to derive not only the spin transfer rate for the carrier spin component parallel to the impurity magnetization (Fermi's golden rule gives only this rate), but also the perpendicular spin transfer rate [2,5] which is the relevant rate for time-resolved Kerr measurements in Voigt geometry.

Furthermore, it turns out that the effective magnetic fields that act on the carrier ($\boldsymbol{\omega}_e$) and impurity spins ($\boldsymbol{\omega}_{Mn}$) also lead to a precession-type movement of the carrier-impurity correlations, which affects the rates even in the Markovian limit [2,5]. In Figure 1, these effects are demonstrated by comparing complete calculations (black lines) for the parallel and perpendicular spin transfer rates with calculations where the impact of the effective fields $\boldsymbol{\omega}_e$ and $\boldsymbol{\omega}_{Mn}$ on the dynamics of the correlations has been switched off (gray points and lines).

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Automated optimization of photonic crystals for broadband slow light and ultra-high-Q cavities

Vincenzo Savona

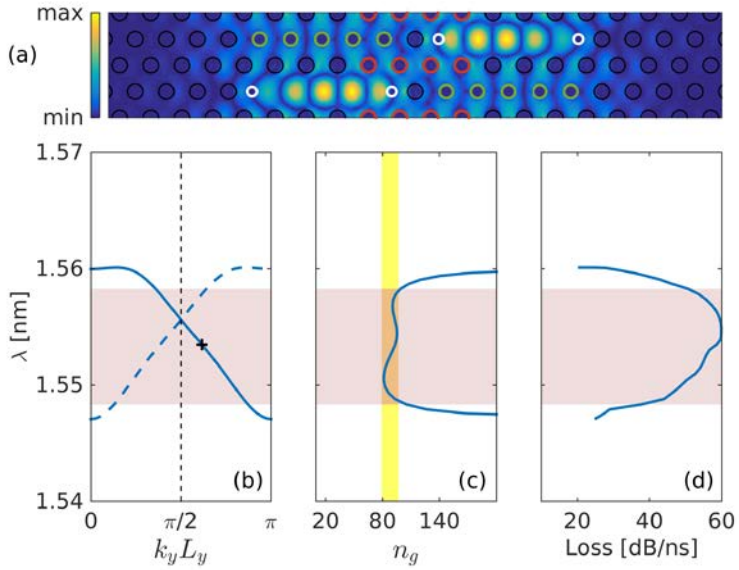
Laboratory of Theoretical Physics of Nanosystems, Ecole Polytechnique Fédérale de Lausanne EPFL, CH-1015 Lausanne,Switzerland

Photonic crystal (PhC) slab structures represent one of the most promising paradigms for a fully integrated photonic platform, with a plethora of applications ranging from semiconductor-based cavity quantum electrodynamics to advanced light sources and photonic devices. Here, we show that a dramatic improvement in the main figures of merit can be obtained using a novel computer-aided optimization procedure. The ensuing designs [1-4] have set a new state-of-the-art both for Q-factors of PhC cavities and for broadband slow-light propagation in a coupled-resonator optical waveguide (CROW).

The optimization method [1] combines a fast simulation tool and a genetic optimization algorithm, enabling the exploration of thousands of variations of the structure under study, in an appropriately selected parameter space.

I will first review our recent results on the optimization of the Q-factor of simple cavity designs [1], where the previous state-of-the-art was improved by at least a factor of 10, as confirmed by several experimental demonstrations [2,3].

I will then show how the method can be applied to the optimization of a novel CROW design for broadband slow light propagation [4]. A commonly adopted figure of merit in this case is the group index-bandwidth product (GBP). The optimization was carried out on a new CROW design that we devised, whose elementary cell is depicted in Fig. 1(a). We have achieved various designs that maximize the GBP at different values of the group index. Fig. 1 shows a design having n_g=88 over a 10nm bandwidth, and GPB=0.56. With slightly different parameters, we obtained n_g=116 over a similar bandwidth, namely GBP=0.66, which to our knowledge is the highest value ever obtained for a slow-light design.



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Coherence of individual emitters in photonic nanostructures

Jacek Kasprzak

Institut Néel, CNRS, BP 166, F-38042 Grenoble Cedex 9, France

I will highlight recent advances in retrieving and manipulating coherent nonlinear responses of semiconductor nanostructures. In particular, wave mixing spectroscopy is a well-established approach to infer coherence and population dynamics of exciton ensembles, for instance confined in quantum wells. I will start by revisiting this physics by demonstrating enhanced four-wave mixing (FWM) response and radiatively limited dephasing of optical transitions in monolayers of transition metal dichalcogenides [1].

Performing FWM spectroscopy on individual transitions, like excitons in single quantum dots (QDs), is more challenging due to an overwhelming ratio (typically $10^{6...8}$ in the field) between the required resonant optical driving and the amount of the emitted FWM signal. The main objective of this presentation is to show that by embedding a QD in well designed photonic devices - like planar microcavities [2], one-dimensional waveguides antennas [3] or deterministic microlenses - one can suppress the background-signal ratio down to $10^{2...4}$, abolishing a long-standing issue regarding a poor retrieval efficiency of coherent responses from single excitons. Such dramatically increased sensitivity of the measurements opens novel opportunities in this field. It enables to verify theoretical proposals, which until now have been considered as experimentally unfeasible. I will highlight two such examples. The first one, is to monitor polaron formation and to reveal corresponding phonon-induced dephasing in a QD [4]. The second one, involves implementation of novel, fast, coherent control schemes via multi-wave mixing [2]. As an outlook, I will focus on ongoing experiments, aiming to demonstrate long-range radiative coupling within a pair of distant excitons.

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[4] ongoing research

The photon ratchet intermediate band solar cell: using nanostructures to improve efficiency

Andreas Pusch, Megumi Yoshida, Nicholas P. Hylton, Anthony Steiner-Vaquero, Oliver J. Curtin, Chris C. Phillips, Nicholas J. Ekins-Daukes, Ortwin Hess

Imperial College London, Blackett Laboratory, South Kensington Campus, SW7 2AZ, London, United Kingdom

The intermediate band solar cell (IBSC) concept aims to improve upon the Shockley-Queisser [1] limit for single bandgap solar cells by also making use of below bandgap photons through sequential absorption processes via an intermediate band (IB) [2]. Despite intense efforts in the last two decades, current IBSC implementations have not delivered yet on the promise of high efficiencies, mainly due to fast recombination of carriers trough the intermediate states.

As a solution to the problem of high recombination via the intermediate states we recently proposed the photon ratchet IBSC (PR-IBSC) [3], see Figure 1, a concept where the electrons excited via the intermediate band undergo a fast non-radiative transition to a lower lying state that is optically disconnected from the state the electrons where excited from.

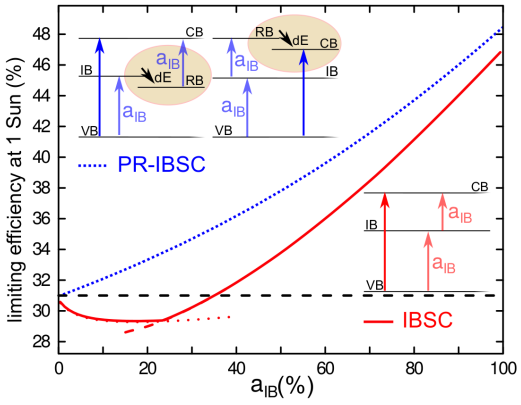

Figure 1: The efficiency of an ideal PR-IBSC and an ideal conventional IBSC shown as a function of absorptivity in the intermediate band a_{IB}. The insets show the level configurations and allowed transitions associated with the concepts.

Thus one trades some of the energy of the excited electrons for a substantial reduction in recombination to achieve a higher efficiency overall, especially in the realistic case of imperfect absorptivity of the transition into and out of the intermediate band [4].

We will show theoretical results on the limiting efficiency of different IBSC configurations and explain how semiconductor nano-structures can be used to implement a PR-IBSC.

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Temperature-stable strong light-matter coupling in the solid state with quantum dot-micropillars

Anna Musiał [1,2], Caspar Hopfmann [1], Max Strauß [1], Andreas M. Barth [3], Martin Glässl [3], Alexei Vagov [3], Micha Strauß [4], Christian Schneider [4], Sven Höfling [4,5], Martin Kamp [4], Vollrath M. Axt [3], Stephan Reitzenstein [1]

[1] *Institut für Festkörperphysik, Technische Universität Berlin, Berlin, Germany*
[2] *Laboratory for Optical Spectroscopy of Nanostructures, Faculty of Fundamental Problems of Technology, Wrocław University of Technology, Wrocław, Poland*
[3] *Institut für Theoretische Physik III, Universität Bayreuth, Bayreuth, Germany*
[4] *Technische Physik, Physikalisches Institut and Wilhelm-Conrad-Röntgen-Research Center for Complex Material Systems, Universität Würzburg, Würzburg, Germany*
[5] *School of Physics and Astronomy, University of St. Andrews, St. Andrews, UK*

Coupled quantum dot (QD)-microcavity systems are of great interest with respect to both, fundamental study of cavity quantum electrodynamics (cQED) and possible applications. In particular strong coupling (SC) regime of cQED is important for the implementation of quantum networks. Due to the tremendous progress in the fabrication of microcavities [1], phonon-induced losses became comparable to the cavity losses with acoustic phonons being the main source of QD exciton decoherence at elevated temperatures. This raises the question of the temperature stability of the coherent coupling regime in solid state systems.

We study experimentally and theoretically the influence of temperature on the vacuum Rabi splitting (VRS) in QD-micropillars within a statistical approach [2]. This is enabled by an unprecedentedly large number of SC cases (89) in a wide temperature range (10 – 50) K for a single sample. The experiment indicates a statistically significant increase of the VRS with temperature in contrast to its expected decrease due to acoustic-phonon induced dephasing. From the theoretical point of view, the phonon-induced renormalization of the VRS is calculated using a real-time path-integral approach for strongly confined QDs [3], which allows for a numerical exact treatment of the coupling between the QD and a continuum of longitudinal acoustic phonons. For comparison with the experiment, we used a hybrid approach and combine these results with a phenomenological treatment of the cavity photon losses [4]. The absence of the expected decrease of the VRS with temperature in experiment can be attributed to a unique optical property of laterally extended $In_{0.4}Ga_{0.6}As$ QDs used in this study: Their electronic structure facilitates an effective temperature-driven increase of the oscillator strength of the excitonic state by up to 40% in the given temperature range. This leads to enhanced light-matter interaction and overcompensates the phonon-related decrease of the VRS. The observed persistence of strong coupling in the presence of phonon-induced decoherence demonstrates the appealing possibility to counteract detrimental phonon effects in the cQED regime via engineering the electronic structure of QDs.

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The role of Coulomb interaction and band mixing on twisted light absorption in semiconductor quantum dots

M. Holtkemper[1], D. E. Reiter[1], G. F. Quinteiro[2], T. Kuhn[1]

[1] *Institut für Festkörpertheorie, Wilhelm-Klemm-Str. 10, 48149 Münster, Germany*

[2] *Departamento de Física and IFIBA, FCEN, Ciudad Universitaria, Pabellón I, 1428 Ciudad de Buenos Aires, Argentina*

Optical control of electronic states in self-assembled semiconductor quantum dots (QDs) is a prerequisite for QD-based spintronics and quantum information devices. In typical QDs heavy-hole (HH) states form the uppermost valence band states and consequently HH excitons are the fundamental optical excitations. Thus most studies on optical transitions have been restricted to excitations from HH states. However, excitations from light-hole (LH) states, due to their different selection rules, have some advantages especially for the optical spin control of the excitons themselves [1] or of a magnetic impurity embedded in the QD [2]. Indeed it has been experimentally demonstrated that for specially strained QDs the uppermost valence band states are of LH character [3].

To achieve the suggested spin control mechanisms [1,2] it is necessary to access all LH exciton states optically, which is not possible with conventional laser pulses at normal incidence. Instead, a combination of excitations by normal incidence and in-plane propagating beams is necessary, which requires undesired cleavage of the samples. By the use of specific twisted light (TL) beams, i.e., light which carries orbital angular momentum, one might be able to overcome this problem and excite all LH excitons in a QD by co-propagating normal-incidence beams [4].

Here we study the effects of Coulomb interaction and band mixing on TL absorption spectra in QDs. To be specific, we model a CdSe QD using a configuration interaction approach with a harmonic confining potential and include the direct Coulomb interaction, the short-range Coulomb exchange interaction as well as band mixing effects via the Luttinger Hamiltonian. Absorption spectra are calculated by Fermi's golden rule using highly focussed Bessel beams, which are an important realization of TL beams.

We discuss trends in absorption spectra caused by the various coupling mechanisms and compare our results for TL beams having different orbital angular momentum and polarization with conventional (plane wave-like) light. In addition, we analyze the absorption spectra of QDs with different geometries. We show that depending on the QD type and exciting light the lowest optical transition is of different character.

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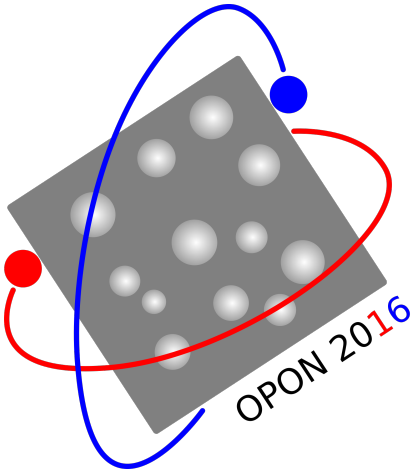

FRIDAY

On-demand indistinguishable photons generated by pulsed fluorescence from quantum dot-micropillar systems

S. Unsleber[1], Y.-M. He[1,2], S. Maier[1], S. Gerhardt[1], X. Ding[2], C.-Y. Lu[2], J.-W. Pan[2], M. Kamp[1], C. Schneider[1], S. Höfling[1,2,3]

[1] *Technische Physik, Universität Würzburg, Am Hubland, D-97074 Würzburg, Germany*

[2] *Hefei National Laboratory for Physical Sciences at the Microscale and Department of Modern Physics, & CAS Center for Excellence and Synergetic Innovation Center in Quantum Information and Quantum Physics, University of Science and Technology of China, Hefei, Anhui 230026, China*

[3] *SUPA, School of Physics and Astronomy, University of St Andrews, St Andrews, KY16 9SS, United Kingdom*

Bright, efficient sources of single photons are key elements for quantum optics applications, including quantum networks and linear optical quantum computing. Embedded in bulk semiconductor, however, quantum dot based single photon sources suffer from poor photon extraction efficiencies (similar to other solid state approaches), since only a minor fraction of the photons can leave the high refractive index material. This problem can be mitigated by integrating QDs into optical microcavities, which can enhance extraction efficiencies significantly. In this contribution, we summarize recent progress we have made on indistinguishable single photon emission [1-8].

We report the emission of bright and indistinguishable single photons via a deterministically excited QD-exciton in a micropillar. Via a cross-polarization configuration, we can suppress the backscattered laser light by approximately seven orders of magnitude. We are then able to excite a QD in a microcavity directly into its s-shell. The obtained results are very encouraging in terms of multi-photon entanglement experiments.

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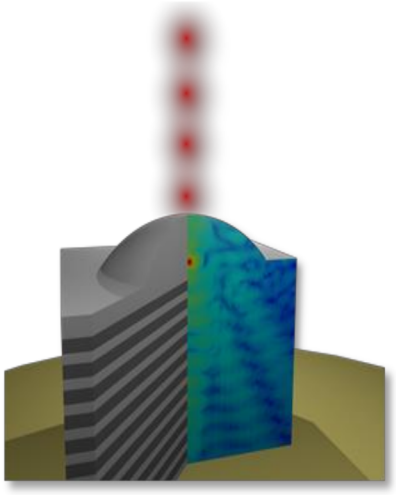
Quantum Dot Microlenses: Building Blocks for Quantum Communication Networks

M. Gschrey[1], A. Thoma[1], P. Schnauber[1], A. Kaganskiy[1], R. Schmidt[1], B. Wohlfeil[2], M. Seifried[1], J.-H. Schulze[1], S. Burger[2], F. Schmidt[2], A. Carmele[3], A. Knorr[3], A. Strittmatter[1], T. Heindel[1], S. Rodt[1], and S. Reitzenstein[1]

[1]*Institut für Festkörperphysik, Technische Universität Berlin, Berlin, Germany*
[2]*Zuse-Institut Berlin (ZIB), Berlin, Germany*
[3]*Institut für Theoretische Physik, Technische Universität Berlin, Hardenbergstraße 36, 10623 Berlin, Germany*

The realization of building blocks for quantum networks has become one of the driving forces for the development of advanced nanophotonic device concepts and nanofabrication technologies [1]. Within this field, significant progress has been achieved regarding for instance the fabrication of efficient quantum dot (QD) based single-photon sources. This work has almost elusively been performed on self-assembled QDs, which is explained by their superb optical and quantum optical properties. However, due to the self-assembled growth, neither the position nor the emission energy of individual QDs is controlled which leads to a very low yield of usable optical devices when standard nano-processing schemes are used. This issue strongly limits the applicability upscaling of single QD based photon sources in practical systems such as multi-partite quantum networks.

In this contribution I will present a nanotechnology platform for the deterministic fabrication of high quality quantum light sources based on self-assembled QDs. Our technique is based on in-situ electron-beam lithography which allows us to integrate pre-selected quantum dots into photonic devices with nm-accuracy and flexible device design [2, 3]. In this way we realize deterministic QD microlenses (see Fig. on the right) which can act as non-classical light sources with superb optical and quantum-optical properties in terms of the photon extraction efficiency, the single photon purity and the degree of photon indistinguishability [4]. I will also discuss effects limiting the photon indistinguishability and show how they can be explored by delay-time and temperature dependent Hong-Ou-Mandel experiments [5].



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Gaussian and directive emission of giant photonic trumpets

P. Stepanov [1], A. Delga [1], N. Gregersen [2], E. Peinke [1], M. Munsch [3], J. Tessier [3], J. Mork [2], M. Richard [1], J. Bleuse,[1] J.-M. Gérard,[1] and J. Claudon[1]

[1] CEA-CNRS-UJF group "Nanophysique et Semiconducteurs," CEA, INAC, SP2M, F-38054 Grenoble, France

[2] DTU Fotonik, Department of Photonics Engineering, Technical University of Denmark, Building 343, DK-2800 KongensLyngby, Denmark

[3] Department of Physics, University of Basel, Klingelbergstrasse 82, CH-4056 Basel, Switzerland

petr.stepanov@cea.fr

Photonic trumpets are broadband dielectric antennas that efficiently funnel the emission of a point like quantum emitter into a Gaussian free space beam [1]. The integration of an isolated quantum dot (QD) in such structures opens appealing prospects for solid-state quantum optics. Trumpet-shaped nanowire antennas exploit the efficient spontaneous emission control provided by a single mode, high index waveguide whose far-field emission is tailored by a top taper. So far, appreciable beam directivity has been demonstrated, but collection optics with a numerical aperture (NA) on the order of 0.7-0.8 is still mandatory to fully collect the emitted light [2].

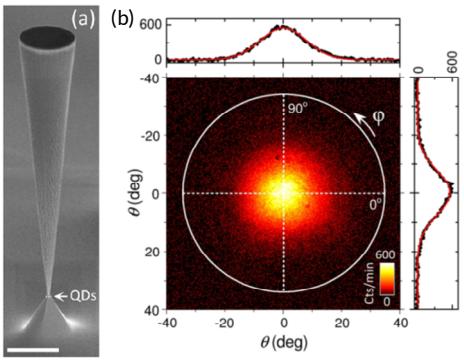

Figure 1: a) Scanning electron microscope image of the 'giant' photonic trumpet. b) Giant trumpet's far-field emission pattern.

In this work [3], we demonstrate 'giant' photonic trumpets (~5 µm wide top facet, ~27 µm height, see Fig.1(a)), which emit a very directive, Gaussian output beam. These structures are made of $Al_{0.05}Ga_{0.95}As$ and embed a single layer of self-assembled InAs QDs at their base, where a waveguide diameter about 200 nm ensures single-mode spontaneous emission. We employ Fourier imaging microscopy to map the far-field emission of a single QD embedded in the trumpet (see Fig.1 (b)). A modest NA of 0.31 is sufficient to intercept 90% of the emitted beam. Moreover, vertical and horizontal beam profiles reveal a highly Gaussian structure.

Moreover, these structures open appealing prospects for the efficient, direct coupling to a single-mode fiber. Envisioned applications include practical sources of quantum light, as well as recently proposed near-field QD-electrical field sensors and single-plasmon launchers (Ref. [4]).Such a coupling was realized recently in Ref [4], using a first generation of trumpets (top diameter 1.5 µm). In that case, the photon collection efficiency at the output of the fiber, around 6%, was mainly limited by the mode mismatch between the trumpet and the fiber. The 'giant' trumpets demonstrated in this work potentially improve the mode overlap by a factor of 5.

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From broadcasting of information to emergence of objectivity from quanta

Paweł Horodecki[1,2]

[1]*Faculty of Applied Physics and Mathematics, Gdańsk University of Technology, ul. G. Narutowicza 11/12, 80-952 Gdańsk, Poland*
[2]*National Quantum Information Centre of Gdańsk, ul. Wł. Andersa 27, 81-824 Sopot, Poland*

Quantum entanglement [1] is the strongest form of quantum correlations, however there is also a weaker version of them, namely quantum correlations beyond entanglement [2], namely the correlations that do not correspond to a random mixture of classical registers. It has been shown that only those classical mixtures represent the correlations that can be locally broadcast [3]. On the contrary some of the correlations that cannot be written in that way can be useful for remote state preparation even if they do not represent entanglement [4,5].

On the other hand, following the concept of quantum Darwinism [6] the states that represent only classical correlations have been recently shown to be important in the context of emergence of classical objectivity from quanta via some sort of micro-macro transition [7,8]. The problem was that derivation of this type phenomena, showing how some properties of a quantum system become objective (ie. possible to be read out by different observers without perturbing them [6]) is in general hard for any single physical model. In this context the important question was, whether there is any chance to show some "shadow" of emergence of objectivity even in the cases when the dynamics is not known at all. It turns out that in the case of a number n of d-level quantum systems (n much greater than d) such a "shadow-behavior is possible [9] suggesting that the classical properties of macroscopic world are deeply encoded in quantum laws of nature.

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Characterization and measurement of qubit-environment entanglement generation during pure dephasing

Katarzyna Roszak[1], Łukasz Cywiński[2]

[1] *Department of Theoretical Physics, Wrocław University of Technology, Wyb. Wyspiańskiego 27, 50-370 Wrocław, Poland*
[2] *Polish Academy of Sciences, Al. Lotników 32/46, 02-668 Warsaw, Poland*

The problem of detecting entanglement between a qubit and its environment is known to be complicated [1]. To simplify the issue, we study the class of Hamiltonians that describe a qubit interacting with its environment in such a way that the resulting evolution of the qubit alone is of pure dephasing type. Although this leads to some loss of generality, the pure dephasing Hamiltonian describes the dominant decohering mechanism for many types of qubits and is of fairly wide applicability. We define this situation by the requirement that the Hamiltonian of the qubit commutes with the qubit-environment interaction term. This relation means that the eigenstates of the qubit Hamiltonian form a preferred basis - they are pointer states [2,3] - selected by the form of the qubit-environment coupling. When both the qubit and the environment can initially be described by a (separable) wavefuntion (their state is pure throughout the evolution), an interaction between them that leads to a pure dephasing of the qubit always leads to the creation of entanglement between the two [4]. It is often assumed that a dephasing mechanism of this type must induce entanglement between the qubit and environment also when the environment is initially in a mixed state. We show that while the creation of qubit-environment entanglement in the pure dephasing case is possible when the environment is initially in a mixed state, the occurrence of this entanglement is by no means guaranteed.

We find that there are three types of situations (specified by the initial state of the environment and a relevant evolution operator which is derived from the Hamiltonian) when qubit-environment entanglement will not be generated. These are, the case when the initial density matrix of the environment is proportional to unity, the case when the relevant evolution operator cannot change the occupation of any of the eigenstates of the density matrix, and a non-trivial mixture of the two cases which allows dynamical evolution within closed subspaces of equal occupation.

Furthermore, we have shown that restricting the class of studied initial environmental states to a certain class of states (which is very common in any realistic qubit-environment setup) enables the use of a very powerful tool to measure the entanglement, since the state of the environment will remain static throughout the evolution (the state of the environment is found by tracing out the qubit degrees of freedom). Hence, the detection of any change of the state of the environment is then equivalent to the detection of entanglement.

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Quantum coherence, time-translation symmetry and thermodynamics

K. Korzekwa, M. Lostaglio, D. Jennings, T. Rudolph

Department of Physics, Imperial College London, London SW7 2AZ, United Kingdom

Fundamental laws of Nature often take the form of restrictions: nothing can move faster than light in vacuum, energy cannot be created from nothing, there are no perpetuum mobiles. It is due to these limitations that we can ascribe value to different objects and phenomena, e.g., energy would not be treated as a resource if we could create it for free. The mathematical framework developed to study the influence of such constraints on the possible transformations of quantum states is known under the collective name of resource theories.

The first and second laws of thermodynamics are such fundamental constraints that force thermodynamic processes to conserve the overall energy and forbid free conversion of thermal energy into work. Thus, a natural question to ask is: what amounts to a resource when we are restricted by these laws? It has been recently identified that apart from *athermality* (the property of a state of having a distribution over energy levels that is not thermal), also *coherence* can be viewed as a second, independent resource in thermodynamics [1]. Here we show that the first law of thermodynamics imposes not just a constraint on the energy content of systems in extreme quantum regimes but also symmetry constraints related to the thermodynamic processing of quantum coherence. We show that this thermodynamic symmetry decomposes any quantum state into mode operators that quantify the coherence present in the state [2]. We then establish general upper and lower bounds for the evolution of quantum coherence under arbitrary thermal operations, valid for any temperature. We identify primitive coherence manipulations and show that the transfer of coherence between energy levels manifests irreversibility not captured by free energy. Moreover, the recently developed thermomajorization relations on block-diagonal quantum states [3] are observed to be special cases of this symmetry analysis.

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Spectroscopy of cross-correlations of environmental noises with two qubits

Piotr Szańkowski[1,2], Marek Trippenbach[2], Łukasz Cywiński[1]

[1] *Institute of Physics, Polish Academy of Sciences, al. Lotników 32/46, PL 02-668 Warsaw, Poland*

[2] *Faculty of Physics, University of Warsaw, ul. Pasteura 5, PL–02–093 Warsaw, Poland*

Decoherence of qubits is caused by their coupling with their environment. The latter can often be well described as source of classical noise perturbing the qubits. Under assumption of stationarity and Gaussian statistics of such environmental noise, the spectral density contains full information about it. A single qubit driven by an appropriate sequence of control pulses can serve as a spectrometer of local noise affecting its energy splitting, i.e. from measurement of pure dephasing uder a sequence of dynamical decoupling pulses one can reconstruct the spectrum of the noise [1]. We show that by driving and observing two spatially separated qubits, it is possible to reconstruct the spectrum of cross-correlations of noises acting at various locations [2]. When the qubits are driven by the same sequence of pulses, real part of cross-correlation spectrum can be reconstructed, while applying two distinct sequence to the two qubits allows for reconstruction of imaginary part of this spectrum. The latter quantity contains information on either causal correlations between environmental dynamics at distinct locations, or on the occurrence of propagation of noisy signals through the environment. We illustrate the former case by modeling the noise spectroscopy protocol for qubits coupled to correlated two-level systems. While entanglement between the qubits is not necessary, its presence enhances the signal from which the spectroscopic information is reconstructed.

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Emergence of classical features in Quantum Brownian Motion

J. Tuziemski[1,2], J. Korbicz[1,2]

[1] *Faculty of Applied Physics and Mathematics, Gdańsk University of Technology, 80-233 Gdańsk, Poland*

[2] *National Quantum Information Centre in Gdańsk, 81-824 Sopot, Poland*

We analyze one of the fundamental models of decoherence and quantum-to-classical transition-Quantum Brownian Motion, and show formation of a, so called, spectrum broadcast structure. As recently shown, this is a specific structure of multi-partite quantum states responsible for appearance of classical objective features in quantum mechanics. Working in the limit of a very massive central system, we derive a time-evolving, rather than time-asymptotic, spectrum broadcast structure, leading to perceived objectivity of a state of motion. We do it for realistic, noisy random environment, modeled as a thermal bath, and present some generalization to arbitrary single-mode Gaussian states. We numerically study the formation of the spectrum broadcast structure as a function of the temperature, showing its certain noise- robustness, and derive timescales of the process using an analytical approach.

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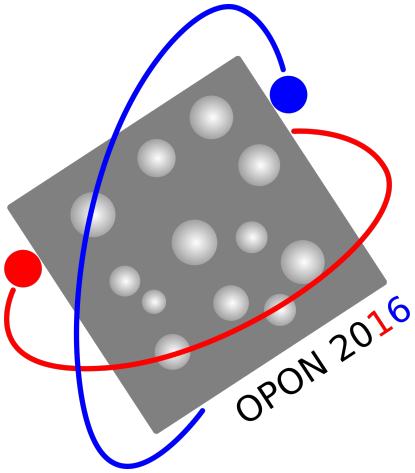

POSTERS

Phonon-impact on the preparation of dark excitons in a quantum dot

S. Lüker[1], D. E. Reiter[1], T. Kuhn[1]

[1] *Institut für Festkörpertheorie, Universität Münster, 48149 Münster, GERMANY*

Dark excitons in quantum dots (QDs) offer a great potential for applications in quantum information technology, e.g., as data storage. In contrast to the commonly considered bright excitons a dark exciton consists of an electron and a heavy hole with parallel spins. According to the dipole selection rules dark excitons do not couple to the light field. Because they are optically inactive, dark excitons possess a significantly longer lifetime than bright excitons. On the other hand, the preparation of a dark exciton is challenging.

While there are in general two bright and two dark excitons in a QD, for excitation with circularly polarized laser pulses it is possible to reduce the complete system to a three-level system, consisting of the ground state, one bright and one dark exciton. To access the dark exciton, a coupling between bright and dark excitons is required, which can be mediated, e.g., via an in-plane magnetic field or via the exchange interaction with a magnetic ion, like a manganese ion. Then the optical preparation of the dark exciton is possible for excitation with detuned or chirped, i.e., frequency-swept, laser pulses [1]. For excitations with chirped pulses we find that the dark exciton preparation is only possible for positive chirp coefficents. A similar asymmetry appears for excitation with detuned laser pulses with respect to the sign of the detuning.

Since the QD is embedded in a semiconductor matrix, the interaction with phonons has to be taken into account. Using the three-level approach we study how the dark exciton preparation is affected by the carrier-phonon interaction. The usual phonon impact as a source of decoherence leads to a slight reduction of the preparation efficiency. Besides this effect the carrier-phonon coupling can even enable transitions to the dark exciton. The phonon-assisted processes result in a more symmetric behavior and enable, e.g., the dark exciton preparation for negatively chirped pulses.

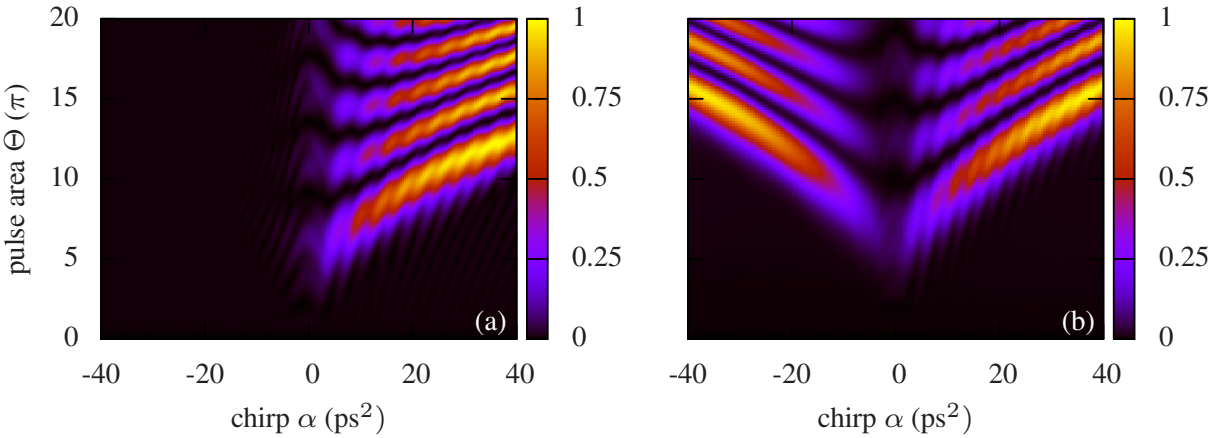

Figure: Dark exciton occupation for excitation with a chirped laser pulse for (a) the phonon-free model, and (b) the model including the carrier-phonon interaction.

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P-shell exciton complexes with neutral-exciton-like exchange interaction in CdTe/ZnTe quantum dots

T. Smoleński [1], T. Kazimierczuk [1], M. Goryca [1], M. Koperski [1], P. Wojnar [2], A. Golnik [1], P. Kossacki [1]

[1] *Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Poland*
[2] *Institute of Physics, Polish Academy of Sciences, Warsaw, Poland*

Carrier-carrier interactions are an important factor determining energy of exciton complexes in self-assembled quantum dots (QDs). In particular, the fine structure of a given excitonic complex is a result of the exchange interaction. For example, in the simplest case of the neutral exciton consisting of a single electron and a single hole there are four eigenstates with characteristic energy spectrum of a pair of bright states separated from a pair of dark states by energy commonly denoted by δ_0. This *isotropic* exchange splitting is usually accompanied by a smaller *anisotropic* exchange splitting of the two bright states by energy δ_1. Such a picture is known to be valid for the ground state neutral exciton in different material systems. In general, more complex excitons exhibit more complex spectra. However, in our work we demonstrate that the same pattern of exchange interaction can be observed for a few other excitonic complexes.

Here we focus on two exciton complexes: a "hot" neutral exciton with both carriers on the *p*-shell and a doubly negatively charged exciton (X^{2-}) recombining to a two-electron singlet state. By using either the excitation spectroscopy or the non-resonant photoluminescence we show that in both cases the optical spectrum features a single pair of orthogonally polarized lines, in close analogy to the neutral exciton. Similarly, in each case the magnetic field in Faraday configuration increases the observed splitting according to a general formula: $\sqrt{(g\mu_B B)^2 + \delta_1^2}$. By applying the magnetic field in Voigt configuration or by comparison against the emission to the triplet state in the case of X^{2-} we additionally determine the corresponding isotropic exchange constant δ_0. As a result, we fully describe three cases of exchange interaction: between *s*-shell electron and *s*-shell hole (from the neutral exciton), between *p*-shell electron and *p*-shell hole (from the "hot" neutral exciton), and between *p*-shell electron and *s*-shell hole (from the doubly negatively charged exciton).

We conclude that both *p*-shell neutral exciton and doubly negatively charged exciton are viable substitutes for the neutral exciton regarding the structure of the energy spectrum, which opens a possibility to explore different regimes of exchange parameter values. A proof-of-concept for this idea is an observation of a characteristic 6-fold splitting of doubly negatively charged exciton in a QD doped with a single Mn^{2+} ion.

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Mechanism and dynamics of biexciton formation from a long-lived dark exciton in a CdTe quantum dot

Tomasz Smoleński [1], Mateusz Goryca [1], Tomasz Kazimierczuk [1], Piotr Wojnar [2], Piotr Kossacki [1]

[1] *University of Warsaw, Faculty of Physics, Institute of Experimental Physics, ul. Pasteura 5, 02-093 Warsaw, Poland*
[2] *Polish Academy of Sciences, Institute of Physics, al. Lotników 32/64, 02-688 Warsaw, Poland*

Numerous optical studies of various quantum dot (QD) systems established a toolbox of techniques effective in characterization of single-dot photoluminescence (PL) spectra. In particular, measurement of the PL spectrum as a function of the excitation intensity is often employed to distinguish between spectroscopic lines related to different excitonic complexes [1]. The results are usually discussed in terms of a power-law behavior of the PL intensity. The simplistic stochastic model states for example that the formation of the biexciton requires a coincidence of two exciton formation events [2], and thus the biexciton PL intensity should increase quadratically with the excitation power. In real experiments, however, the biexciton PL intensity does not follow this prediction and exhibits less steep dependence [3].

Here we analyze the dependence of a single CdTe QD PL on pulsed excitation intensity and demonstrate contributions of two mechanisms of the biexciton formation: either from an empty dot by capture of two electron-hole pairs within a single excitation pulse or from a resident dark exciton created earlier [4]. We show that in the wide range of intensities the latter mechanism is dominant, which provides a natural explanation for subquadratic biexciton PL intensity power dependence. It is also a general example of the importance of the dark exciton state, which is often neglected [3,5], but should be taken into account in the rate-equation models to correctly describe the QD physics under various excitation regimes, including the CW excitation.

The discussed mechanism allows us to create the single biexciton with the use of two different laser pulses, polarization of which can be controlled independently. We exploit this possibility in the time-resolved experiments to study the impact of a carrier spin-blockade effect on the biexciton (and other excitonic complexes) formation dynamics. Our results show that the formation of the biexciton is slowed down when the two consecutive pulses used to create this complex have opposite circular polarization. Such effect is caused by relatively long relaxation time of a spin blockaded electron pair, while the spin-blockaded holes relax rapidly to their ground state.

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Design, growth and spectroscopy of coupled ZnTe planar optical microcavities

M. Ściesiek[1], J. Suffczyński[1], W. Pacuski[1], J. G. Rousset[1], M. Parlińska-Wojtan[2], and A. Golnik[1]

[1] *Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland*
[2]*Facility of Electron Microscopy & Sample Preparation, Center for Microelectronics and Nanotechnology, Faculty of Mathematics and Natural Sciences, University of Rzeszow, Rzeszów, Poland*

Coupled photonic structures have recently attracted much attention, mostly due to perspective of applications in quantum information science and laser technology. Here, we demonstrate the design, growth and results of spectroscopy measurements on samples containing two vertically coupled planar ZnTe microcavities.

The structures are designed by Transfer Matrix Method calculations. A Distributed Bragg Reflector (DBR) constituted by a stack of ZnTe layers and MgSe/ZnTe/MgTe/ZnTe superlattices (playing a role of respectively high and low refractive index material) is grown on a ZnTe buffer. Next, two λ-cavities separated by either 6 or 12 DBR pairs are grown. A mutually perpendicular gradient of the cavities thicknesses results in variation of a detuning between the cavities modes dependent on the position on the sample. It enables a continuous change of a coupling between microcavities. The upper microcavity contains a layer of CdTe Quantum Dots and it is covered with 16 DBR pairs. The result of scanning transmission electron microscopy (STEM) characterization of the structure is shown in Figure 1.

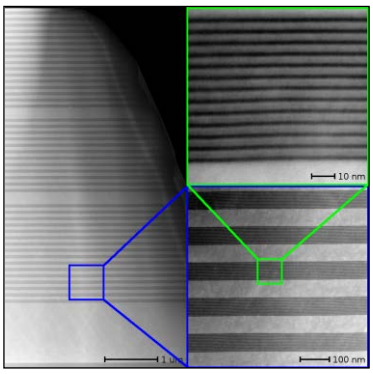

Figure 1: STEM images of the sample in consecutive enlargements.

Linewidths of the modes determined in reflectivity measurements resolved in momentum space are equal to 0.76 meV, what yields a quality factor of the cavities Q = 2500. Energies of the modes and edges of the DBR stopband are determined as a function of the position on the sample by photoluminescence (E_{exc} = 3.06 eV) and reflectivity mapping measurements performed at 10 K or 300 K. A spatial resolution attains 50 μm and a scanned area covers a whole surface of a 2-inch wafer.

The cavity mode energies found in the reflectivity agree well with the ones evidenced in the photoluminescence. In regions of the sample, where the modes are strongly detuned, their energies and intensities vary independently of each other when the position on the sample is varied. However, in the region, where the modes are at resonance, a clear anticrossing (see Figure 2) and equal intensities of the modes are observed. This proves the coupling between the modes of the cavities predicted by the calculations. The modes splitting at resonance as large as 45 meV is found when cavities are separated with 6 DBR pairs. The splitting drops down to 17 meV when the separation is increased to 12 DBR pairs, indicating a possibility of control of the modes interaction strength.

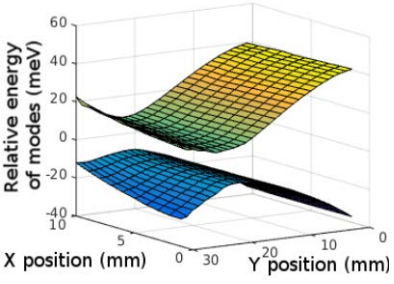

Figure 2: Energies of the optical modes as a function of a spatial position on the sample. A mode anticrossing with the splitting equal to 17 meV is evidenced.

Circular Bragg grating cavity design for efficient sources of single photons fabricated within a deterministic technology platform

Anna Musiał [1,2], Benjamin Wohlfeil [3], Sven Burger [3], Tobias Heuser [1], Arsenty Kaganskiy [1], Esra Yarar Tauscher [1], Ronny Schmidt [1], Sven Rodt [1], Stephan Reitzenstein [1]

[1] *Institut für Festkörperphysik, Technische Universität Berlin, Berlin, Germany*
[2] *Laboratory for Optical Spectroscopy of Nanostructures, Faculty of Fundamental Problems of Technology, Wrocław University of Technology, Wrocław, Poland*
[3] *Computational Nano Optics, Zuse Institut Berlin, Berlin, Germany*

Growing interest in the field of quantum information processing, data transmission and security requires realization of very efficient non-classical light sources. Practical realization of quantum protocols makes the deterministic fabrication technologies of such devices very desirable [1]. Main limitation of up-to-date solutions is the extraction efficiency of emission from quantum dots (QDs) embedded in semiconductor material. Various type of nanostructures and geometries, e.g., microcavities or waveguiding photonic nanowires, were proposed to enhance the efficiency of single photon sources (SPSs). To tackle these issues we propose to deterministically integrate single QDs into circular Bragg grating cavities (CBGC) which have been theoretically proven highly beneficial for vertical extraction efficiency η [2]. Moreover, SPSs featuring photon collection efficiencies as high as 0.48±0.05 into numerical aperture of NA=0.4 have been realized with CBGC positioned with respect to the single self-assembled QD using photoluminescence imaging approach [3].

The presented work focuses on the modelling of CBGC using finite element method within commercially available solver – *JCMWave* which allows one to optimize the cavity design parameters for maximum η. This is an important step towards realization of efficient fully deterministic SPSs. It is planned to combine high η in an optimized cavity design with our deterministic in-situ cathodoluminescence lithography (CLL) [1] which allows for spatial and spectral matching of target QDs and CBGCs. To accomplish this goal it is very important to be able to design the final device with respect to its output characteristics. For this purpose, a detailed knowledge of the influence of cavity geometry on the electro-magnetic field distribution, mode energy, cavity quality factor and optimal position of the QD in the CBGC is indispensable. For a passive cavity modes with emission energy within the QD emission band have been investigated and for these providing the highest electric field energy within the CBGC the grating parameters have been optimized with η into NA=0.4 as a figure of merit. High η over 0.8 into low NA of 0.2 beneficial for increasing final device output into multi- or single-mode fibers is predicted. First cavities – passive and with active medium of high density QDs have been realized, optically characterized and compared to the numerical results. These results are very important as the active medium of the device would consist of self-assembled QDs and the resonator has to be designed and matched to the chosen high quality single QD and its optical properties (mainly the emission energy) and fabricated precisely relatively to the QD position.

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Size dependence and spatial range of plasmon effect in photovoltaics - theory and experiment

Artur Henrykowski, Witold Jacak

Wrocław University of Technology, Wybrzeże Wyspiańskiego 27, Wrocław, Poland

The efficiency of photovoltaic devices may be increased by proper incorporation of metallic nanoparticles into the device structure. A variety of experiments showed significant photocurrent enhancement due to deposition of noble-metals (mainly gold and silver) spherical nanoparticles. The effect has been observed for solar cells of various technologies, such as silicon or CIGS. It also strongly depends on concentrations, size and material of metallic components [1].

Mechanism of plasmon-mediated energy transfer can be described in terms of the microscopic quantum RPA-type model of plasmons in large metallic nanocomponents [2]. In this approach the competition between two opposing factors governs this phenomenon: the field concentration in plasmon oscillations and the admittance of indirect inter-band transitions in a semiconductor substrate induced by dipole coupling to plasmons at the nanoscale. The former effect favors larger metallic nanocomponents, whereas the latter one prefers smaller nanocomponents. Both factors are quantitatively addressed within the quantum Fermi golden rule scheme, which allows for the size-dependence analysis of the plasmon effect as one of the critical factors important for the technology and applications.

Theoretical predictions are supported by experimental verification including the demonstration of the proximity and size effect in double-layer photo-active substrate. The experiment reveals that the plasmon effect is still present if metallic nanoparticles are separated from substrate by the distance of order of 1 μm [3].

Moreover the effect reveals sensitivity to device geometry and nanoparticle deposition type. The coupling efficiency between plasmon and semiconductor electrons has been estimated for the nanoparticle immersed in the active layer of solar cells and deposited on the top on its surface.

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Surface plasmon resonance in metallic nano-particles: comparison of RPA, FEM calculations and Mie theory

K. Kluczyk [1], W. A. Jacak [1]

[1] *Department of Quantum Technologies, Faculty of Fundamental Problems of Technology, Wrocław University of Technology, Wybrzeże Wyspiańskiego 27, 50-370 Wrocław, Poland*

Metallic nano-structures, due to their remarkable optical properties related to plasmon excitations, have numerous prospective applications for photonics and photovoltaic devices. One of many examples are solar cells with enhanced efficiency, sub-diffraction light waveguides and single molecule detectors (based on enhanced Raman scattering) [1].

The experiment shows that the surface plasmon resonance (SPR) heavily depends on the nanoparticle size, shape and refractive index of the surrounding media. A proper understanding of those correlations is therefore crucial for designing future plasmon devices. The first explanation of this phenomena based on classical electrodynamics was presented by Mie in 1908 [2]; nevertheless, Mie theory does not describe the underlying microscopic mechanism of electron oscillations, which is included phenomenologically by the crude Drude-Lorentz model dielectric function of the metal.

We have investigated the plasmon resonance frequency dependence on the nanoparticle size and shape within theoretical and numerical approaches, comparing the results with the available experimental data and Mie theory. The proposed microscopic approach [3] is based on random phase approximation for electrons in the metallic nanosphere, including plasmon damping by electron scattering and by radiative losses (i.e., by the so-called Lorentz friction).

The numerical approach employs the finite element method (FEM) solution to Maxwell equations for the incident planar wave and nanoparticle geometry and material, and was carried out by the commercial system COMSOL [4]. The calculations are supplemented with the phenomenologically modelled dielectric function of the metallic nano-particle. We present the comparison of SPR dependence on size for different plasmon damping mechanisms (scattering, radiative losses), implemented into the model dielectric function for Au and Ag particles.

The comparison of theoretical predictions, numerical calculations and experimental data for Au and Ag nano-particles demonstrates a strong correlation of SPR with the size and shape of the nano-system and supports the importance of the Lorentz friction in plasmon damping.

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Simulation of electric field patterns modified by metallic nanoantennas

Richard Kerber[1], Jamie Fitzgerald[2], Sang Soon Oh[2], Ortwin Hess[2], Tilmann Kuhn[1], Doris E. Reiter[1]

[1] *Institut für Festkörpertheorie, Universität Münster, Wilhelm-Klemm-Straße 10, 48149 Münster, Germany*
[2] *Blackett Laboratory, Department of Physics, Imperial College London, London SW7 2AZ, United Kingdom*

Metallic nanoantennas are known to greatly enhance light fields and the geometry of nanoantennas influences the polarization properties of the electric field. When a nanoantenna is coupled to a semiconductor nanostructure, e.g., a quantum dot, the polarization plays an important role in the creation of electron-hole pairs. Focussing on linear and circular polarization, we perform a systematic study of nanoantennas, revealing effects of geometry on the electric field polarization. For the simulation we use the boundary element method. We consider nanoantennas consisting of gold nanostripes, which are arranged in a circle around a gap region. Different geometries are studied by varying length and number of the stripes. The impact of symmetry in a dimer nanoantenna is analyzed by changing the angle between the two nanostripes.
The results show a strong dependence of the electric field on the excitation polarization and the antenna geometry. For a dimer nanoantenna, which consists of two nanostripes, the field patterns show the characteristic behavior of a dipole. If the excitation polarization is along the antenna, the light field in the gap region is enhanced. The antenna radiation is mostly perpendicular to the antenna. When we rotate the polarization axis, only the part along the antenna contributes to the enhancement. Next, the nanostripes have a certain angle to each other as shown in the left part of fig. 1. The time response indicates that the polarization can be converted into circular or elliptical polarization. We will show that the results of dimer antennas are helpful for the interpretation of the field patterns of gold nanostructures, which consist of more nanostripes.

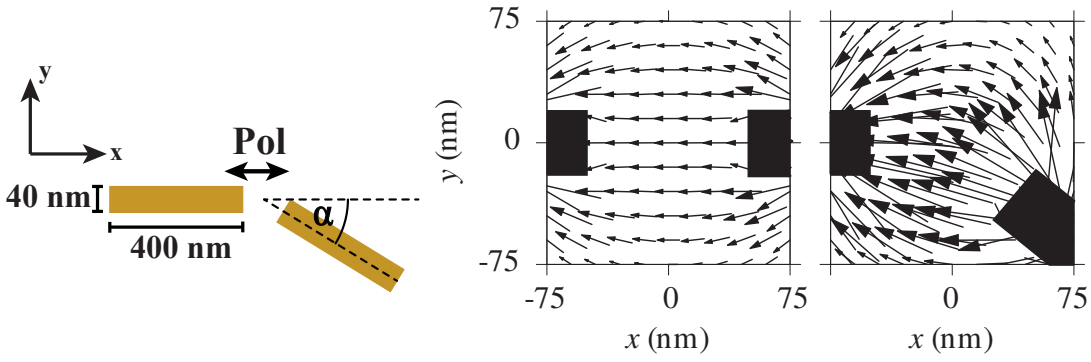

Figure 1: Left: Sketch of nanoantenna with two nanostripes, which have an angle α between each other. Right: Electric field patterns of dimer nanoantenna with $\alpha = 0°$ and $\alpha = 40°$.

Recombination losses in n-ZnO nanorods/p-Si plasmonic solar cells

K. Gwóźdź[1], E. Popko[1], Z. Gumienny[1], E. Zielony[1], R. Pietruszka[2], B. S. Witkowski[2], K. Kopalko[2], M. Godlewski[2,3]

[1]Department of Quantum Technologies, Faculty of Fundamental Problems of Technology, Wroclaw University of Technology, Wybrzeze Wyspianskiego 27, 50-370 Wroclaw, Poland
[2]Institute of Physics, Polish Academy of Sciences, al. Lotnikow 32/46, 02-668 Warsaw, Poland
[3]Department of Mathematics and Natural Sciences College of Science, Cardinal Stefan Wyszynski University, Dewajtis 5, 01-815 Warsaw, Poland

Fast development of different kinds of solar cells and greater interest in application of photovoltaics motivate the researchers to concentrate not only on increasing the efficiency but also lowering the prices of production. One way of increasing the efficiency of cheap solar cells is using the plasmonic effect by covering them with metal nanoparticles[1].

In our studies we focused on ZnO and Si based solar cells covered with silver nanoparticles of two sizes 20-30 nm and 50-60 nm and density equal $2x10^9$ cm^{-2}. The illumination dependent current voltage characteristics were measured to obtain the source of recombination losses at the junction. From the dependence between short-circuit current and the illumination intensity the recombination coefficients for both samples were obtained to be 1.3, which indicates that in both cases the surface recombination dominates. It was found that under 1-sun illumination the efficiency for the samples with nanoparticles of sizes 20-30 nm equals 1.6 % whereas for the sample with nanoparticles of sizes 50-60 nm reaches higher value of 3.34 %. Obtained result confirms theoretical model [2], that the optimal size of the nanoparticles is close to 50-60nm. Further research is necessary to find out the reason of the low efficiency of the cells.

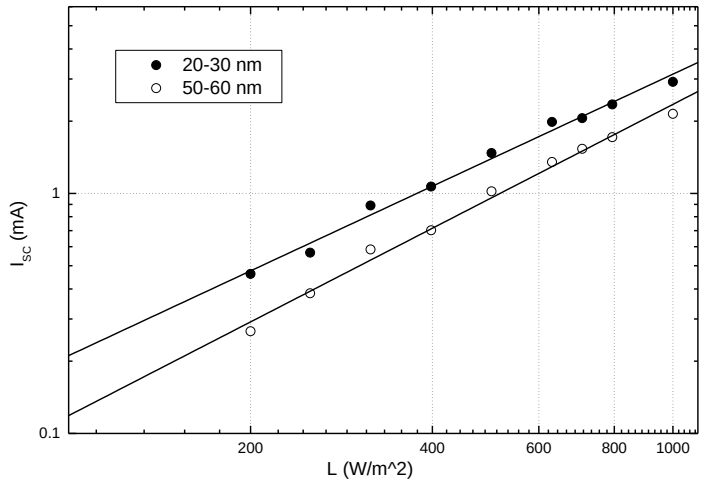

Figure 1 Short-circuit current vs illumination in the logarithmic scale. The dots are the experimental results, the solid lines are linear approximation, from which the recombination coefficients were determined.

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Intensity dependence of the Third Harmonic Generation from a Semiconductor Quantum Well

S. Guazzotti[1], A. Pusch[1], D. E. Reiter[1,2] , and O. Hess[1]

[1] *Department of Physics, Imperial College London, London SW7 2AZ, UK*
[2] *Institute for Solid State Physics, University of Münster, 48149 Münster, Germany*

The generation of ever shorter optical pulses enables a host of techniques for material characterization, allowing for the exploration and manipulation of electron dynamics on its intrinsic time-scales. Semiconductor saturable absorber mirrors (SESAMs) are commonly used for femtosecond pulse generation [1], however an adequate theoretical description of the optically induced non-linear phenomena in the semiconductor is quite challenging. We combine a finite difference time domain (FDTD) description of the light field propagation that allows us to track the full light field dynamics, beyond the rotating wave and slowly varying envelope approximations, with wave-vector resolved electron dynamics in a semiconductor quantum well (QW). We describe the QW in a two band model and include Coulomb interaction [2] to account for excitonic effects which are expected to play a crucial role in the non-linear physics. With this method we go beyond commonly used FDTD approaches which model the semiconductor as a simple few level model. We employ this approach to describe the process of third harmonic generation in a InGaAs QW that is illuminated with intense femtosecond pulses.

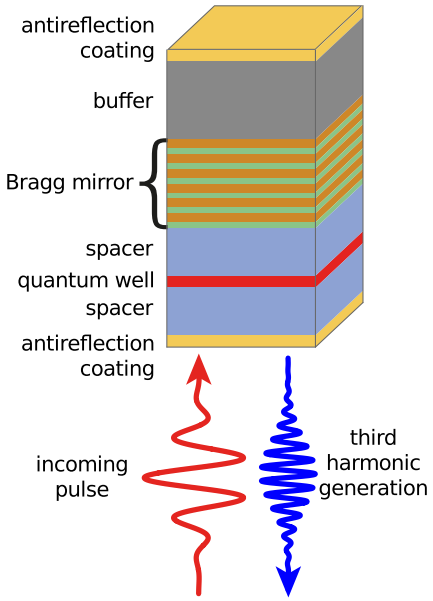

Figure 1: Schematic of the structure and setup

A typical SESAM structure is presented in Fig. 1. The optically active region is composed of a $In_{0.2}Ga_{0.8}As$ quantum well embedded in GaAs host material. In order to allow for an efficient in-coupling of the light we assume an antireflection coating on the structure tuned to the central wavelength of the pulse. We locate the QW in a node of the electric field distribution generated by the Bragg mirror to get an enhancement of the field amplitude at the QW compared to the incoming pulse in free-space.

Intense femtosecond pulses impinging on the semiconductor structure initially experience excitonic absorption, which generates a substantial carrier density in the conduction band. This acts to weaken the excitonic absorption and red-shifts the band-gap of the QW due to band-gap renormalization effects. Depending on the detuning of the excitation we find a different relation between the intensity of the harmonics and that of the exciting pulse.

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Impact of the dynamically tuned 2DEG density on the photoluminescence of CdTe and CdMnTe quantum wells

J. Rautert[1], J. Debus[1], D. Braukmann[1], V. Yu. Ivanov[2], D. R. Yakovlev[1,3], G. Karczewski[2], T. Wojtowicz[2], and M. Bayer[1,3]

[1] *Experimental Physics 2, TU Dortmund University, Dortmund, Germany*
[2] *Institute of Physics, Polish Academy of Sciences, Warsaw, Poland*
[3] *Ioffe Institute, Russian Academy of Sciences, St. Petersburg, Russia*

A highly concentrated two-dimensional electron gas (2DEG) in a modulation-doped semiconductor quantum well (QW) shows many interesting features in both transport measurements and optical spectroscopy, like the integer and fractional quantum Hall effect. It is known that the formation of trion and exciton complexes in a modulation-doped QW strongly depends on the 2DEG density, which can be controlled by the laser power and its energy as well as by an external magnetic field.

We study the competition between the 2DEG and negative trion photoluminescence in the stationary and time-resolved regime, which shows up for several hundreds of microseconds, for a CdTe/CdMgTe modulation-doped QW at different magnetic fields. By comparison, in a CdMnTe/CdMgTe modulation-doped QW the exciton magneto-photoluminescence demonstrates variations in the energy for transitions between different quantum Hall regimes at elevated temperatures above 1.5 K. Moreover, the 2DEG- and exciton-photoluminescence lines may anticross at different points of time with increasing magnetic field.

Bismuth diluted III-V semiconductor materials for quantum well based optoelectronic devices.

Maciej P. Polak, Paweł Scharoch, Robert Kudrawiec

Wroclaw University of Technology, Faculty of Fundamental Problems of Technology, Wybrzeże Wyspiańskiego 24, 50-370 Wroclaw, Poland

Highly mismatched alloys (HMAs), which Bi diluted III-V semiconductors are a representative of, exhibit some extraordinary properties such as very strong reduction of the band gap and its giant bowing. A group of most common III-V semiconductors has been studied theoretically within the density functional theory (DFT) in order to determine the changes in their bandstructure with the incorporation of Bi in a dilute regime. Particular attention was paid to the relative band alignment of Bi diluted materials and their pure III-V counterparts, and for that purpose a novel method of band offset determination based on the comparison of the Kohn-Sham potential of pure and diluted alloys has been developed. The study allowed us to determine the confinement of carriers in hypothetical quantum wells (QWs) based on these materials. In all cases we found that the addition of bismuth lowers the energy of the conduction band (CB) and increases the energy of the valence band (VB) which would result in confinement of both electrons and holes, therefore creating a type I QW, the most convenient type for optoelectronic applications, light emitting devices in particular. The calculated values have also been carefully compared with available experimental data and found to be in an excellent agreement, which proved the reliability of the techniques used. For each of the six studied alloys ($GaP_{1-x}Bi_x$, $GaAs_{1-x}Bi_x$, $GaSb_{1-x}Bi_x$, $InP_{1-x}Bi_x$, $InAs_{1-x}Bi_x$, and $InSb_{1-x}Bi_x$) we present the parameters needed for modeling of QW devices such as the band gap reduction rates with the contribution of CB and VB to these reductions, the band gap bowing and the parameters used in the valence band anticrossing model (VBAC). We then use simple models to approximate the energies of optical transitions in QWs based on these materials and propose the compositions and widths of the QWs for which the most interesting results can be achieved. For more details please see [1].

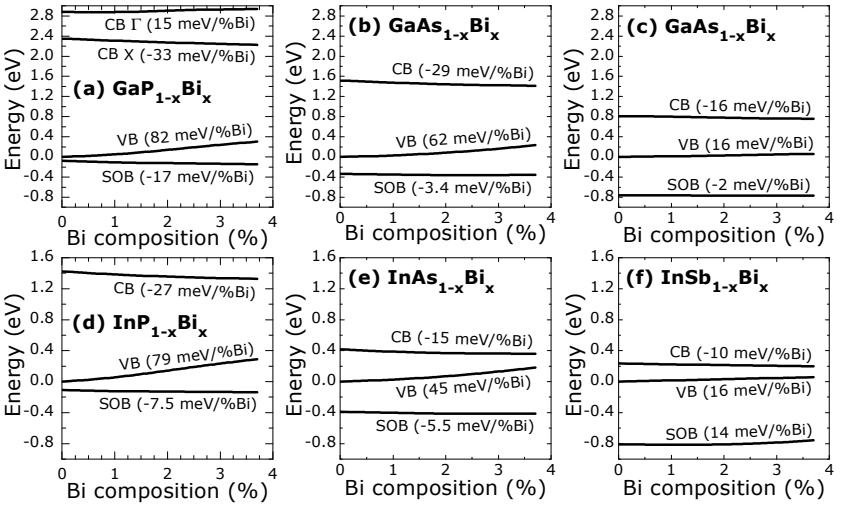

Fig. 1. Relative alignment of bands as a function of composition in all studied alloys in their dilute regime.

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Spin relaxation studies of an individual Co^{2+} ion in a CdTe/ZnTe quantum dot

A. Bogucki , M. Goryca , K. Oreszczuk , T. Smoleński , J. Kobak , W. Pacuski , P. Kossacki

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Ul. Pasteura 5, 02-093 Warsaw, Poland

Studies of single dopants in semiconductors constitute one of the research areas of the dynamically developing field of solotronics [1]. The progress of the field is driven by the perspectives of the ultimate miniaturization of information storage and processing devices, as well as by the possibility to investigate interactions between impurities and the host crystal in a single-atom scale. From scientific point of view quantum dots (QDs) containing single magnetic dopants seem to be as a model system to study those interactions. Until recently, only QDs with single manganese ions have been investigated, since other magnetic impurities were believed to quench any photoluminescence (PL) of the dots. However, this turned out not to be true in the case of a single impurity embedded in the dot, as a few new systems of single magnetic ions in semiconductor QDs were presented [2]. Systematic investigations on spin dynamics in those systems are important in the context of future optoelectronic devices.

In this work we present studies of spin dynamics of a single Co^{2+} ion embedded in a CdTe/ZnTe QD. The sample used in the experiment contains a single layer of MBE-grown, self-assembled dots. The presence of a single Co^{2+} ion in selected dots was confirmed by observation of characteristic patterns in the excitonic PL spectrum with and without magnetic field [2]. In order to determine spin-relaxation time of the single Co^{2+} ion we performed time-resolved measurements of the QD PL under quasi-resonant, modulated excitation (see Fig. 1). It is experimentally simpler than the method previously used for the Mn^{2+} ion [3]. The measurements were carried out at various magnetic fields. The obtained values of relaxation time stay in an agreement with the values determined previously under non-resonant excitation [2] and are much shorter than those reported for the Mn^{2+} ion [3].

We discuss the impact of the local strain on the spin relaxation. The Co^{2+} ion has non-zero orbital momentum, thus it is more sensitive to the local anisotropy of surrounding lattice than the Mn^{2+} ion. Analyzing different dots, we show that local distortion has minor influence on the cobalt relaxation time. This new observation can help to determine the spin-lattice relaxation mechanism of a single magnetic ion in a QD.

We also show that similarly to the case of the QDs with Mn^{2+} ions [3], qusi-resonant injection of spin polarized excitons leads to the orientation of the Co^{2+} spin. The time resolved measurements of this effect reveals that the spin orientation efficiency per one exciton for a Co^{2+} ion in a CdTe dot is much larger than for Mn^{2+} ion in a similar dot.

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Charge and spin injection in a quantum well–quantum dot system

Adam Mielnik–Pyszczorski, Krzysztof Gawarecki, Paweł Machnikowski

Department of Theoretical Physics, Faculty of Fundamental Problems of Technology, Wrocław University of Technology, Wybrzeże Wyspiańskiego 27, 50-370 Wrocław, Poland

The system composed of a quantum well and a quantum dot (QW–QD) has been studied in experiment and theory [1,2]. It turns out that the high density of states in the QW increases efficiency of injection of carriers into QDs. The observed efficient tunneling of carriers combined with techniques of optical orientation and coherent spin control suggest that the QW could also serve as an effective spin injector for the QD structures.

In this contribution we theoretically investigate the process of electron tunneling from a QW to a nearby QD. In order to study the charge and spin dynamics we first determine the strain distribution in the system [3]. The lattice deformation is important in the consideration of a realistic structure since it has strong influence on the band edges, generates a piezoelectric field, which results in additional localization of electrons in the vicinity of the QD, and also, in an external magnetic field, contributes to the effective g–factor. We calculate electronic wave functions within 8–band $k\cdot p$ Hamiltonian including the strain field and the spin–orbit interaction, reduced to a 2–band ($|e\uparrow\rangle$, $|e\downarrow\rangle$) model by Löwdin perturbation theory. We then use the resulting single electron spinor wave functions to calculate the electron evolution within the correlation expansion approach.

We study phonon–induced system relaxation to its ground state localized in the QD (carrier injection), as well as the spin dynamics during this process (spin injection). For carrier injection, we obtained non–monotonic dependence of the relaxation rate on the distance between the QD and the QW. We found an exponential evolution of the average number of electrons in the dot and a non–exponential evolution of the state occupations in the well [1]. We study also the spin evolution during tunneling in order to estimate the spin–flip probability and assess the efficiency of spin injection. We compare spin flip processes generated by various spin–phonon coupling mechanisms.

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Spin dynamics and magneto-optical response in charge-neutral tunnel-coupled quantum dots

Michał Gawełczyk, Paweł Machnikowski

Department of Theoretical Physics, Wrocław University of Technology, Wybrzeże Wyspiańskiego 27, 50-370 Wrocław, Poland

In this contribution, we provide a model of the electron and hole spin dynamics in a double quantum dot structure [1], considering the carrier tunneling between quantum dots, which is enhanced by an electric field. Taking into account also the presence of an in-plane or tilted magnetic field, we provide the simulation of magneto-optical experiments which are performed currently on such structures to probe the temporal spin dynamics.

Probing exciton spin dynamics in neutral structures is limited by recombination much faster than the actual spin dynamics. In doped structures, in turn, the initialization of resident spins is subject to the intrinsic dephasing [2] affecting the results of experiments sensitive to spin coherence [3]. The search for undoped systems with long-living spins brought a proposal and first realizations of double quantum wells and dots, in which exciton is spatially separated due to the carrier tunneling.

In our model of such system, spin precession in the magnetic field is treated exactly, while the dissipative dynamics of the system (spin relaxation, dephasing, carrier tunneling between quantum dots, and recombination) is described in the Markov limit by the universal Lindblad superoperator in the master equation for the density matrix evolution. Moreover, we include the spin-orbit coupling effects, which give rise to the mixing of states with different angular momenta and in cosequence to the probability of spin-flip tunneling of carriers. To obtain the direct correspondence with experimentally measured quantities we employ the numerical solution for the density matrix and construct substantial dynamical variables such as spin polarization and coherences for each of QDs.

We reproduce the experimentally observed effect of the extension of the spin polarization life time caused by the charge separation, which occurs in structures of this type. Moreover, we provide a number of qualitative predictions concerning the necessary conditions for observation of this effect as well as about possible channels of its suppression. We consider also the impact of the magnetic field tilting, which results in an interesting spin polarization dynamics. Finally, we discuss the relevance of the spin-flip tunneling caused by the spin-orbit interaction for typical systems.

We find that the effect of spin polarization life time extension depends essentially on the ratio of tunneling time to direct exciton recombination time. The spin-orbit interactions and spin-flip tunneling caused by it lead to the loss of spin coherence which occurs once during the tunneling process at low temperature and accumulates in time at higher temperature. The strength of this effect scales with the localization length, which makes it negligible for small QDs.

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Competition between exchange interaction and spin-orbit coupling in the spin dynamics of paramagnetic II-VI diluted magnetic semiconductors

F. Ungar[1], M. Cygorek[1], P. I. Tamborenea[2], V. M. Axt[1]

[1] *Theoretische Physik III, Universität Bayreuth, 95440 Bayreuth, Germany*
[2] *Departamento de Física and IFIBA, FCEN, Universidad de Buenos Aires, Ciudad Universitaria, Pab. I, C1428EHA Buenos Aires, Argentina*

The spin dynamics of paramagnetic II-VI diluted magnetic semiconductors (DMS) is, on a picosecond time scale, usually dominated by the sd exchange interaction (EI) between quasi-free conduction band electrons and localized dopants, while other mechanisms such as spin-orbit interaction (SOI) are typically neglected. Nevertheless, regimes can be found where EI and SOI are of comparable strength [1], such as in extremely diluted systems excited with excess energies of the order of 10 meV above the band gap. Here, we explore the interplay between the EI and the SOI with respect to the time evolution of the total electron spin.

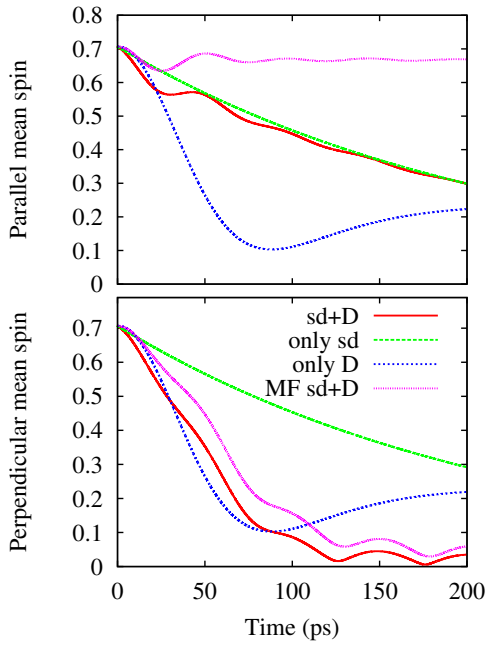

Figure 1: Time evolution of the mean electron spin component parallel (top) and perpendicular (bottom) to the net Mn magnetization in bulk $Zn_{1-x}Mn_xSe$ with sd EI (sd) and Dresselhaus SOI (D). Also shown is the mean-field part of the EI (MF sd) together with the SOI. All parameters are taken from [1].

Figure 1 shows the temporal evolution of the mean electron spin component parallel and perpendicular to the averaged Mn magnetization in a bulk DMS system under the influence of Dresselhaus SOI. The calculations have been performed using a quantum-kinetic formalism [2,3] which accounts for genuine correlations between the electronic and the Mn system. We find that the SOI generally introduces oscillations of the carrier spin or, in case of the perpendicular spin component, even leads to a significantly faster spin decay.

Furthermore, parallel to the Mn magnetization, already the mean-field part of the sd EI suppresses the dephasing caused by the SOI, as can be seen from the MF sd+D result in the upper picture. Thus, the precession of the carriers around the axis defined by the net Mn magnetization effectively suppresses spin dephasing along this axis.

Apart from bulk systems one can also consider quantum wells where the SOI is often dominated by the Rashba field. Here, similar to the bulk case, the SOI leads to strong oscillations of the total electron spin but leaves the decay rate virtually unchanged.

As a consequence, both in bulk and quasi-two-dimensional systems, regimes can be found where a strong interplay between the sd EI and the SOI exists, so that the exchange coupling no longer dominates the spin dynamics.

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Hole spin dynamics in coupled quantum dots

M. Krzykowski, M. Gawełczyk, P. Machnikowski

Department of Theoretical Physics, Faculty of Fundamental Problems of Technology, Wrocław University of Technology, Wybrzeże Stanisława Wyspiańskiego 27, 50-370 Wrocław, Poland

Understanding of spin dynamics in a system of coupled quantum dots (QDs) is important due to its potential for future use in spintronic devices. Spin-preserving tunneling in such structures [1] can be exploited to implement a spin-initialization scheme based on exciton dissociation [2].

In this contribution we show that spin coherence is not preserved during carrier tunneling in an external magnetic field if there is a misfit between g-factors in QDs. This decoherence is present even in the absence of direct coupling between the spin and the phonon bath. It is a "welcher-weg" type of decoherence [3], where phonon bath "measures" spin as the carrier tunnels.

Our model consists of a hole coupled to a phonon bath in an external magnetic field. We model spin dynamics using a Markovian master equation in Redfield form in a broad range of parameters, such as temperature, g-factors and energy levels in QDs by solving the equation numerically.

We have found that the decoherence resulting from tunneling of the hole with emission of a phonon is strongly correlated to the difference between g-factors in the QDs. Even for a small mismatch of parameters ($\approx 10\%$) effects of decoherence during hole tunneling become important. We have also studied temperature effects on decoherence. Simulations showed a significant effect in the moderate-temperature regime, with spin decoherence times for a state in thermal equilibrium with respect to the spatial degrees of freedom being 3 orders of magnitude shorter at $T = 30$ K compared to $T = 5$ K. This exponential decay of spin coherence can be attributed to the accumulated coherence loss at repeated thermally activated tunneling between the lowest states in different QDs.

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Dynamics of entanglement between two singlet-triplet qubits: role of nuclear spin baths and charge noise

Igor Bragar and Łukasz Cywiński

Laboratory for Cryogenic and Spintronic Research, Institute of Physics, Polish Academy of Sciences, al. Lotników 32/46, 02-668 Warszawa, Poland

A singlet-triplet (S-T) qubit is a promising realization of a spin qubit [1], in which a quantum state of the qubit is stored in the joint spin state of two electrons located in two quantum dots. Specifically, the two states of the qubit are the singlet $|S\rangle$ and spin-unpolirized triplet $|T_0\rangle$. Recently it has been shown that it is possible in the experiment to perform a procedure of entangling of two S-T qubits [2]. However, the two-qubit states obtained in that experiment were not maximally entangled – due to the presence of environmental noise they were partially mixed.

We present a theoretical analysis of factors that do not allow for obtaining maximally entangled states of two S-T qubits. In particular, we consider the influence of fluctuations of gradient of effective magnetic field (the Overhauser field due to the nuclei) between the two dots, ΔB_z, as well as fluctuations of the exchange splitting between $|S\rangle$ and $|T_0\rangle$ states, J, on the efficiency of entangling procedure.

First, we consider the influence of these two factors on free evolution decay (FID) signal as well as on spin echo (SE) signal of single S-T qubit. It turns out that even quasistatic fluctuations of either ΔB_z or J lead to complete decay of the signal in the case of FID while in the case of SE the signal is only lowered proportionally to the standard deviation of quasistatic fluctuations.

The analysis of the entangling procedure of two qubits [2], in which a Hahn echo-like sequence of single-qubit rotations is employed in order to suppress the influence of environmental noise, shows that main obstacle in obtaining highly entangled states are fluctuations of two-qubit coupling, $J_{12} \propto J_1 J_2$, which are not removed by SE. We will present analytical and numerical calculations of decoherence caused by fluctuations of J_1 and J_2 due to random telegraph and $1/f^\beta$-like charge noises. In particular, we will refer to different mechanisms that can lead to decay of the efficiency of the entangling procedure in case of $1/f^\beta$ noise: decay caused by decreasing of fidelity of single-qubit manipulations (for $\beta < 1$) and decay caused by increasing infidelity of the entangling gate (for $\beta > 1$). The issue of correlated $1/f^\beta$ noises that affect the system vs two uncorrelated noises, each of which affects different qubit, will also be discussed.

This research is supported by funds of Polish National Science Centre (NCN), grant no. DEC-2012/07/B/ST3/03616.

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Optical control of charge carrier density in monolayer MoS_2 and WS_2

Joanna Kutrowska [1], Joanna Jadczak [1], Ewelina Zdanowicz [1], Piotr Sitarek [1], Ying-Sheng Huang [2], Leszek Bryja [1]

[1] *Laboratory for Optical Spectroscopy of Semiconductors, Department of Experimental Physics, Department of Fundamental Problems of Technology, Wrocław University of Technology, Wyb. Wyspiańskiego 27, 50-370 Wrocław, Poland*
[2] *Department of Electronic Engineering, National Taiwan University of Science and Technology, Taipei 10607, Taiwan*

The family of the transition metal dichalcogenides (TMDs) such as MoS_2 and WS_2 have recently attracted a big attention due to two dimensional character of covalently bonded layers held together by weaker van der Waals forces. A single layer of MX_2 (M = Mo or W and X=S, Se or Te) consist of one atomic layer of metal atoms hexagonally packed between two trigonal atomic layers of chalcogenide atoms. In single-layer form the lack of inversion symmetry leads to remarkable optical and electronic properties different from those of bulk form. Unlike different 2D crystals, such as graphene and boron nitride, they are semiconductors, hence they reveal properties more attractive for specific application e.g. in optoelectronic devices.

In this work we focus on optical properties of MoS_2 and WS_2 monolayers. The studied flakes were mechanically exfoliated from bulk crystals grown by chemical vapour transport method (CVT) and transferred on Si/SiO_2 substrates. Prepared samples were identified and characterized by optical microscopy and atomic force microscopy (AFM). The power-dependent μ-Raman scattering investigations were carried out in backscattering geometry under ambient conditions at room temperature. The excitation power varied from 10 μW to 1 mW and from 12.5 μW to 1.25 mW for the laser lines λ=532 nm and λ=633 nm, respectively.

The Raman spectra of MoS_2 and WS_2 reveal two prominent first-order phonon modes: the E^1_{2g} and the A_{1g} modes. The E^1_{2g} mode is an in-plane vibration, for which the atoms are oscillating parallel to the basal plane of the van-der Waals coupled crystal layers. The A_{1g} mode is an out-of plane vibration, where the sulfur atoms are moving in opposite directions. We observe that in case of WS_2, similarly to MoS_2, the A_{1g} mode shifts towards lower energies when the power of laser beam increases, whereas E^1_{2g} phonon mode remains essentially inert. This is due to stronger coupling of A_{1g} mode with the excited d_{z^2} states. Those results are consistent with previous studies of MoS_2 in FET geometry [1]. Comparison of both studied TMDs suggests that WS_2 is more sensitive to change of charge carrier density. Our results show that the charge carrier density can be effectively tunable by the light intensity.

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Electronic properties of 2-dimensional bilayer bismuth topological insulator

M. Bieniek, T. Woźniak, P. Potasz, A. Wójs

Faculty of Fundamental Problems of Technology, Wrocław University of Technology, Wyb. Wyspiańskiego 27, 50–370 Wrocław

Topological insulators (TI) [1] are fascinating new materials, which posses many properties interesting for both applied and fundamental physics. Even though in last decade these materials were thoroughly studied, there is only limited number of real 2D materials where this effect was proved to exist.

In the following work we study electronic and structural properties of bilayer bismuth Bi (111). First we compare electronic structure for infinite system obtained from density functional theory (DFT) and tight-binding (TB) model after Liu, Allen [2]. Then we study electronic structure in function of spin-orbit interaction, analyzing spin texture and orbital compositions around the band gap. Also the multi-layer systems are investigated within both DFT and TB models. Next the structural and electronic properties of zigzag nanoribbons in function of width and edge passivation are analyzed. The stability of edge states in multilayer geometries is also investigated.

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Entanglement spectrum of a Chern insulator on the Lieb lattice

M. Brzezińska, P. Potasz, and A. Wójs

Department of Theoretical Physics, Wrocław University of Technology, Wybrzeże Wyspiańskiego 27, 50-370, Poland

In this contribution, we investigate the properties of Chern insulators on the two-dimensional Lieb lattice through entanglement spectrum and trace index. Topological band insulators have garnered a considerable interest in recent years, motivated by promising applications in the context of quantum Hall effect [1]. Topologically non-trivial flat bands combined with strong interactions are potential hosts of fractional Chern insulators, lattice analogs of fractional quantum Hall states.

Within the tight-binding approximation, Lieb lattice has a dispersionless but topologically trivial band in the middle of the energy spectrum. The presence of spin-orbit coupling and staggered sublattice potential can give rise to a topological phase transition. Topological ordered phases lie beyond the Landau paradigm and manifest non-local correlations within the system, therefore one may study its ground state by employing methods associated with the quantum entanglement.

We consider a free fermion Chern insulator on a cylinder geometry, with a spatial cut parallel to physical edges. For a particular subsystem, we compute the correlation matrix defined as a two-point correlation function [2]. The entanglement spectrum is obtained from the eigenvalues of this matrix, whereas the trace index is the trace of the single-particle entanglement spectrum [3,4]. The calculations are performed for various model parameters.

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Analysis of symmetry in the graphene quantum dots

P. Bugajny [1], P.Potasz [1], A. Wojs[1]

[1] *Wroclaw University of technology, Wybrzeze Wyspianskiego 27, Wroclaw, Poland*

We investigate optical properties of symmetric graphene quantum dots (GQD) [1] using the theory of representation of point groups. We classify symmetry of electronic states in the energy spectra obtained within tight-binding model (TB) of GQD with different sizes and edge termination. This allows us to determine allowed optical transitions. We next analyze the influence of edge effects on optical properties by studying structures with similar sizes, and zigzag and armchair edges. Optical transitions between edge-type and bulk-type states are investigated. A comparison between analytical and numerical results is presented. Absorption spectra for symmetric graphene quantum dots for different sizes and edges are shown.

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Natural and reverse lexicographic order of partitions and fractional quantum Hall effect

Bartosz Kuśmierz and Arkadiusz Wójs

Wrocław University of Technology, wybrzeże Wyspiańskiego 27, 50-370 Wrocław, Poland

Important role of the symmetric polynomials theory in the fractional quantum Hall effect has been discussed in a series of papers [1-4]. This poster is devoted to the analysis of one aspect of the symmetric polynomials theory in a physics of Hall systems i.e. role of ordering of the partitions.

Partition is a sequence of nonnegative integer numbers [5], partitions are used as an index of the basis functions in the space of symmetric/antisymmetric functions. Spinless fermionic wave function of a fractional quantum Hall state can be expanded in the Slater determinant basis $\{sl_\alpha\}_\alpha$. Symmetric polynomials theory suggests that partitions should be ordered according to the reverse lexicographic order, which corresponds to the natural order. Such ordering of a basis reveals that coefficients of certain spinless FQH states are nonzero only for basis functions indexed by the partitions smaller in natural order than certain partition. This is the case of the famous Laughlin state $\nu=1/3$ (highest nonzero partition: [1001001...001]) and More-Read state (partition[110011..0011]). We examine whether such property can be of use in examination of other fractional quantum Hall states.

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Ab initio studies of structural, electronic and dynamical properties of chosen group VI-B transition metal dichalcogenides systems

T. Woźniak[1], M. Bieniek[1], J. Jadczak[1], P. Scharoch[1], A. Wójs[1]

[1] *Faculty of Fundamental Problems of Technology, Wrocław University of Technology, wyb. Wyspiańskiego 27, 50–370 Wrocław*

Recently, group-VIB transition metal dichalcogenides attract significant interest due to their extraordinary and tunable electronic and optical properties [1]. We study from first principles (DFT) the geometry, electronic structure and dynamical properties of several MX_2 bulks and monolayers (M=Mo, W, Re; X=S, Se, Te), using various techniques [1]. For band structure calculations we employ MBJLDA exchange-correlation functional, which gives good agreement with experimental data [2].

Basing on the obtained band structure for MoS_2 we derive a parametrization for a tight binding model, which can accurately reproduce energy bands in the vicinity of the band gap. Special attention is paid to orbital composition of bands, for which we are able to reproduce correct trends.

Dynamical properties of $MoS_{2(1-x)}Se_{2x}$ alloys are investigated within a supercell model for different compositions x. The calculated phonon dispersions and densities of states reproduce well the measured Raman spectra [3]. We are able to explain the evolution of Raman modes analysing the projected phonon density of states at the Γ point of reciprocal space.

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Controllable properties of polygonal quantum rings

Anna Sitek[1,2], Gunnar Thorgilsson[3], Vidar Gudmundsson[1], and Andrei Manolescu[3]

[1] *Science Institute, University of Iceland, Dunhaga 3, IS-107 Reykjavik, Iceland*
[2] *Department of Theoretical Physics, Faculty of Fundamental Problems of Technology, Wroclaw University of Technology, 50-370 Wroclaw, Poland*
[3] *School of Science and Engineering, Reykjavik University, Menntavegur 1, IS-101 Reykjavik, Iceland*

Polygonal quantum rings may be viewed as very short core-shell nanowires in which electrons are confined only within the shell areas. Such radial hetero-structures have recently attracted considerable attention due to their unique physical properties, some of them related to corner effects. In this presentation we address the energy levels, electron localization, and optical absorption of polygonal quantum rings. We show how those features depend on the sample geometry, in particular, on the number of corners, side thickness, and system symmetry. Further, we show how they may be manipulated by appropriately applied magnetic and electric fields.

The energy level degeneracy is governed by the number of vertices. The eigenstates of symmetric rings are arranged into equal groups of two times the number of corners. Within each group the lowest and highest eigenvalues are twofold (spin) degenerate while all the states in between form fourfold (spin and angular) degenerate levels. The fourfold degenerate eigenvalues my be split into pairs of only spin degenerate levels if the sample symmetry is broken. Furthermore, both degeneracies are lifted if the ring is exposed to an external magnetic field. For sufficiently thin samples the lowest group of states is separated from higher levels by an energy gap which increases with decreasing number of corners and side thickness. The localization probabilities associated with the lowest states are concentrated only around corner areas. For regular polygons they are equally distributed between all corner areas, but if the sample symmetry is broken it may form maxima of different heights or even single peaks. The electrons excited to higher energy levels are mostly distributed over the sides of the polygon.

Irrespective of the number of corners and side thickness a ground state electron confined in a symmetric ring may be optically excited to only one corner state or to only one side state. This situations changes in the case of non-symmetric rings, where all energy levels are optically accessible. Positions of absorption peaks are determined by energy splittings between particular eigenstates, and thus the absorbed frequency may be established during the fabrication process via geometric details like side length or thickness, and further tuned, to a high extend, with external magnetic or electric fields [1,2].

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Microphotolumienscence excitation spectroscopy on single $In_{0.3}Ga_{0.7}As$/GaAs quantum dots

P. Podemski [1], A. Maryński [1], M. Pieczarka [1], J. Misiewicz [1], A. Löffler [2], S. Höfling [2,3], S. Reitzenstein [4], G. Sęk [1]

[1] *Laboratory for Optical Spectroscopy of Nanostructures, Department of Experimental Physics, Faculty of Fundamental Problems of Technology, Wrocław University of Technology, Wrocław 50-370, Poland*
[2] *Technische Physik, University of Würzburg, Wilhelm-Conrad-Röntgen-Research Center for Complex Material Systems, Am Hubland, Würzburg D-97074, Germany*
[3] *School of Physics and Astronomy, University of St. Andrews, North Haugh, St. Andrews KY16 9SS, United Kingdom*
[4] *Institute of Solid State Physics, Berlin University of Technology, Berlin D-10623, Germany*

$In_{0.3}Ga_{0.7}As$ quantum dots (QDs) grown on GaAs substrate have already shown many unique features, including the first demonstration of the strong coupling between quantum-dot-confined excitons and optical microcavity electromagnetic field [1]. $In_{0.3}Ga_{0.7}As$/GaAs QDs have shown to be insensitive to the quantum dot asymmetry, providing almost no polarization dependence on the nanostructure shape [2], making them ideal candidates for polarization-insensitive optoelectronic applications. Similarly, the exciton fine structure splitting, usually increased for asymmetric structures, has also been found to be unexpectedly low (of the order of 5 μeV) [2], opening the path for entangled photon pairs generation based on these dots.

Properties of quantum dot are defined not only by their shape, composition and strain but are also strongly influenced by the dots surroundings, especially a wetting layer (WL). It has a form of a thin quantum well formed during dots self-assembly and plays an important role in the energy transfer between QD states and the remainder of the structure. In this report we focus on the energy transfer from WL states to states confined in single large and elongated $In_{0.3}Ga_{0.7}As$/GaAs quantum dots. The transfer is probed by photoluminescence excitation spectroscopy on single dot level. There is presented an evidence of the energy transfer from wetting layer to a single $In_{0.3}Ga_{0.7}As$/GaAs quantum dot. Moreover, the signal intensity shows a well-defined correlation with the energetic separation between QD and the WL ground states. For $In_{0.3}Ga_{0.7}As$/GaAs quantum dots it has been shown that lower emission energy corresponds to smaller dots but with higher In content [2]. Efficiency of the energy transfer from WL can be influenced by larger energy dissipation during the feeding of In-richer QDs, resulting in the decreased signal intensity at the excitation in the WL region. The other explanation can be decreased oscillator strength of these dots. There are also observed and discussed sharp features in excitation spectra which can be attributed to dot excited states or can originate from localization in WL, which has been already shown in the investigated structures [3]. The carrier localization is investigated in temperature-dependent excitation experiment.

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Barrier layer dependence of the carrier dynamics in InAs/InP quantum dot structures

A. Maryński[1], M. Syperek[1], J. Misiewicz[1], V. Liverini[2,*], M. Beck[2] J. Faist[2] and G. Sęk[1]

[1] *Laboratory for Optical Spectroscopy of Nanostructures, Department of Experimental Physics, Wrocław University of Technology, Wrocław, Poland*
[2] *Institute of Quantum Electronics, ETH Zürich, Zürich, Switzerland*
[*] *currently at: Albis Optoelectronics AG, Rüschlikon, Switzerland*

In certain realization of photonic devices based on quantum dots (QDs) e.g. photon detectors, one needs to assure lateral electronic coupling between ground states among ensemble of confined states. However, such coupling must be avoided in other type of devices e.g. lasers or amplifiers and can lead to deterioration of their efficiency. In the following work we have focused on self-assembled QDs with their ground state emission centered around 1.55 μm. These dots are be well suited for optoelectronic devices (lasers, amplifiers, or detectors) operating in the C-band window of the silica fibers. As we demonstrate, properties of a ground state of an entire system can be efficiently tuned by manipulating the chemical composition of the barrier and thus influencing the overall electron-hole confinement conditions.

We consider two kinds of QDs made of InAs immersed in different barriers lattice matched to InP: (i) InAlAs or (ii) InGaAlAs. While for the former, one expects conditions of a strong e-h confinement, in the latter case the confinement is weaker (for both electrons and holes). Such QD structures where examined by temperature-dependent photoluminescence (PL) and time-resolved photoluminescence (TRPL) experiments at T = 5K under quasi-resonant excitation at 0.855eV.

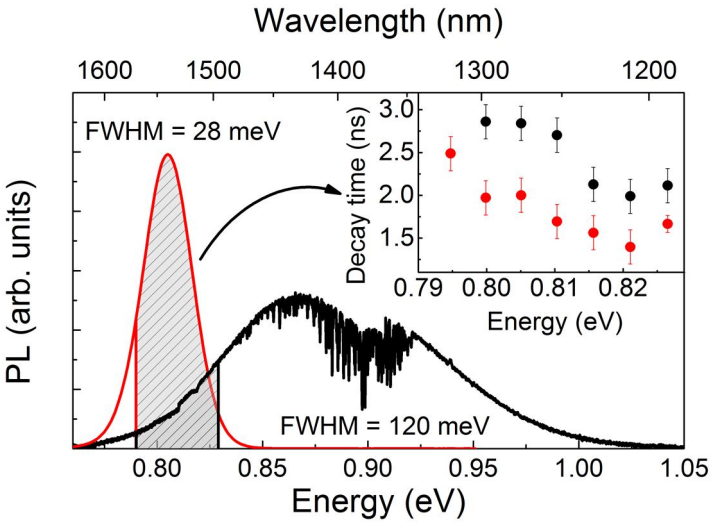

Figure 1. Photoluminescence at 5K. Red line corresponds to InGaAlAs barrier sample; black one corresponds to InAlAs barrier sample. The inset shows the respective decay times.

A significant difference between both types of structures is observed as considering the PL quenching that is much weaker for the InAs/InAlAs QDs structure than for the InAs/InAlGaAs one. For the latter the PL intensity starts to decrease efficiently right above 5K. As far as barrier is assumed to be well lattice-matched, i.e. without structural defects, and the wetting layer density of states is not extended down to the QD ground state thus the PL quenching process can be explained as related to the in-plain coupling among the ensemble of QDs. This property could additionally be confirmed in the TRPL experiment. While for the QD structure with a strong e-h confinement the PL decay time lies in the range of ~2-2.8 ns, for the structure with weaker confinement the PL decay time is by 0.4-0.6 ns shorter that suggests existence of carrier transfer between adjacent QDs influencing the overall PL decay.

Tailoring the polarization anisotropy of exciton emission from InAs/InGaAlAs quantum dashes

P. Mrowiński [1], K. Tarnowski[2], J. Olszewski[2], W. Urbańczyk[2], P. Machnikowski[3], J. Misiewicz[1], A. Somers[4], J. P. Reithmaier[5], S. Höfling[4,6], G. Sęk[1]

[1] Laboratory for Optical Spectroscopy of Nanostructures, Department of Experimental Physics, Wrocław University of Technology, Wrocław, Poland
[2] Department of Optics and Photonics, Wrocław University of Technology, Wrocław, Poland
[3] Department of Theoretical Physics, Wrocław University of Technology, Wrocław, Poland
[4] Technische Physik and W. C. Röntgen-Center for Complex Material Systems, Universität Würzburg, Germany
[5] Institute of Nanostructure Technologies and Analytics, Universität Kassel, Germany
[6] SUPA, School of Physics and Astronomy, University of St. Andrews, North Haugh, KY16 9SS St. Andrews, United Kingdom

Linearly polarized single photon emitter as a source of deterministic qubits can alter for the better the efficiency of coding information using BB84 quantum cryptography protocol [1]. InAs/InGaAlAs/InP quantum dashes (QDashes) offer a great potential for quantum communication and cryptography schemes due to a non-classical character of emission ($g^2(0)$=0.18 [2]) and spectral compatibility to long-distance fiber-based telecommunication systems. We present a systematic study on the influence of asymmetries in the surrounding dielectric medium on the polarization anisotropy of an excitonic quantum emitter. We studied excitons emitting over a broad spectral range covering 2nd and 3rd silica low-loss windows looking for a link between a relative intensity ratio of the orthogonally polarized exciton states – degree of linear polarization (DOLP) – and geometry of a submicrometer mesa structure containing a limited number of QDashes. Microphotoluminescence experiment has been carried out for rectangular mesas (2:1) oriented along and perpendicular to the elongation axis of QDashes (i.e. [1-10] direction), and for squared symmetric structures as a reference. Together with intrinsic DOLP of a QDash on the level of ~ 25 % caused by heavy-hole light-hole mixing effect, we determined the tuning range of about +/- 30 % leading to an enhanced DOLP up to ~ 60 % for mesa structure of 500 nm x 250 nm and – 10 % for the same size but oriented along [110] direction.

For better understanding of the DOLP tuning, we performed numerical simulations of the electromagnetic field distribution in the plane of QDash layer for arbitrary dielectric structure of n = 3.4 using FDTD method (Lumerical Solutions). First, we obtained a satisfactory agreement between simulated rectangular or squared mesa structures and the experimental DOLP. Secondly, we calculated the DOLP dependence on various sizes, asymmetry and orientation of the mesas from 250 nm x 250 nm to 500 nm x 250 nm and the size dependence for the fixed ratio of 2:1 These results allowed us to propose a specific geometry for maximizing DOLP of QDash that can exceed 80 %, which shows the relevance of this technologically simple approach in the post-growth modification and control of the polarization properties of epitaxial quantum-dot-like emitters.

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Temperature dependence of photon emission statistics and dynamics of a charged exciton in an InAs/InP quantum dash

Ł. Dusanowski[1], M. Syperek[1], J. Misiewicz[1], A. Somers[2], J. P. Reithmaier[3], S. Höfling[2,4], G. Sęk[1]

[1] *Laboratory for Optical Spectroscopy of Nanostructures, Department of Experimental Physics, Wrocław University of Technology, Wrocław, Poland*
[2] *Technische Physik, University of Würzburg, Würzburg, Germany*
[3] *Institute of Nanostructure Technologies and Analytics, Universitaet Kassel, Kassel, Germany*
[4] *School of Physics and Astronomy, University of St Andrews, St Andrews, United Kingdom*

Quantum dashes (QDashes) are epitaxially grown nanostructures strongly elongated in one of the in plane directions. Exciton complexes confined in such systems are shown to be more robust against phonon-induced decoherence, due to the enlarged wave function extension, decreasing the exciton-phonon coupling strength and limiting the number of phonon modes that can effectively couple [1]. A single QDash in an InAs/InP material system is a unique example of such nanostructure. It can emit photons at telecommunication wavelengths (1.3-1.55 μm). Moreover the emitted photons exhibit sub-Poissonian statistics. So far, emission non-classicality was shown in InP based QDashes for charged and neutral exciton complexes at low temperatures (5 K) only [2]. In this contribution the photon emission statistics and dynamics of a charged exciton (CX) confined in a single InAs/InP QDash are studied at elevated temperatures up to 80 K, which indicates on the practical relevance of such a system.

The CX emission line at energy around 0.8 eV was identified based on the low-temperature excitation power-dependent and polarization-resolved micro-photoluminescence (μPL). In order to check the photon emission statistics, auto-correlation measurements were performed at temperatures ranging from 5 up to 80 K. Clear photon antibunching deeps of the second order correlation function $g^{(2)}$ at zero time delay were observed in the entire range, with the as measured $g^{(2)}(0)$ values well below 0.5 limit ($g^{(2)}(0) = 0.34$ at 80 K). It clearly indicates that a CX confined in an InAs/InP QDash can act as a single photon emitter even at elevated temperatures. Time-resolved μPL (TRμPL) experiments were performed on CX in function of the excitation power density and temperature. The time evolution of the CX emission with the excitation power demonstrates characteristic slowdown of its initial relaxation and mono-exponential decay with characteristic time 1.55 ns (independent of the excitation power). The observed CX refiling process may be controlled either via long relaxation from the QDash higher confined states or charged biexciton (CXX) radiative transition to excited charged exciton (CX*) and subsequent non-radiative transition to the CX. Temperature dependent TRμPL studies performed at high excitation densities show opposite behavior, vanishing of CX refiling with temperature and afterwards mono-exponential decay. Temperature dependence of the decay time is rather atypical, as it shows decay time increase from 1.55 ns up to 2.0 ns for 5-30 K, decrease down to 1.7 ns for 30-55 K and another increase up to 2 ns for 55-80 K. Such changes in the emission dynamics can be explained by an increase of non-radiative transition rates with temperature in particular CX*-CX and dark CX*-CX relaxation, CX* and dark CX* repopulation from CX, and carrier escape out of a dash. To verify above interpretation temperature dependent rate equation model was utilized taking into account transitions between CXX, CX*, dark CX* and CX states and non-radiative carrier escape out of a dash.

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Microscopic Model of Hot Electron Generation in a Metal Nanosphere

Alexandra Crai[1], **Andreas Pusch**[1], **Doris E. Reiter**[1,2], **Ortwin Hess**[1]

[1] *Department of Physics, Imperial College London, United Kingdom*
[2] *Institute of Solid State Physics, University of Münster, Münster, Germany*

Hot electrons are defined as non-equilibrium electrons with a large excess energy compared to their equilibrium state. They are of importance due to their ability to enhance photochemical reactions and increase efficiency of photovoltaic and photodetection devices. Recently, particular interest is focused towards hot electrons in plasmonic nanostructures, because they provide ways to manipulate light on the nanoscale and at subfemtosecond timescales, thereby increasing the control over the hot carrier processes.

Photo-excitation of conduction electrons in metallic nanostructures leads to a short-lived non-equilibrium electronic distribution, followed by electron-electron and electron-phonon scattering processes. Finally, a relatively slow heat dissipation process equilibrates the system with the environment [1]. Focusing on the first step of the aforementioned processes, we study the generation and the dynamics of hot electrons in nanoplasmonic systems by a ultra-fast laser excitation.

To describe the physical mechanism behind the short-lived non-equilibrium distribution, we use a microscopic density matrix theory. Our model describes a metal nanosphere with discrete electronic states and analytic wave functions. The Hamiltonian takes into account both the electron-electron interaction and the interaction with an external electric field. We analyse the strength of the dipole and the Coulomb matrix elements for different transition. We identify selection rules for the dipole transitions and show that transitions between energetically closed states are strongest. We find a similar behaviour for the Coulomb matrix elements. For an ultra-fast excitation, we simulate the dynamics of the occupation of the states in a many-level system. During the pulse, a strongly oscillatory behaviour is found. After the pulse, the system ends up in excited states indicating the hot carrier generation in the nanosphere.

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The role of adiabatic undressing for fast phonon-assisted quantum dot state preparation

A. M. Barth [1], S. Lüker [2], F. Ungar[1], S. Wolf[1], A.Vagov[1], V. M. Axt[1], D. E. Reiter [2], T. Kuhn[2]

[1] *Institute of Theoretical Physics III, University of Bayreuth, 95440 Bayreuth, Germany*
[2] *Institute of Solid State Theory, University of Münster, 48149 Münster, Germany*

Selective manipulation of the electronic states of a quantum dot (QD) is at the core of many proposals for QD-based applications such as qubits and sources for single or entangled photons. One possibility to achieve fast state preparation is phonon-assisted off-resonant driving [1-4]. This relatively new method leaves the QD-transition laser-free and in contrast to resonant Rabi flopping and protocols relying on adiabatic rapid passage works particularly well when the coupling to the phonon environment is strong.

To achieve a detailed understanding of the preparation process using ultra-fast laser pulses, here, we examine in detail the temporal evolution of the QD states during the off-resonant excitation and the resulting preparation fidelity for different shapes of the laser pulse. We find that besides the phonon-induced relaxation between the dressed states also the *undressing* of the dressed states, i.e., the transformation of the eigenstates of the coupled light-matter system back to the uncoupled bare QD states, that takes place towards the end of the pulse, has a significant impact on the result of the preparation process. The switch-off of the laser needs to be slow enough to enable an *adiabatic* transformation between the dressed states and the bare states. This transformation is especially important when using short pulses, because an intense laser field is needed to complete the relaxation in a short time which in turn leads to a strong change of the character of the QD states and therefore can lead to a strong reduction of the preparation fidelity. Our results obtained by a numerical complete path-integral approach also reveal that the incoherent phonon scattering leads to an initial loss and a subsequent restoration of coherence and that the system trajectory takes a way *through* the Bloch sphere during the inversion of the QD using the phonon-assisted protocol [5].

Further we demonstrate that in the exciton-biexciton system also an incomplete phonon-induced relaxation, as for example it is given if the pulse is too short, can be beneficial for state preparation and that besides the detuning of the laser and the biexciton binding energy even the pulse length can be exploited to select the state targeted by the off-resonant preparation scheme.

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Injection Locking in the Quantum Regime

Steffen Holzinger[1], Elisabeth Schlottmann[1], Benjamin Lingnau[1], Kathy Lüdge[1], Christian Schneider[2], Martin Kamp[2], Sven Höfling[2], Janik Wolters[1], Stephan Reitzenstein[1]

[1] *Technische Universität Berlin, Hardenbergstraße 36, 10623 Berlin, Germany*
[2] *Julius-Maximilians-Universität Würzburg, Am Hubland, 97074 Würzburg, Germany*

Nonlinear oscillators can eventually synchronize to a periodic external force of a master oscillator. We study this widely applied phenomenon of injection locking on electrically pumped quantum dot (QD) microlasers in the regime of cavity QED close to the quantum limit with on average only few tens of photons in the laser mode. In contrast to classical predictions, a regime of partial locking is found where the laser simultaneously oscillates phase-synchronized to the external signal and at its solitary frequency.

Figure 1(a) shows the input-output characteristics of the investigated QD microlaser exhibiting two orthogonally polarized modes [1]. In the operating region above threshold the laser effectively emits single mode at a total output power < 1 µW [2]. A commercial external cavity laser tunable in energy and intensity I_m is injected into the microlaser of emitting intensity I_s [Fig 1(b)]. Phase locking between master and slave laser is proven by their ability to interfere on a fiber beam splitter. The amplitude of the interference fringes reflects the intensity of the phase locked slave laser emission. Figure 1(c) shows a map of this locked intensity, depending on injection rate $K = (I_m/I_s)^{1/2}$, with detuning Δ between master and solitary slave laser frequency. Fabry-Pérot spectra show that strong emission at the master's frequency is evident for negative detuning [Fig 1(d)]. Surprisingly, this is accompanied by significant emission at the slave laser's solitary frequency. This behavior is attributed to the strong contribution of spontaneous emission in QD microlasers [2].

For insights into the emission dynamics measurements of the second order autocorrelation function $g^{(2)}(\tau)$ were performed. Our results pave the way for further studies on the dynamics of high-β lasers and the external quantum control of nanophotonics systems which promises exciting insight into the underlying physics of single photon nonlinearities.

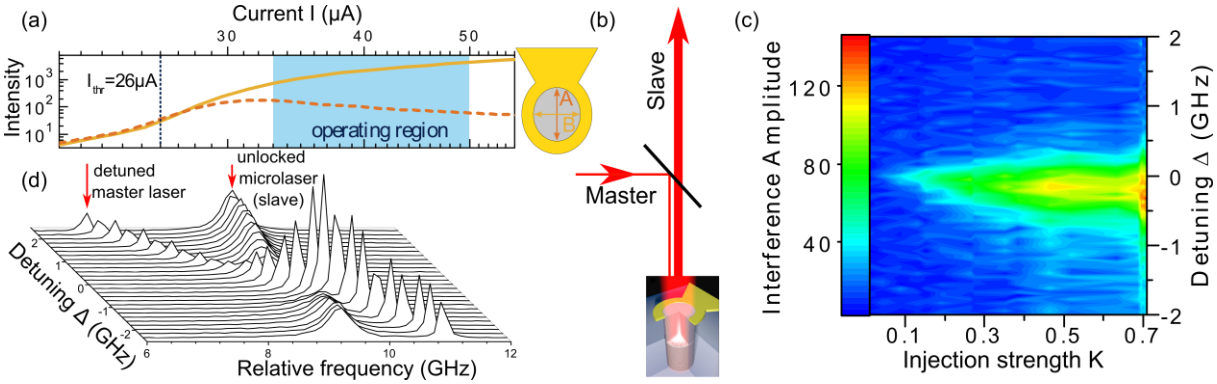

Fig. 1 (a) Input-output characteristic of the bimodal micropillar laser. The schematic inset shows the micropillar seen from the top exhibiting two orthogonal modes (called A and B, indicated by arrows). (b) Sketch of the injection locking experiment. (c) Colormap showing the intensity of the phase locked slave laser emission in dependence on the detuning Δ between master and slave and injection strength *K*. (d) High resolution spectra for varying Δ show partial injection locking.

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Inter-type superconductivity in multi-band materials

A. Vagov[1], A. A. Shanenko[2], S. Wolf[1], J. A. Aguiar[2], and V.M. Axt[1]

[1] *Institut für Theoretische Physik III, Universität Bayreuth, 95440 Bayreuth, Germany*
[2] *Departamento de Física, Universidade Federal de Pernambuco, Recife, Brazil*

Multi-band superconductivity occurs when carriers of several different bands form a superfluid condensate. The widespread interest in such systems is attrracted by their unusual properties and often abnormally high critical temperatures. The interaction between the bands notably modifies the superconducting properties. The critical temperature is enlarged when one of the bands is shallow such that the Fermi level lies close to its bottom. In this case one observes a dramatic reduction of the Cooper-pair size analogously to the so-called BCS-BEC crossover. Bands with distinct properties can be formed in systems with complex topology of the Fermi surface with isolated pockets of the Fermi surface lying in separated parts of the Brillouin zone. Multi-band superconductivity is also found in nano-size superconductors, where the geometrical quantization distinguishes a set of carrier subbands and leads to quantum size resonances in the superconductive properties. Such superconductors often have unconventional magnetic properties that are most visibly manifested in a non-standard spatial pattern of the penetrating magnetic field [1]. The characteristics of the mixed state in such materials in some cases cannot be attributed to one of the known superconductivity types stimulating discussions of a possibly novel superconductivity type.

Our theoretical approach accounts for contributions beyond the standard Ginzburg-Landau theory [2-4]. We demonstrate that the involvement of many bands in the superconductivity manifests itself, among other characteristics, in a considerable enlargement of the parameter range, where the superconductivity does not classify as any of the two known types. This inter-type domain appears due to the removal of the infinite degeneracy of the Ginzburg-Landau equations which takes place at the Bogomolny point. Such a domain can also be found in single-band superconductors. However, the interactions between different carrier bands enormously enlarge its dimensions. The enlargement generally increases for systems with a large dissimilarity between the bands and reaches extremal values when one of the bands is shallow. The enhancement is caused by the increased non-locality in the condensate interactions which is a generic feature of multi-band superconductivity and is only weakly dependent on the fine details of the band structure. Magnetic properties in the inter-type domain, in particular spatial patterns of the vortex state, can be quite different from the standard superconductivity types. The physics of the mixed state in the systems in this domain is expected to be qualitatively similar irrespective of the number of bands as well as of their structure. Thus, our conclusions for the vortex matter apply to all multi-band superconductors whatever is the nature of their multi-band structure. Furthermore, a similar behavior is expected in samples of finite geometry, that are driven into the inter-type domain by the stray fields outside a superconductor.

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Exotic vortex configurations in superconductors with deep and shallow bands

S. Wolf[1], A. V. Vagov[1], A. A. Shanenko[2], J. A. Aguiar[2], V. M. Axt[1]

[1] *Institut für Theoretische Physik III Universität Bayreuth, 95440 Bayreuth, Germany*
[2] *Departamento de Física, Universidade Federal de Pernambuco, Av. Jorn. Aníbal Fernandes, s/n, Cidade Universitária 50740-560, Recife, PE, Brazil*

It is known from various experiments that materials which fall into the inter-type domain superconductivity, i.e. that are neither of type I nor of type II, may form vortex distributions that differ from the standard Abrikosov lattice [1,2]. For example MgB_2 may develop a configuration consisting of alternating stripes with high and zero vortex density at low magnetic fields [2]. Other possible configurations may include clusters, chains and also different local vortex ordering of quadratic or hexagonal shape. The cause of these non-standard configurations is a minimum in the vortex interaction energy at a finite inter-vortex distance, introducing long range attraction and short range repulsion. For weak applied magnetic fields, i.e. when the average vortex density becomes small enough such that the inter-vortex distance for a homogeneous distribution surpasses the minimum in the interaction energy, clusterization of the vortices appears.

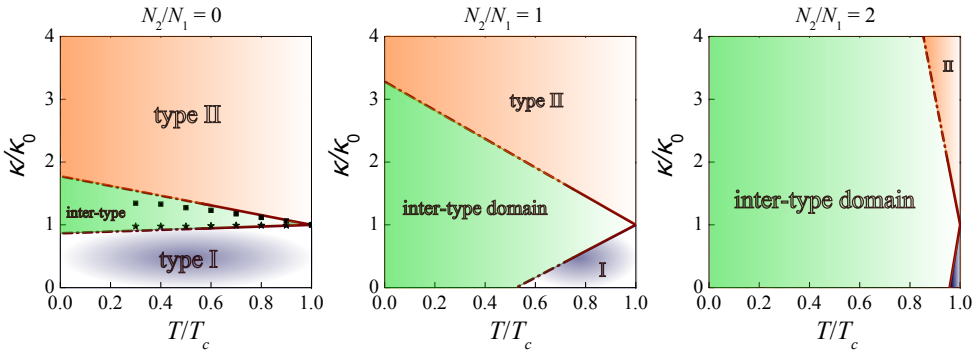

Figure 1: Phase-diagramm κ-T of the superconduction types for different DOS ratios N_s/N_d of the two contributing bands. In the left figure, squares and stars denote numerical Eilenberger results from Ref. 3.

Our model to study this exotic domain theoretically is the extended Ginzburg-Landau theory [4], using a two-band superconductor consisting of a three dimensional deep and a two dimensional shallow band, imitating the electronic structure of MgB_2. When the shallow band is dominant, i.e. for a ratio of the densities of states $N_s/N_d \gg 1$, the inter-type domain widens strongly (see fig. 1). The resulting energy function of the theory is then used to search for energetically preferred vortex configurations for different values of the system parameters: The Ginzburg-Landau parameter κ, the temperature and the applied magnetic field.

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Ab initio vs k·p $Ge_{1-x}Sn_x$ electronic structure for QW modelling

Krzysztof Wittek, Herbert Mączko, Maciej Polak, Marta Gładysiewicz, Paweł Scharoch

Faculty of Fundamental Problems of Technology,
Wroclaw University of Technology,
Wybrzeże Wyspiańskiego 27, PL50-370 Wroclaw, Poland

A great deal of research has been done to find materials suitable for applications in semiconductor-based lasers, as well as other optoelectronic devices based on heterostructures. The designing of such devices is usually preceded by a theoretical modelling exploring the bulk electronic structures of the constituent materials. The *ab initio* computational methods are known to provide the currently most accurate theoretical data of that kind. Unfortunately, a direct application of these methods in device modelling is technically very inconvenient and would involve an enormous computational effort. Hence we have developed an approach, which makes it possible to use the *ab initio* calculated bulk materials' electronic structures in our own independent code designed specifically for modelling the electronic structure of semiconductor multilayer systems. The preliminary results for a single quantum well $Ge/Ge_{0.875}Sn_{0.125}/Ge$ of varying thickness have been compared with those based on **k·p** method and a satisfactory agreement has been achieved. However, we believe that the use of *ab initio* methods opens up a perspective of much more realistic predictions of device characteristics than the approximations used so far, and the presented work is just a first step towards this aim.

Thermal lasing in nanoscopic quantum systems

P. Karwat[1,2], D. E. Reiter[2], T. Kuhn[2], O. Hess[3]

[1] *Department of Theoretical Physics, Wrocław University of Technology, Wybrzeże Wyspiańskiego 27, 50-370 Wrocław, Poland*
[2] *Institut für Festkörpertheorie, Westfälische Wilhelms-Universität Münster, Wilhelm-Klemm-Strasse 10, 48149 Münster, Germany*
[3] *The Blackett Laboratory, Department of Physics, Imperial College London, South Kensington Campus, SW7 2AZ, United Kingdom*

With the rapid progress in miniaturization many types of devices have reached the nanoscale where quantum effects become more prevalent, e.g., quantum lasers. On properly designed nanoscopic quantum systems a heat gradient can lead to inversion in parts of it, that could be utilized e.g. for the generation of coherent light.

We study a theoretical concept of nanoscopic quantum system representing the active medium of a thermal laser. Our model consists of a central three-level system interacting with a two-level subunit at each side. Each two-level system is coupled to a heat bath. The different temperature of the baths imposes a heat gradient. The heat gradient leads to a flow of excitation from the hotter to the colder bath. At the central unit the flow is accompanied by the emission of a photon or phonon. For certain parameters, this transition can generate lasing. Our description of the system kinetics is based on the Lindblad form of a Quantum Master Equation and coupling to the lasing field is described via a semiclassical equation.

In this presentation, we show that a positive inversion within the upper two levels of the central system takes place, which is a requirement to enable lasing. We also discuss how to turn the above concept into reality. We suggest as envisioned nanoscopic quantum system three semiconductor quantum dots stacked upon each other.

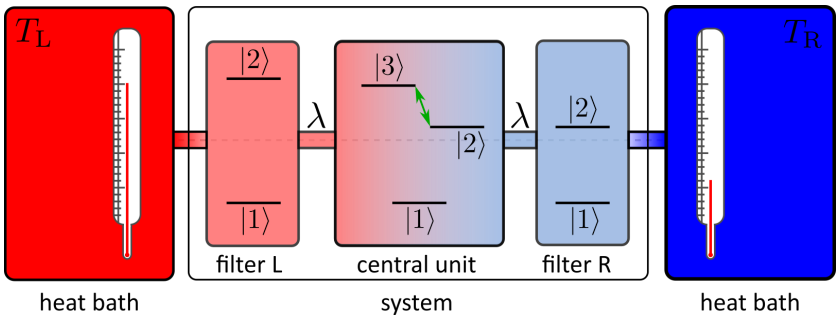

Figure 1: The model system.

Decoherence of an NV center coupled to a bath of ^{13}C nuclear spins

Damian Kwiatkowski[1], **Łukasz Cywiński**[1]

[1] *Institute of Physics, Polish Academy of Sciences, al. Lotników 32/46, PL 02-668 Warsaw, Poland*

The nitrogen-vacancy (NC) color center in diamond [1] is one of the most actively researched semiconductor-based spin qubits [2]. It is especially promising for applications involving using it as a sensor of magnetic field noise. This noise can either be intrinsic, i.e. caused by other spins present inside the diamond crystal (electronic spins of nearby nitrogen impurities, or nuclear spins of ^{13}C isotopes present among the carbon atoms forming the diamond lattice), or extrinsic, caused e.g. by spins of molecules present close to the surface of the diamond nanocrystal [3]. In the former case a careful analysis of decoherence signal can be used to identify NV centers having a few ^{13}C nuclear spins in close proximity [4], and such complexes of spins can be used as few-qubit quantum registers [5]. Such an identification of environment of the NV center requires a very good theoretical understanding of nuclear-induced decoherence in this system. The best available theory is the Correlated Cluster Expansion (CCE) [6], in which contributions to NV decoherence [7] coming from groups (clusters) of increasing numbers of nuclei are systematically taken into account. We will present our recent progress in implementing this method and using it for calculation of NV center decoherence.

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Investigation of recombination centers in CdTe – based photodiodes

E. Zielony[1], M. Morawski[1], E. Płaczek-Popko[1], Z. Gumienny[1], S. Chusnutdinow[2] and G. Karczewski[2]

[1] Department of Quantum Technologies, Faculty of Fundamental Problems of Technology, Wroclaw University of Technology, Wybrzeże Wyspiańskiego 27, 50-370 Wroclaw, Poland
[2] Institute of Physics, Polish Academy of Sciences, al. Lotnikow 32/46, 02-668 Warsaw, Poland

The objects of investigations were *n-i-p* photodiodes based on CdTe grown by MBE technique on the semi-insulating (100)-GaAs substrate. The heterostructures have been analyzed for the presence of defects in their structure, namely recombination centers. To study their origin in the investigated junctions the temperature- and power-dependent photoluminescence (PL) measurements have been performed. In these experiments He-Ne (633nm) laser was used. The PL-T measurements have been taken in the temperature range from 20 – 300 K, whereas the power-dependent ones have been done as a function of laser excitation power. The analysis of photoluminescence experiments revealed presence of recombination centers in the investigated samples. Two types of optical transitions were observed in the PL spectra, designated as *A* and *B* (cf. Fig. 1). It has been found that their activation energies of about 6 and 11 meV correspond to the free excitons and donor-acceptor pair radiative recombination, respectively [1].

In our work, these measurements confirmed that peak *A* could be related to DA transitions since the shift of peak energy is of the order of 5 meV, and may arise from the increasing contribution of the Coulomb interaction as the distance between participating impurities decreases when the density of photoexcited carriers increases. Peak *B* has a constant energy value and thus can be associated with excitons (cf. Fig. 2) [2]. Summarizing, the PL technique allowed for characterization of defects responsible for radiative recombination in the CdTe-based *n-i-p* junctions.

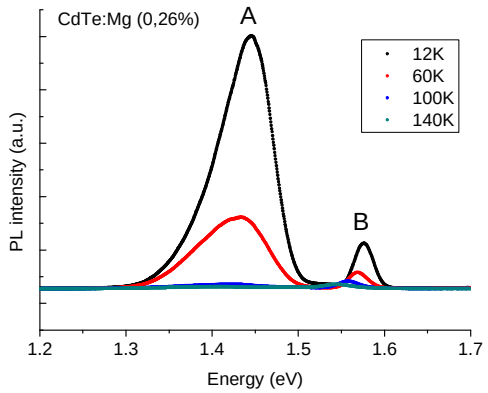

Fig. 1. PL intensity spectra of CdTe:Mg photodiode.

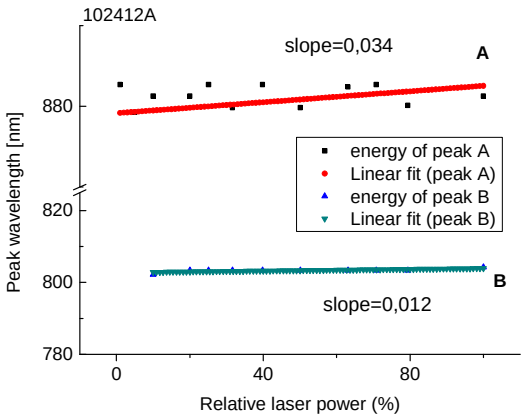

Fig. 2. A plot of transition's wavelength versus excitation intensity for peak A and B (sample 102412A).

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Optical and electrical properties of ZnO-based structures for ultraviolet detection

K.M. Paradowska[1], E. Płaczek-Popko[1], M.A. Pietrzyk[2], A. Kozanecki[2]

[1]Department of Quantum Technologies, Faculty of Fundamental Problems of Technology, Wroclaw University of Technology, Wybrzeże Wyspiańskiego 27, 50-370 Wroclaw, Poland
[2] Institute of Physics, Polish Academy of Sciences, al. Lotnikow 32/46, 02-668 Warsaw, Poland

The direct band-gap ZnO film has many attractive properties in physics and chemistry, but it is rarely applied in semiconductor devices because of big problems with achievement of a p-type ZnO. The heterojunction based on ZnO is an alternative. In this work p-Si was used to fabricate n-type ZnO-based heterojunction diodes. Two ZnO-based structures grown by plasma-assisted molecular beam epitaxy (PA-MBE) on Si(111) substrates were characterized in terms of their electrical and optical properties. A few techniques have been applied, such as: current-voltage (I-V) and capacitance-voltage (C-V) measurements together with deep level transient spectroscopy (DLTS). The photoluminescence (PL) and photoresponsivity spectra were also investigated. First, the structures were examined for their electrical parameters, such as built-in voltage V_{bi}, series resistance R_S and ideality factor n. Then, the DLTS studies revealed the existence of four electrically active deep traps (one in the first structure and three others in the second one), which were further investigated in order to characterize their electrical properties, such as activation energies E_a and capture cross-sections σ_n. At the end, the photoresponsivity spectra were determined. Both structures have potential application in ultraviolet detectors, however some improvement in fabrication process is necessary.

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AUTHOR INDEX

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