NOEKS13

13th International Workshop on Nonlinear Optics and Excitation Kinetics in Semiconductors

Dortmund, 9. - 13. October, 2016

technische universität
dortmund

Welcome to the NOEKS 13 in Dortmund

The International Workshop on Nonlinear Optics and Excitation Kinetics in Semiconductors is the 13th meeting in a series that started back in 1987 in Bad Stuer and continued with workshops in Bad Stuer (1989), Bad Honnef (1992), Gosen near Berlin (1994), Graal-Müritz (1997), Marburg (2000), Karlsruhe (2003), Münster (2006), Klink an der Müritz (2008), Paderborn (2010), Stuttgart (2012) and Bremen (2014). Traditionally, it covers the whole range of topics from nonlinear optics and kinetics of electronic excitations in semiconductors. Previous NOEKS meetings have always been of high standard and brought together leading scientists in the field from all over the world.

At the last meeting it was decided to hold NOEKS 13 at Dortmund, a city with a still pretty young academic tradition, but a huge reputation for its heavy industry history. While coal mines and steel factories have declined, the conference site, the "Dortmunder U" (U for Union), reflects this history as hard work causes big thirst – a demand which was at least partly addressed by the beer formerly brewed in this building. After stop of operation as brewery (unrelated to the beer quality) the building was renovated and converted into a cultural center so that we can use it now for the conference.

We, the local organizers, very much hope that you will appreciate not only the science presented during the meeting, but also the stay in our city. If you have any problem, please feel free to drop by and we will do our best to solve it. During the conference excursion and the subsequent banquet we will try to give you an impression of the industrial past through a visit at a colliery and of the flourishing soccer tradition through a dinner in the VIP area of the soccer stadium of Borussia Dortmund – the most beautiful soccer stadium in the world as confirmed by election through the Times.

Glückauf![*]

[*]Local salutation in the Ruhr area

Contents

General Information

Conference Office

The conference office is located in the entrance area of the Dortmund U-Tower. It will be open for registration during the welcome reception on Sunday, October 9th from 18:00 until 20:00. You will receive your conference bags after registration here. The conference office will also be occupied during conference sessions. Feel free to drop by if you have any questions.

Conference Hall

All talks will take place in the RWE-Forum on the ground floor of the Dortmund U-tower. It is technically fully equipped for presentations and lectures and offers space for almost 200 people.

Getting Around

Walking from the main train station to the conference venue will take about ten minutes. The conference venue is also located directly next to the subway station "Westentor". The public transport system in Dortmund is very convenient. The subway schedule offers trains approximately every 5 minutes during the day until about midnight. Additional public transport services by bus and regional trains also operate on a regular basis. See the Ruhr area public transport journey planner for details: http://vrr.de/en/index.html

Oral Presentations

We kindly ask speakers to show up at the RWE-Forum about 30 minutes prior to the beginning of their respective session in order to check for possible technical difficulties with their equipment and presentations. Presentations can be transferred to the conference laptop via USB stick or private laptops may be used. In the latter case, please make sure that your laptop contains a standard DVI, HDMI or display port connector. **Note that analog VGA connectors are not supported.** Please keep in mind that contributed talks are supposed to last 12 minutes followed by a 3 minute discussion and invited and upgraded talks are scheduled for 25 minutes with a 5 minute discussion.

Poster Presentations

The poster sessions will take place on Monday, October 10th and Tuesday, October 11th, from 15:30 to 18:00 in the exhibition area located at the first level of the Dortmund U-Tower. All posters should be prepared in portrait DIN A0 format (approximately 84 cm wide and 119 cm high). Poster walls will be provided all day, so feel free to put up your poster already on the morning of the day of your poster session. We kindly ask presenters to remove their posters at the end of the poster session.

Coffee Breaks, Lunch and Dinner

Between the sessions, coffee, tea and snacks will be served in the lobby outside of the main lecture hall. For lunch and dinner, there are plenty of possibilities to dine around the conference venue. See the map on page 6 for an overview of the area. The welcome reception on Sunday evening, the coffee breaks and the conference dinner on Wednesday evening are included in the conference fee.

Excursion and Conference Dinner

All participants of the conference are invited to join the excursion and the conference dinner on Wednesday, October 12th. The trip will take you to the Zollern Colliery.

Its palatial redbrick facades and the iconic Jugendstil portal of the engine house are among the most beautiful and impressive testimonies to industrial culture in Germany. The conference dinner will take you to the VIP area of the Signal Iduna Park, home of Borussia Dortmund and the most beautiful football stadium in the world as voted by the Times. Excursion and dinner are covered by your conference fee. See page 4 for details.

WLAN

Free access to the internet by wireless LAN will be available at the conference site (and several other places) via Freifunk, the open wireless LAN initiative in Dortmund. Visitors just need to connect to SSID "Freifunk" to get access. No password is required.

Program Committee

[†]It is with deep regret and profound sadness that we inform you about the passing of long-time program committee member and renowned experimentalist Galina Khitrova.

Conference Chair

Prof. Dr. Manfred Bayer

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Conference Excursion and Dinner

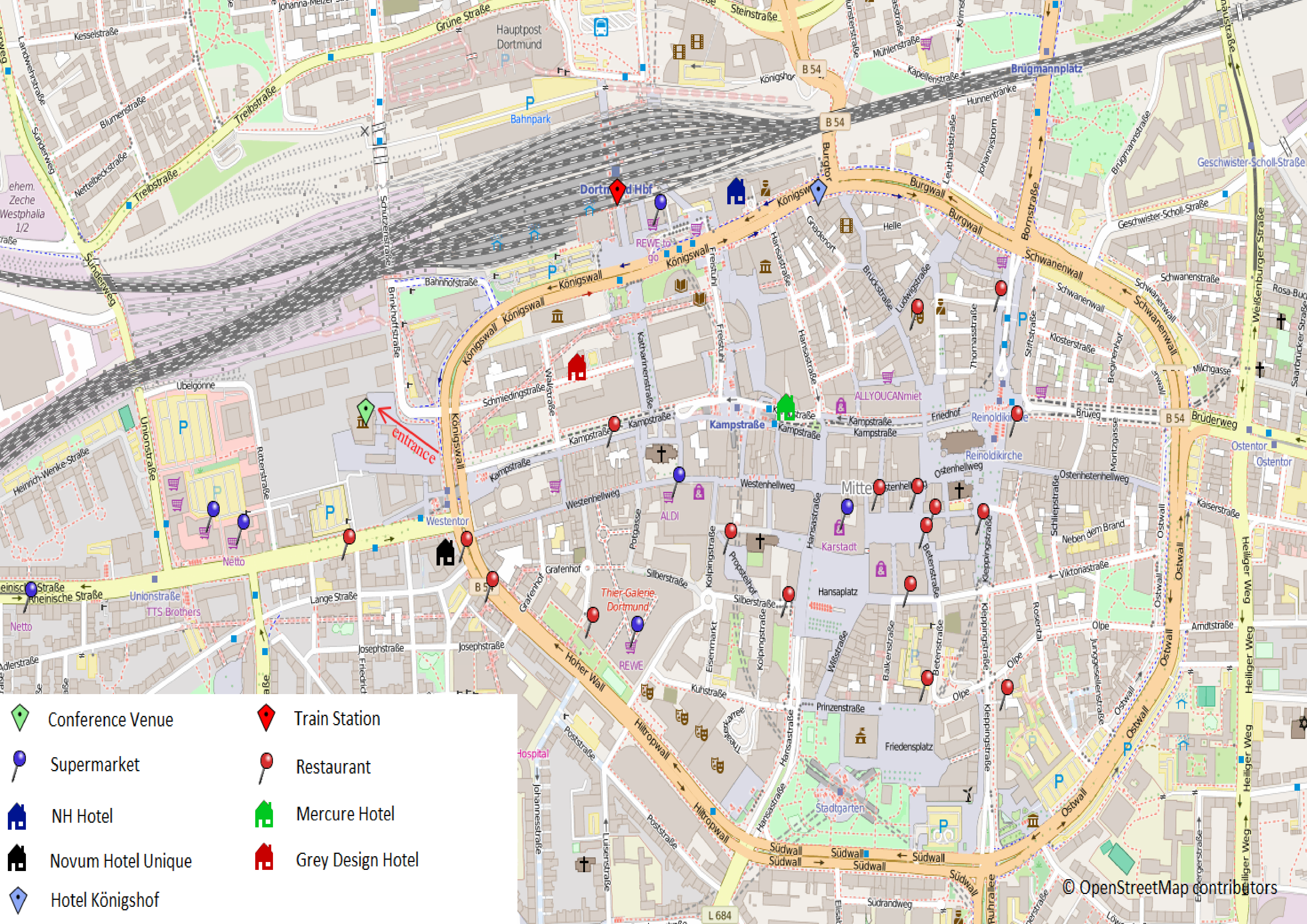
14:00: Departure to Zollern Colliery

17:30: Departure to Signal Iduna Park

18:00: Stadium Tour

19:00 - 21:00: Conference Dinner

Zollern Colliery by night


Conference Venue
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Supermarket
Restaurant
NH Hotel
Mercure Hotel
Novum Hotel Unique
Grey Design Hotel
Hotel Königshof
entrance
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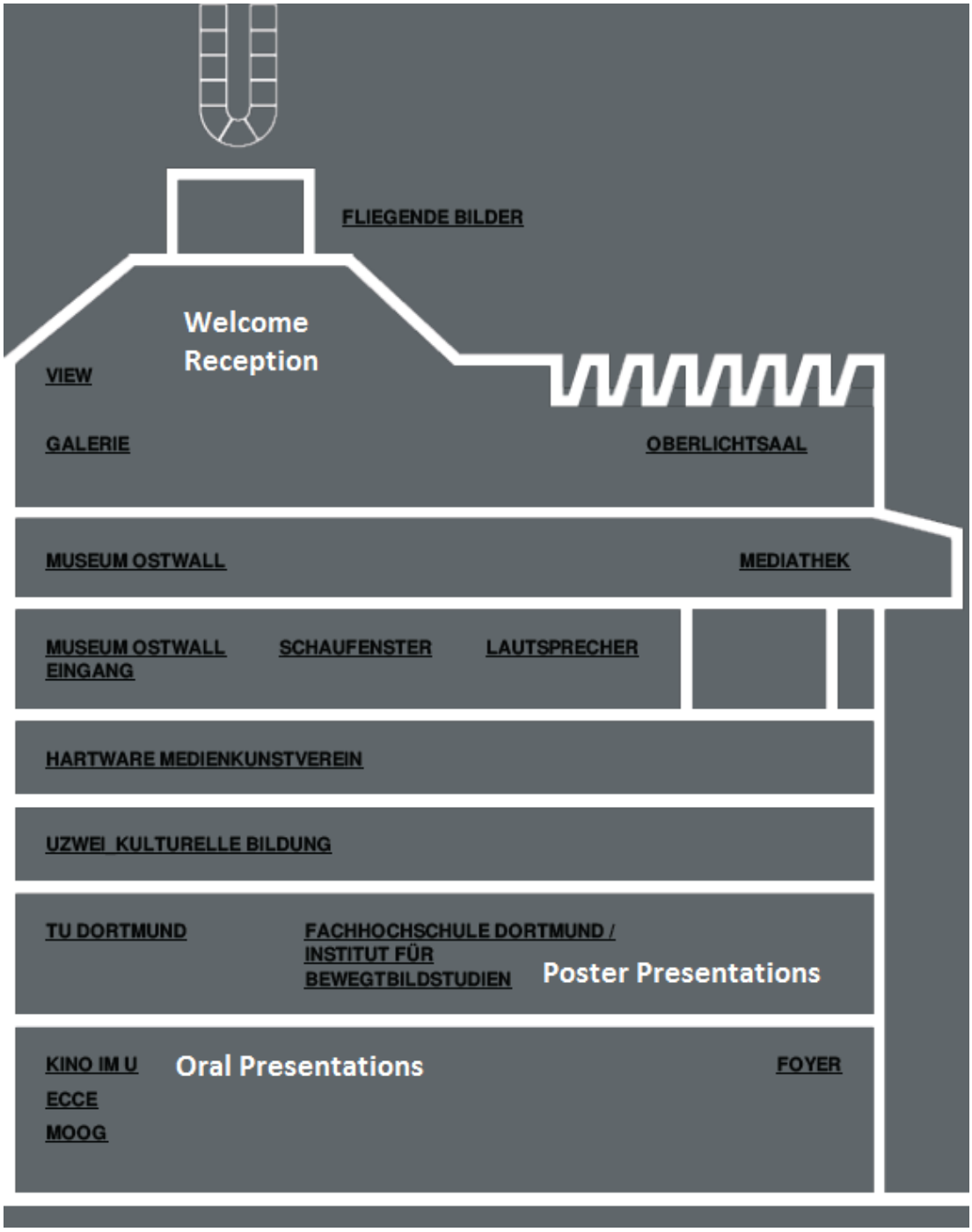
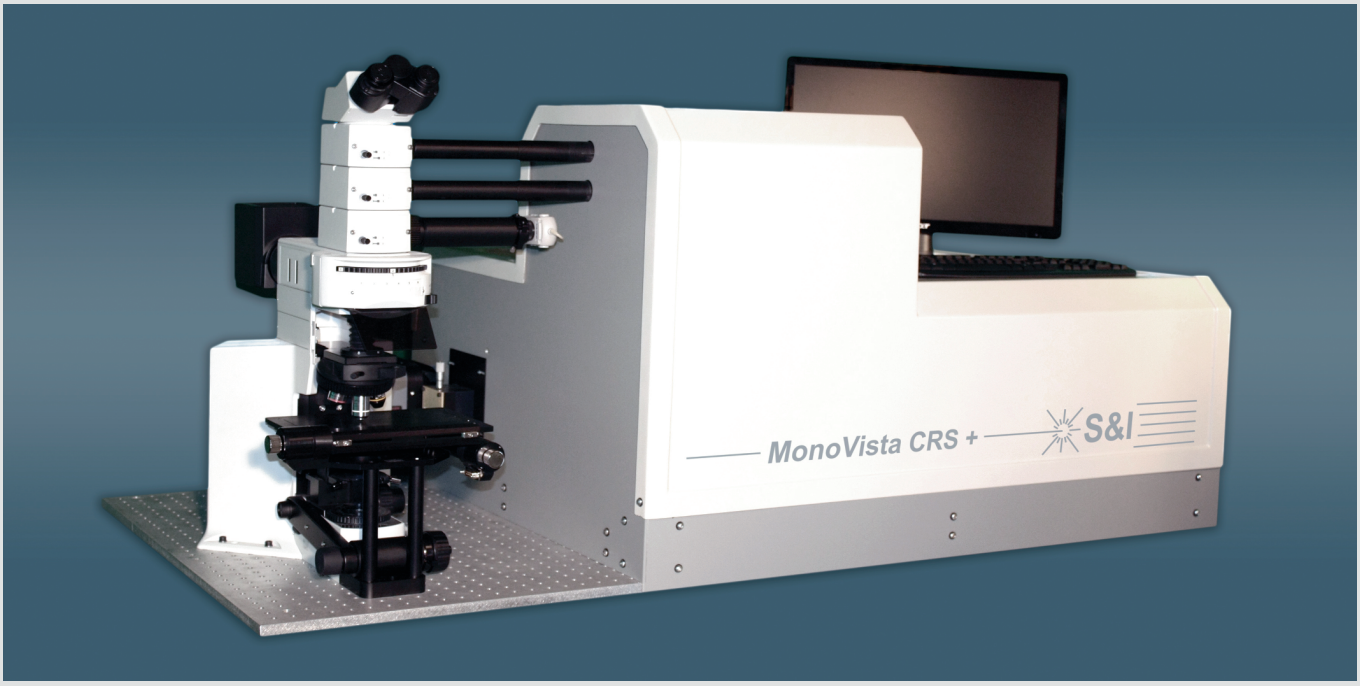
Session Overview



All oral contributions will be presented in the RWE Forum/Kino im U located on the ground floor of the Dortmund U-Tower. Poster presentations will take place in the TU Dortmund area on the first floor. The welcome reception will be held in the View located on the top floor of the U-Tower.

MonoVista CRS+

Confocal Raman Microscope



MonoVista CRS+ Benefits

- Deep UV to NIR wavelength range
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- Dual beam path for UV and VIS/NIR
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- High frequency range up to 9.000 cm-1 (@ 532nm), useful for photo luminescence
- Peltier and liquid nitrogen cooled detectors
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- Stepper motor and piezo driven XYZ stages
- Fast Raman mapping
- Heating/ cooling stages and Helium temperature cryostats
- Combined Raman and AFM
- Motorized polarization optics

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Monday, 10. 10. 2016

09:00 - 09:15	Opening Session
Session Mo1	Nanocrystals
09:15 - 09:45	**Time resolved modulation of QD photoluminescence by an electric field mimicking the effect of the action potential** Alexander Efros
09:45 - 10:15	**Excitons in two-dimensional colloidal chalcogenide nanoplatelets** Benoit Dubertret
10:15 - 10:30	**Excited State Luminescence in CdSe Nanoplatelets: The Role of Lateral Confinement and an LO-Phonon Bottleneck** Alexander Achtstein
10:30 - 11:00	Coffee Break
Session Mo2	TMDC 1
11:00 - 11:30	**Optical properties of semiconducting transition metal dichalcogenides** Marek Potemski
11:30 - 11:45	**Positioning of single-photon emitters in atomically thin WSe_2 on the nanoscale** Johannes Kern
11:45 - 12:00	**Electrically pumped quantum emitters in van der Waals heterostructures** Luca Sortino
12:00 - 12:30	**Microscopic theory of optical properties and excited-carrier dynamics of atomically thin transition metal dichalcogenides** Frank Jahnke
12:30 - 14:00	Lunch Break
Session Mo3	Quantum Optics 1
14:00 - 14:30	**Quantum Photonics with Quantum Dots** Andrew Shields
14:30 - 14:45	**Polarization-based purification of a single photon nonlinearity** Henk Snijders
14:45 - 15:00	**Hyper-entangled photons emitted by a single semiconductor quantum dot** Markus Müller
15:00 - 15:30	**Electro-Optic Sampling of the Quantum Vacuum and Sub-Cycle Squeezing** Andrey Moskalenko and Denis Seletskiy
15:30 - 18:00	Poster Session P1

Poster Presentations, Monday, 10. 10. 2016

P1-1	**Dispersion laws of the two-dimensional cavity magnetoexciton-polaritons** Sveatoslav Moskalenko
P1-2	**Interaction of the two-dimensional magnetoexcitons under the influence of the Rashba spin-orbit coupling and Zeeman splitting effects** Sveatoslav Moskalenko
P1-3	**Charge Transfer or Energy Transfer between Quasi-zero-dimensional Nanostructures** Karel Kral
P1-4	**Terahertz spectroscopy of the Berry Curvature** Shekhar Priyadarshi
P1-5	**Excitonic spectra in high external fields** Frank Schweiner
P1-6	**Dynamics of dipolaritonic optical parametric oscillator** Petr Ivanovich Khadzhi
P1-7	**Influence of Electron Interference Effects on Reflection of Electron Waves from Potential Barrier in 2D Semiconductor Nanostructures** Vadim Petrov
P1-8	**Theoretical model for the operating characteristics of semiconductor quantum well lasers** Zinaida Sokolova
P1-9	**Nuclear spin relaxation in InGaAs quantum dots under slow polarization modulation of optical excitation** Maria Kuznetsova
P1-10	**Dynamics of optically induced nuclear spin polarization in fluorine-doped ZnSe** Evgeny Zhukov
P1-11	**Ultrafast response of the lower exciton-polariton branch in CdZnTe** Matthias Reichelt
P1-12	**Pump dynamics of nuclear spins in GaAs quantum wells** Raphael Mocek
P1-13	**Unified Microscopic Analysis of Photocurrents using k.p-based Semiconductor Bloch Equations** Reinold Podzimski
P1-14	**Many quantum dots in mesoscopic quantum optical systems: numerically exact solution for full quantum statistics and entanglement** Michael Gegg
P1-15	**Quantum kinetic spin dynamics of carriers in paramagnetic II-VI diluted magnetic semiconductors with spin-orbit coupling** Florian Ungar
P1-16	**Properties of II/VI microdisk-waveguide structures grown on III/V semiconductor substrates** Alexander Pawlis

P1-17	**All-optical control of the spectral properties of a single photon emitted from a quantum-dot microcavity system** Dominik Breddermann
P1-18	**Controlling the optical spin Hall effect of microcavity polaritons** Przemyslaw Lewandowski
P1-19	**Optical grating and fluxes of colloidal quantum dots** Vladimir Mantsevich
P1-20	**Two-level quantum dot susceptibility and polarization peculiarities caused by strong Coulomb correlations** Vladimir Mantsevich
P1-21	**Spin-photon chiral coupling in photonic crystals** Ben Lang
P1-22	**Implementation of an electro-optical polariton transistor switch** Holger Suchomel
P1-23	**Temporal shifts of photon echo from semiconductor quantum wells and quantum dots** Sergey Poltavtsev
P1-24	**Simulations and design of integrated quantum optical systems** Polina Sharapova
P1-25	**Speeding up a single quantum dot experiment** Gerhard Johannes Schäfer
P1-26	**Optical second harmonic generation on excitons in ZnSe and ZnSe-based quantum wells** Johannes Mund
P1-27	**Dynamics of the dressed biexciton in a deterministically fabricated quantum dot microlens** Samir Bounouar
P1-28	**Fundamental limits to coherent scattering and photon coalescence from solid-state quantum emitters** Jake Iles-Smith
P1-29	**Drastic energy concentration in plasmonic-excitonic composite multilayered structures** Takuya Matsuda
P1-30	**Computer-aided cluster expansion** Alexander Foerster
P1-31	**Energy transfer in transition metal dichalcogenide heterostructures** Gerd Plechinger
P1-32	**ZnO-based microdisk resonators under nonlinear optical excitation** Christina Bader
P1-33	**Noise processes in singly charged quantum dot–cavity system** Emil Vosmar Denning
P1-34	**Coherent dynamics of excitons in $MoSe_2$ monolayers explored with four-wave mixing micro-spectroscopy** Valentin Delmonte

P1-35	**Micro-Photoluminescence Spectroscopy and Imaging of Optically Coupled Microdisk Dimers** Fabian Hargart
P1-36	**Magnetic-Field-Induced Third Harmonic Generation on Exciton-Polariton in GaAs** Walter Warkentin
P1-37	**Nonlinear excitation of fully undercut ZnO-based photonic crystal membranes with 3D optical confinement** Sandro Hoffmann
P1-38	**Robustness of photon indistinguishability versus temporal delay and temperature for a quantum dot in a cavity** Guillaume Coppola
P1-39	**Enhancement of second harmonic generation by plasmonic nanoantennas** Nils Weber
P1-40	**Tamm plasmons and exciton polaritons in hybrid microcavities** Kathrin Sebald
P1-41	**Study of electron and spin transport in p-type $Al_xGa_{1-x}As$ layers by optical orientation** Nikolai Poletaev
P1-42	**Valley Zeeman splitting and valley polarization in monolayer $MoTe_2$ at high magnetic fields** Ashish Arora
P1-43	**Theory of 2D spectroscopy of dynamics of localized excitons in disordered Quantum wells** Marten Richter
P1-44	**Robust trion emission in two-dimensional $Mo(S_xSe_{1-x})_2$ alloys** Joanna Jadczak
P1-45	**Nanowire Crystal Phase Quantum Dots** Klaus Jöns
P1-46	**The role of spatial non-locality of the dielectric response for surface plasmon-polaritons** Alexei Vagov
P1-47	**Kinetic of spin-lattice relaxation and energy transfer in II-VI DMS nanostructures** Vitalii Ivanov
P1-48	**Second-order coherence of radiation field from population-inverted two-level systems with frequency up-conversion** Ryosuke Hata
P1-49	**Radiative coupling of free and bound excitons** Takashi Kinoshita
P1-50	**Thermal lasing in nanoscopic quantum systems- challenges and recent results** Pawel Karwat
P1-51	**Photon emission statistics and dynamics of a trion confined in an InAs/InGaAlAs/InP quantum dash – temperature dependence study** Łukasz Dusanowski

P1-52	**Nonlinear optical properties of dynamic one-dimensional photonic crystals in colloidal solution of quantum dots** Alexander Smirnov
P1-53	**Reflected degenerate four-wave mixing on colloidal solution of CdSe/ZnS quantum dots** Alexander Smirnov
P1-54	**Frenkel excitons in zero-dimensional photonic structures** Christof P. Dietrich
P1-55	**Highly indistinguishable on-demand resonance fluorescence photons from quantum dots** Stefan Gerhardt
P1-56	**Temperature dependent two-photon-coalescence probability in quantum dot single photon sources** Valia Voliotis
P1-57	**Exciton spin relaxation in InAs quantum dash emitting at 1.55 μm** Marcin Syperek
P1-58	**Optical Absorption and Emission Properties of Single Solid State Defect Centers** Tim Schröder
P1-59	**Cooperative fluorescence of optical emitters exposed by whispering gallery modes** Nobuhiko Yokoshi
P1-60	**Polarization noise of polariton laser emission** Ivan Ryzhov
P1-61	**Quantum state reconstruction and photon statistics for coherent states interacting with quantum dot ensembles** Ulrike Woggon
P1-62	**Non-linear two-photon resonance fluorescence of a single artificial atom** Lukas Hanschke
P1-63	**Long-lived quantum emitters in hBN/WSe_2 van-der-Waals heterostructures** Jakob Wierzbowski
P1-64	**Carrier dynamics in InAs/InP coupled Quantum Well - Quantum Dot system** Aleksander Maryński
P1-65	**Reversible uniaxial strain tuning in monolayer WSe_2** Robert Schmidt

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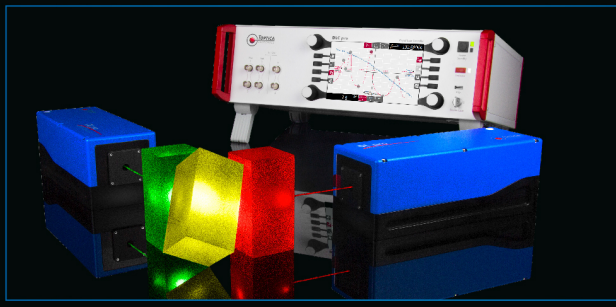

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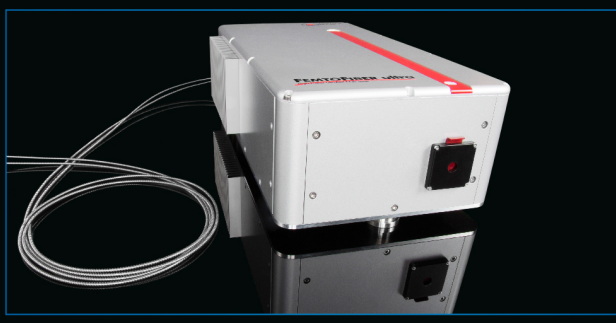

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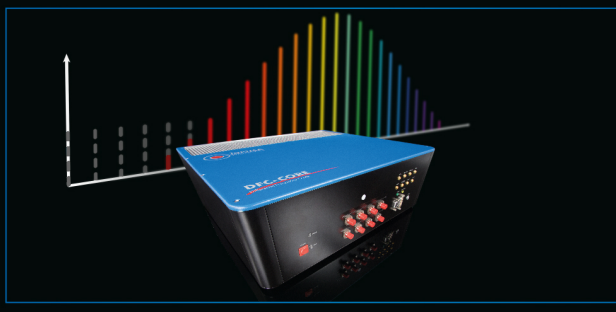

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Tuesday, 11. 10. 2016

Session Tu1	Novel Light Sources
09:00 - 09:30	**Bosonic Cascade Lasers** Alexey Kavokin
09:30 - 09:45	**Quantum Light Sources based on Two-Photon Emission from a Quantum-Dot Biexciton** Dirk Heinze
09:45 - 10:00	**Nonequilibrium thermodynamics of quantum fluids of polaritons** Sebastian Klembt
10:00 - 10:30	**Directional white-light generation in $[(RSn)_4S_6]$-Cluster Molecules** Sangam Chatterjee
10:30 - 11:00	Coffee Break
Session Tu2	Quantum Dots 1
11:00 - 11:30	**Quantum Dots–On-Demand Sources for Long Strings of Entangled Photons and Photonic Custer States** David Gershoni
11:30 - 12:00	**Probing nuclear spin dynamics of a quantum dot using nuclear magnetic resonance** Evgeny Chekhovich
12:00 - 12:15	**Direct preparation of the dark exciton in a quantum dot by a chirped laser pulse** Doris Reiter
12:15 - 12:30	**Optical coherent control of lattice-defect spins in SiC device structures** Caspar van der Wal
12:30 - 14:00	Lunch Break
Session Tu3	Ultrafast Nonlinear Optics
14:00 - 14:30	**A New Understanding of Nonlinear Light Scattering from Gold Nanoparticles** Ted Norris
14:30 - 14:45	**Revealing and characterizing dark excitons in semiconductor quantum wells with coherent multidimensional spectroscopy** Jeff Davis
14:45 - 15:00	**Single solid-state quantum emitters for plasmonics** Markus Lippitz
15:00 - 15:30	**Transient Excitonic Tweezing in Quantum Wells** Steven Cundiff
15:30 - 18:00	Poster Session 2

Poster Presentations, Tuesday, 11. 10. 2016

P2-1	**Towards deterministic high-efficiency single photon sources based on quantum dots in circular Bragg grating cavities** Anna Musial
P2-2	**Resonantly-driven mutually strongly-coupled coherent optical field-quantum dot-microcavity systems** Anna Musial
P2-3	**Three-stage decoherence dynamics of an electron spin qubit in an optically active quantum dot** Tobias Simmet
P2-4	**Inhomogeneous nuclear spin polarization induced by helicity-modulated optical excitation of fluorine-bound electron spins in ZnSe** Fabian Heisterkamp
P2-5	**Optical Transitions in Type-II Heterostructures** Julian Veletas
P2-6	**Towards linearly polarized quantum emitter and entangled photon pairs at telecommunication wavelengths utilizing InAs-InP based nanostructures** Paweł Mrowiński
P2-7	**Coherent 2D excitons in disordered quantum wells** Jeff Davis
P2-8	**Influence of excited carriers on the optical properties of monolayer transition metal dichalcogenides** Alexander Steinhoff
P2-9	**Atomic-vapor-enabled variable optical delay for triggered single-photons from a semiconductor quantum dot** Hüseyin Vural
P2-10	**Distinct valley dynamics associated with intra-valley trions in monolayer WSe_2** Nina Owschimikow
P2-11	**Fundamental and applied optical properties of submonolayer quantum dots** Nina Owschimikow
P2-12	**Time-resolved photoluminescence spectroscopy on blends of pentacene and perfluoropentacene** Katharina Broch
P2-13	**Optical characterization of Au nanoparticles embedded TiO_2 thin films** Arshad Saleem Bhatti
P2-14	**Mass anisotropy in germanium revealed by terahertz spectroscopy** Markus Stein
P2-15	**Faraday rotation induced by the electron gas and nuclear spins in Si:GaAs in a GaAlAs/AlAs microcavity** Mikhail Petrov
P2-16	**Impact of nuclear spin bath on carrier spin relaxation in InGaAs/GaAs self-assembled quantum dots** Alex Greilich

P2-17	**Bandstructure formation of exciton polaritons in lattice potential landscapes** Sebastian Klembt
P2-18	**Manipulation of dark solitons and vortices of exciton-polariton condensates in semiconductor microcavities** Xuekai Ma
P2-19	**Nanowire quantum dots tuned to atomic resonances** Lorenzo Leandro
P2-20	**Systematic study of quantum dot laser emission controlled by coherent phonon wave packets** Daniel Wigger
P2-21	**Carrier dynamics in transition metal dichalcogenides** Michael Lorke
P2-22	**A triggered twin-photon source in the solid state** Tobias Heindel
P2-23	**Correlation of Carrier Dynamics and Molecular Packing in Pentacene-Perfluropentacene Hybrids** Andre Rinn
P2-24	**Time-resolved photoluminescence studies of charge transfer states in weakly interacting organic mixtures** Marc Halbich
P2-25	**Generation of indistinguishable single photons from incoherent solid-state emitters** Thomas Grange
P2-26	**Experimental and theoretical investigations on the transition from spontaneous emission to lasing in high-β microcavity emitters** Sören Kreinberg
P2-27	**Excitonic linewidth and coherence lifetime in monolayer transition metal dichalcogenides** Malte Selig
P2-28	**Optical properties of plasmonic nano-waveguides and their coupling to proximal atomically thin materials** Michael Kaniber
P2-29	**Ultrafast electric phase control of a quantum dot exciton** Alex Widhalm
P2-30	**Bright Solid State Source of Photon Triplets** Max Prilmüller
P2-31	**Coherence of excitation and degree of time-bin entanglement from quantum dots** Max Prilmüller
P2-32	**Ultra-low power all-optical switch using a single quantum dot embedded in a photonic wire** Jean-Philippe Poizat
P2-33	**Spatio-temporal evolution of electronic wavepackets in one-dimensional nanosystems** Roberto Rosati
P2-34	**Excitation-energy dependent carrier dynamics in silicon** Nobuko Naka

P2-35	**Nonlocal coupling of light and weakly confined excitons in Cu_2O thin films** Mitsuyoshi Takahata
P2-36	**Charge carrier dynamics at the Pentacene - C60 interface** Robin Carl Döring
P2-37	**The study of thermal dissociation of acceptor-bound positively charged excitons in GaAs/$Ga_{1-x}Al_xAs$ quantum wells** Leszek Bryja
P2-38	**Two-color two-photon biexciton generation in single quantum dots** Björn Jonas
P2-39	**Polygon patterns in a polariton parametric oscillator** Charles Whittaker
P2-40	**Giant Nonlinear Spatio-Temporal Modulation in Polaritonic Waveguides** Paul Walker
P2-41	**The influence of Coulomb attraction on the carrier diffusion in semiconductors of mixed dimensionality** Mirco Kolarczik
P2-42	**Nonlinear modulation response of PbS/CdS quantum dots to excitation with high repetition rate** Mirco Kolarczik
P2-43	**Nuclear spin dynamics in bulk n-GaAs** Paul Sokolov
P2-44	**Free induction decay cutoff in Brewster angle reflection spectroscopy** Ivan Solovev
P2-45	**Plasmon induced enhancement of four-particle radiative reconmbination in SiGe/Si quantum well** Vladimir Krivobok
P2-46	**Isolated (quantum) emitters related with extended defects in ZnSe/ZnMgSe quantum well** Vladimir S. Krivobok
P2-47	**Gate Tuning of Förster Resonance Energy Transfer in Graphene - Quantum Dot Photo-Detection** Arash Rahimi-Iman
P2-48	**Ultrafast Control of Few-Fermion Spin and Inversion Dynamics in Single CdSe/ZnSe Quantum Dots** Christian Traum
P2-49	**Localization Dynamics of Excitons in Disordered Semiconductor Quantum Wells** Steven Cundiff
P2-50	**Phase and Amplitude Demodulation in Quantum Dot Spectral Hole Burning Spectroscopy** Galan Moody
P2-51	**Spin relaxation due to electron-phonon coupling revisited** Hans Christian Schneider
P2-52	**Exciting a quantum dot resonantly with thermal light** Max Strauß

P2-53	**Dynamical calculation of third harmonic generation in 2-dimensional semiconductors** Stefano Guazzotti
P2-54	**Collective Emission from Quantum Dot Ensembles: Numerical Simulation of Second Order Correlations** Paweł Machnikowski
P2-55	**Subwavelength solitons in graphene-coated nanowire lattices** Yao Kou
P2-56	**Probing the coherent and incoherent responses of a quantum dot cavity-QED device with polarization tomography** Christian Kessler
P2-57	**Room-temperature polariton superfluidity in a cavity with embedded MoS_2 monolayer: theory and applications in nanophotonics** German Kolmakov
P2-58	**Mid-Infrared Quantum-Dot Quantum Cascade Laser: A Theoretical Analysis** Stefan Michael
P2-59	**Electric Field Effects on Excitons and Quantum Coherence of Rydberg-Excitons in Cu_2O** Julian Heckötter
P2-60	**Quantum Chaos of Rydberg Excitons in Cu_2O** Johannes Thewes
P2-61	**Advanced pump-probe Faraday rotation spectroscopy of electron spin dynamics in n-type GaAs** Vasilii Belykh
P2-62	**Tuning valley polarization in a WSe_2 monolayer with a tiny magnetic field** Tomasz Kazimierczuk
P2-63	**Photon echo from InGaAs quantum dots embedded in Tamm-plasmon microcavity** Matthias Salewski
P2-64	**Interlayer Excitons in van der Waals heterostructures** Evgeny Alexeev
P2-65	**Band-edge exciton fine structure and circular polarization in CdSe colloidal nanoplatelets** Elena Kozhemyakina
P2-66	**High optical orientation degree of the indirect excitons in indirect band-gap (In,Al)As/AlAs quantum dots** Janina Rautert
P2-67	**Single photons from dissipation in coupled cavities** Hugo Flayac
P2-68	**The broadening and narrowing of high-gain parametric down conversion spectrum** Polina Sharapova
P2-69	**Higher Order Spin Correlation in Semi-Conductor Quantum Dots** Nina Fröhling

P2-70	**Non-equilibrium nuclear spin distribution function in quantum dots subject to periodic pulses** Natalie Jäschke
P2-71	**2DEG and exciton dynamics in highly doped CdTe and CdMnTe quantum wells** Janina Schindler

Wednesday, 12. 10. 2016

Session We1	Quantum Dots 2
09:00 - 09:30	**Ultrafast cavity switching: a novel resource for solid-state CQED** Jean-Michel Gérard & Willem Vos
09:30 - 09:45	**Polarisation Independent In-plane Spin Initialisation of a Quantum Dot in a Nanobeam Waveguide** Rikki Coles
09:45 - 10:00	**GaAs Quantum Dots in AlGaAs Nanowires** Christine Pepke Pedersen
10:00 - 10:30	**Quantum Nanophotonics** Kai Müller
10:30 - 10:45	**Phonons as a major source of decoherence in quantum-dot-based single-photon sources** Petru Tighineanu
10:45 - 11:00	**Determining the photon number distribution of a bimodal quantum dot microlaser via a transition edge sensor** Elisabeth Schlottmann
11:00 - 11:30	Coffee Break
Session We2	TMDC 2
11:30 - 12:00	**Exciton and Valley Dynamics in MoS_2, $MoSe_2$ and WSe_2 monolayers** Xavier Marie
12:00 - 12:30	**Room temperature Tamm-Plasmon Exciton-Polaritons with a WSe_2 monolayer** Christian Schneider
12:30 - 12:45	**Electric field controlled linear and non-linear light emission from few-layer MoS_2 and plasmonic antennas** Michael Kaniber
12:45 - 13:00	**Intervalley coupling in transition metal dichalcogenides** Gunnar Berghäuser
13:00 - 13:30	**Coupled spin-valley dynamics in monolayer Tungsten Disulfide** Tobias Korn
13:30 - 14:00	Break
14:00 - 19:00	Conference Excursion
19:00 - 21:00	Conference Dinner

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Thursday, 13. 10. 2016

Session Th1	Quantum Optics 2
09:00 - 09:30	**Revealing the single-exciton coherence with photonic nanostructures** Jacek Kasprzak
09:30 - 09:45	**A single-photon Fock state filter in the solid state** Carlos Antón Solanas
09:45 - 10:00	**New Regimes of Lasing** Matthias Florian
10:00 - 10:30	**Rotational Doppler Effect in Nonlinear Optics** Thomas Zentgraf
10:30 - 11:00	Coffee Break
Session Th2	Spin Effects
11:00 - 11:30	**Generating correlations between multiple spins via optical measurement** Mete Atatüre
11:30 - 11:45	**Interplay of Electron and Nuclear Spin Noise in n-Type GaAs** Jens Hübner
11:45 - 12:00	**Optical spin orientation of an individual Fe^{2+} ion in a QD** Mateusz Goryca
12:00 - 12:15	**Optically probing spin qubit coherence without coherent control** Tobias Simmet
12:15 - 12:45	**Picosecond control of excitons and spins in InGaAs quantum dots** Mark Fox
12:45 - 13:00	Closing Session

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Monday, 10.10.2016

Session Mo1: 09:15 - 10:30 (Nanocrystals)

Session Mo2: 11:00 - 12:30 (TMDC 1)

Session Mo3: 14:00 - 15:30 (Quantum Optics 1)

Poster Session P1: 15:30 - 18:00

Time resolved modulation of quantum dot photoluminescence by an electric field mimicking the effect of the action potential

Alexander Efros

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Understanding how the brain operates and how memories are created and retrieved are among the most exciting and challenging problems in science today. The basic structural unit of the brain—the neuron—does not operate in the same way as the basic structural unit of a contemporary computer, which exists in one of two discrete values—either zero or one. Although at present we have limited insight into how the brain carries out complex operations, it is clear that our memories and brain activity are distributed among many neurons. Neurons communicate with one another via action potentials. The typical spike of the action potential shown in the Fig. 1 is connected with local electrochemical recharging of the neuron membrane. The propagation of this action potential from one neuron to the next is the basis of how the brain functions. To understand brain activity, we must be able to "listen to" or visualize the action potential among large numbers or networks of neurons simultaneously. In my talk I will show nanocrystal quantum dots are an ideal tool for optically imaging neuronal cells. Not only because (i) they possess a tunable photoluminescence that is completely controlled by nanocrystal size and (ii) broad absorption spectra, allowing simultaneous excitation of all nanocrystal , and (iii) have a large, two-photon cross section, which allows us to use them deeply in the body, using infrared photons, and, finally, (iv) can be efficiently delivered to living cell via biofunctionalization. I will show you today that nanocrystal optical readout can be effectively coupled with the action potential and allow to measure neuronal activity in a real time. We demonstrate that an electric field typical of those found in neuronal membranes results in suppression of the quantum dot photoluminescence and, for the first time, that nanocrystal photoluminescence is able to track the action potential profile of a firing neuron with millisecond time resolution. This effect is shown to be connected with electric- field-driven nanocrystal ionization and consequent nanocrystal photoluminescence quenching [1].

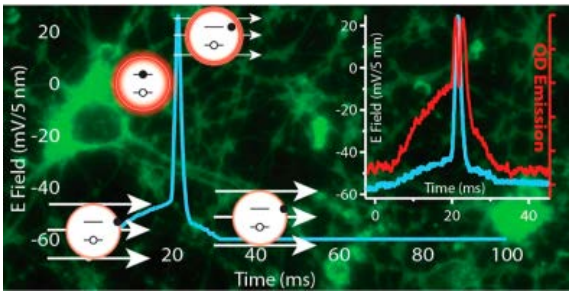

Fig.1 Typical shape of an electric field profile in neuronal membrane during action potential. The circles show the effect of the electric field on the nanocrystal charge state after nanocrystal ensemble illumination. The insert shows a time-resolved photoluminescence trace of a nanocrystal ensemble subject to an electric field pulse mimicking the action potential neuronal spike.

[1] Rowland, C. E. *et al. Nano Lett.* **15**, 6848−6854, (2015).

Excitons in 2 dimensional colloidal chalcogenide nanoplatelets

B. Dubertret
CNRS, ESPCI, 10 rue Vauquelin, 75005 Paris

We will present the synthesis of colloidal atomically flat, fluorescent chalcogenide nanoplatelets with a thickness that is controlled between 2 and 7 monolayers with atomic precision[1]. These nanoplatelets can be extended laterally into nanosheets up to the micron-scale. As their spherical counter parts, the quantum dots, they can be grown into 2D core/shell structures which are the first demonstration of colloidal multiple quantum wells[2]. We will discuss the physical properties and the spectroscopy of this novel generation of 2D system that have quantum yield that can reach 80% at room temperature, and radiative fluorescence lifetime as short as 300ps[3]. The auger recombination in these structures will be discussed and compared to the non-blinking core-thick shell spherical QDs we have recently synthesized and characterized[4], or to the golden QDs (fluorescent/plasmonic hybrid structures)[5]. We will present the first example of core/crown CdSe/CdS core/crown structures.

1 Ithurria, S. *J Am Chem Soc* **130**, 16504-16505, (2008).
2 Mahler, B., *et al. J Am Chem Soc* **134**, 18591-18598, (2012).
3 Ithurria, S. *et al. Nat Materials* **10**, 936-941, (2011).
4 Javaux, C. *et al. Nat. Nanotechnol.* **8**, 206-212, (2013).
5 Ji, B. et al. *Nat. Nanotechnol.* **10** (2), 170-5, (2015).

Excited State Luminescence in CdSe Nanoplatelets: The Role of Lateral Confinement and an LO-Phonon Bottleneck

Alexander W. Achtstein[a,b,*], Riccardo Scott[a], Stefan T. Jagsch[c], Sotirios Christodoulou[e], Guillaume H. V. Bertrand[e], Anatol Prudnikau[d], Artsiom Antanovich[d], Iwan Moreels[e], Mikhail Artemyev[d], Andrei Schliwa[c] and Ulrike Woggon[a]

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[b]*Current address: Optoelectronic Materials Section, Delft University of Technology, Delft, The Netherlands*
[c] *Technical University of Berlin, Institute Solid State Physics, Berlin, Germany*
[d] *Belarusian State University, Institute for Physico-Chemical Problems, Belarusian State University, 220030 Minsk, Belarus*
[e] *Istituto Italiano di Tecnologia, Istituto Italiano di Tecnologia, Genova, Italy*

We report excited state (ES) emission well below ground state (GS) saturation in CdSe nanoplatelets. Size dependent exciton ground state-excited state energies and dynamics are determined by three independent methods, time-resolved photoluminescence (PL), time-integrated PL and Hartree renormalized k*p calculations – all in very good agreement. The ground state-excited state energy spacing strongly increases with the lateral platelet quantization. Our results suggest that the observed bi-exponential PL decay of CdSe platelets is governed by a phonon bottleneck suppressing inter-relaxation of excited and ground state. This phonon Bottleneck is related to the reported low exciton phonon coupling in CdSe platelets and only observable as bimodal PL due to the very large oscillator strength and energy spacing of both states. As we can show that the bottleneck can be tuned by the lateral platelet size, the recombination dynamics can be tuned independently from the optical transition energies. The transition energies can be engineered by the strong transversal confinement of those colloidal quantumwells, whereas the effective transition rates can be tuned via the lateral size of the platelets.

Due to the LO-bottleneck a dynamic thermal equilibrium between ES and GS states mediated by LO phonon scattering is observed. The existence of a phonon bottleneck between ES and GS is confirmed by three methods: A rate equation model for the temperature dependence, the temporal course of ES and GS emission and the observation of an ES/GS intensity ratio minimum in the time-integrated PL for size dependent ES-GS energy spacings resonant to the LO phonon energy of 25.4 meV in the CdSe nanoplatelets. We show that the observed high energy emission peak originates systematically from the NPL's ES and correlates to the lateral confinement dependent ES–GS energy difference. Calculations and time integrated PL show a strong increase of the ES-GS energy spacing from about 18 to 36meV with increasing lateral quantization of the exciton wavefunction. The observed but yet not understood bi-exponential PL decay of nanoplatelets is therefore related to a phonon bottleneck between ES and GS populations allowing to observe ES luminescence. The presented existence of an excited p-state with high oscillatorstrength makes it necessary to reconsider several recently published results on CdSe nanoplatelets, e.g. with respect to lasing, FRET, and other properties like field controlled modulators.

Reference: [1] Achtstein and Scott et al. PRL **116**, 116802 (2016)

Optical properties of semiconducting transition metal dichalcogenides

M. Potemski

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25, rue des Martyrs, 38042 Grenoble, France

Atomically-thin layers of semiconducting transitions metal dichalcogenides (S-TMDs) represent a new class of two-dimensional systems which are interesting from the viewpoint of their fundamental electronic properties (unusual band structure, unconventional excitons, valley selective circular polarization of optical transitions) and possible optoelectronic applications (light emitting- and photo-diodes).

The summary of our recent works on mono- and multi-layers of WSe_2-, $MoSe_2$-, and WS_2-compounds will be presented. Optical response (excitonic resonances) of these two-dimensional structures will be first discussed in dependence of a number of layers and as a function of temperature [1,2,3]. Next, the magneto-optical response (reflectance and luminescence spectra) of the WSe_2 and $MoSe_2$ monolayers will be examined and commented in view of the distinct alignment of the spin-orbit split electronic subbands in each of these monolayers (bright- or dark-exciton ground state) [4]. Finally, the observation of single photon emitters associated to S-TMD monolayers will be exposed [5] and a possibility to modulate (increase) the efficiency of optical pumping in W-based monolayers will be highlighted [6].

Considerable emphases will be focused on striking effects and unresolved problems which we met in our studies of S-TMD layers, and which will be discussed in the context of the apparent experimental data and related theoretical concepts.

[1] *Excitonic resonances in thin films of WSe_2: from monolayer to bulk material*
Ashish Arora, Maciej Koperski, Karol Nogajewski, Jacques Marcus, Clément Faugeras and Marek Potemski, Nanoscale **7**, 10421 (2015).

[3] *Exciton band structure in layered $MoSe_2$: from a monolayer to the bulk limit*
Ashish Arora, Karol Nogajewski, Maciej Molas, Maciej Koperski and Marek Potemski Nanoscale **7**, 20769 (2015).

[2] *Optical study of monolayer, few-layer and bulk tungsten disulfide*
M.R. Molas, K. Nogajewski *et al.*, to be published.

[4] *Bright and dark excitons in transition metal dichalcogenides: High field magneto-optics of $MoSe_2$ and WSe_2 monolayers*, M. Koperski *et al*, to be published.

[5] *Single photon emitters in exfoliated WSe_2 structures*
M. Koperski, K. Nogajewski, A. Arora, V. Cherkez, P. Mallet, J.-Y. Veuillen, J. Marcus, P. Kossacki, and M. Potemski, Nature Nanotechnology **10**, 503 (2015).

[6] *Tuning valley polarization in a WSe_2 monolayer with a tiny magnetic field*
T. Smoleński, M. Goryca, M. Koperski, C. Faugeras, T. Kazimierczuk, K. Nogajewski, P. Kossacki, M. Potemski, Phys. Rev. X**6**, 021024, (2016).

Positioning of single-photon emitters in atomically thin WSe_2 on the nanoscale

Johannes Kern[a], Iris Niehues[a], Philipp Tonndorf[a], Robert Schmidt[a], Daniel Wigger[b], Robert Schneider[a], Torsten Stiehm[a], Steffen Michaelis de Vasconcellos[a], Doris E. Reiter[b], Tilmann Kuhn[b] and Rudolf Bratschitsch[a]

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Single-photon sources are important building blocks for quantum technology. Recently, bright and stable single-photon emitters have been found in the atomically thin semiconductor WSe_2. However, so far, the localized light sources occur at random positions at the edges of the material [1]. Here, we demonstrate the deterministic positioning of single-photon emitters in monolayer WSe_2 on the nanoscale [2]. The monolayer is placed on top of a gapped single-crystalline gold rod nanostructure. The atomically thin semiconductor conforms to the metal nanostructure and is bent at the position of the gap (Fig. 1a).

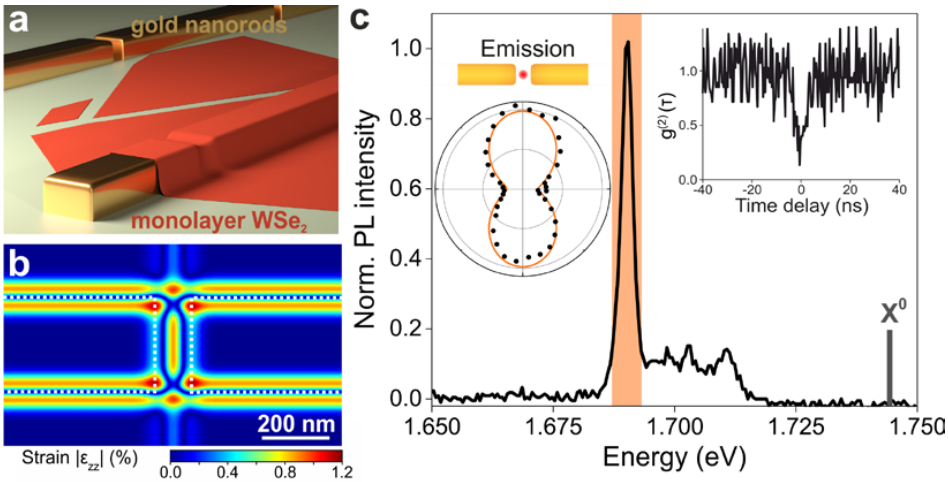

Figure 1: a) Artistic view of the sample. A WSe_2 monolayer folds around a gapped gold nanorod. b) Calculated strain. A localized strain maximum forms inside the gap. Dashed line shows the outline of the gapped nanorod. c) Photoluminescence (PL) spectrum at the gap location. Right Inset: Second-order correlation function of the marked single-photon emitter. Left Inset: PL intensity as a function of emission polarization. The emission polarization correlates with the orientation of the elongated confinement potential in (b).

Due to the deformation of the monolayer, local strain is induced, which leads to the formation of a potential well inside the gap (Fig. 1b). The photoluminescence spectrum of the sample exhibits localized light emission at the position of the gaps covered by the monolayer. The single-photon nature of the emitters is confirmed by measuring the second-order correlation function $g^{(2)}(\tau)$ (Fig. 1c). Furthermore, we prove that the single-photon emitters are localized to a region smaller than 140 nm by a super-localization measurement.
Our results pave the way to on-chip quantum optics with atomically thin semiconductors. The presented concept is scalable, and nanostructure designs are readily conceivable for gaining even higher positioning accuracy or complexity.

[1] P. Tonndorf et al., „Single-photon emission from localized excitons in an atomically thin semiconductor", Optica **2**, 347 (2015).
[2] J. Kern et al., „Nanoscale positioning of single-photon emitters in atomically thin WSe_2", Advanced Materials, in press (2016).

Electrically pumped quantum emitters in van der Waals heterostructures

L. Sortino[a], S. Schwarz[a], F. Withers[b], J. K. Maguire[a], A. P. Foster[a], S. Dufferwiel[a], L. Hague[b], A. Kozikov[b], M.N. Makhonin[a], L.R. Wilson[a], K.S. Novoselov[b], A.I. Tartakovskii[a]

[a] *Department of Physics and Astronomy, University of Sheffield, Sheffield S3 7RH, UK*
[b] *School of Physics and Astronomy, University of Manchester, Manchester M13 9PL, UK*

Van der Waals heterostructures allows to combine the unique properties of two-dimensional materials to produce functional optoelectronic devices [1-2]. Recently, quantum emitters have been reported in atomically thin layers of transitional metal di-chalcogenide (TMDC) WSe2 [3-7]. Here we demonstrate the luminescence under electric charge-injection of a defect emitter in a light-emitting device (Fig. 1a) consisting of a vertical heterostructure of a single layer of TMDC, hexagonal boron nitride (hBN) and graphene [8]. This design allows the vertical injection of carriers from graphene contacts into the active material, with hBN acting as a tunneling barrier (Fig. 1b). The spectroscopic analysis of the electroluminescence from these localized emitters is shown Fig 1c. At low voltage, the quantum dot emission is dominant, while at higher voltage excitonic features appear.

The adaptability of van der Waals heterostructures on arbitrary substrates, and the electric control of quantum light sources, makes these devices new candidates for the integration with existing optoelectronic and photonic systems.

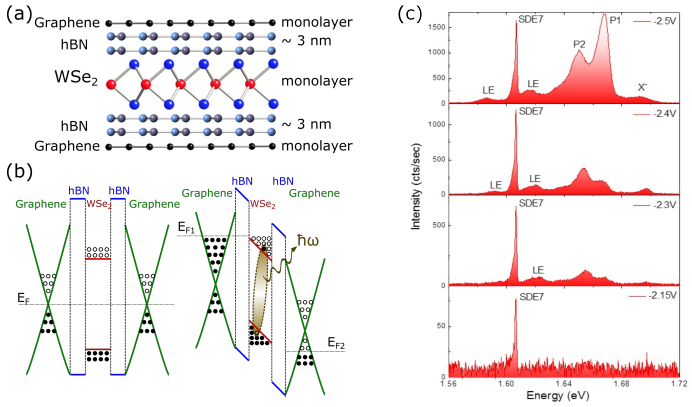

Figure 1: (a) Schematic of the electrically pumped light-emitting device. (b) Band structure of the device with and without applied bias voltage. (c) Emission spectra at different applied bias voltage.

[1] F. Withers, et. al, Nature Materials,**14**, 301-306, (2015)
[2] F. Withers, et. al, Nano Letters,**15**, 8223-8228, (2015)
[3] A. Srivastava, et. al, Nature Nanotechnology,**10**, 491-496, (2015)
[4] Y.-M. He, et. al, Nature Nanotechnology,**10**, 491-496, (2015)
[5] M. Koperski, et. al, Nature Nanotechnology,**10**, 491-496, (2015)
[6] C. Chakraborty, et. al, Nature Nanotechnology,**10**, 491-496, (2015)
[7] P. Tonndorf, et al, Optica, **2**, 347 (2015).
[8] S. Schwarz, et al, arXiv:1605.01921, (2016) *accepted in 2D Materials*

Microscopic theory of optical properties and excited-carrier dynamics of atomically thin transition metal dichalcogenides

A. Steinhoff[1], M. Lorke[1], M. Rösner[1,2], M. Florian[1], C. Gies[1], T.O. Wehling[1,2], and F. Jahnke[1]
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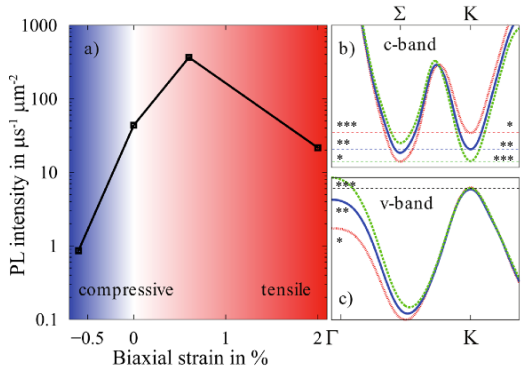
Atomically thin layers of transition metal dichalcogenides have emerged in the wake of graphene as new class of optically active materials. New and exciting optical properties are the result of the two-dimensional carrier confinement and a particularly strong Coulomb interaction due to strongly reduced dielectric screening. Many theoretical investigations were concerned with band structure and ground-state absorption properties in the framework of ab-initio (GW/BSE) calculations. Accessing the emission properties in the presence of excited carriers requires to go beyond these methods [1,2]. Our approach combines ab-initio models for the calculation of electronic properties with semiconductor many-body theory to describe the dynamics of excited carriers [3] and their influence on optical properties [1,2,4].

Optical recombination at the A and B exciton resonances relies on the presence of carriers in the corresponding K-valleys of the band structure. We discuss two different excitation scenarios: Above-band gap excitation leads to a quasi-equilibrium distribution of carriers in the Brillouin zone. The band structure is subject to momentum-dependent renormalization due to the excited carriers which, for the example of a MoS_2 monolayer, can cause a transition from a direct to indirect band gap. Strain can also make the band gap more indirect or direct at K, and for the resulting carrier distributions, we find quenching or enhancement of the light output by an order of magnitude (see the figure), a trend that has also been observed in recent experiments. The second scheme is quasi-resonant excitation, which takes place within the single-particle band gap and is only possible due to the existence of bound excitonic states. Here, carriers are created directly in the K-valleys and we predict efficient photoluminescence even in the presence of an indirect band gap.



(a) Integrated PL intensity as function of biaxial strain applied to the freestanding MoS_2 monolayer at a carrier density of 10^{13} cm^{-2}. (b) Lowest conduction band and (c) highest valence band for the unstrained case (**), 0.6% compressive strain (*) to 2% tensile strain (***).

For investigations of the carrier dynamics in MoS_2 we present results of a quantum-kinetic theory for the carrier-carrier Coulomb scattering and carrier-phonon scattering. Again the calculations are based on ab-initio band structure and interaction matrix elements. Ultrafast relaxation of initial nonequilibrium carrier distributions due to optical excitation are demonstrated. Large excess energies of 400meV can be dissipated within a few ten fs due to efficient carrier scattering. Momentum relaxation after resonant excitonic excitation takes place on a slower time scale of 1ps.

[1] A. Steinhoff, M. Rösner, F. Jahnke, T. O. Wehling, and C. Gies, *Influence of excited carriers on the optical and electronic properties of MoS_2*. Nano Letters 14, 3743 (2014)
[2] A. Steinhoff, J.-H. Kim, F. Jahnke, M. Rösner, D.-S. Kim, C. Lee, G.H. Han, M.S. Jeong, T. O. Wehling, and C. Gies, *Efficient Excitonic Photoluminescence in Direct and Indirect Band Gap Monolayer MoS_2*. Nano Letters 15, 6841 (2015)
[3] A. Steinhoff, M. Florian, M Rösner, M. Lorke, T.O. Wehling, C. Gies and F. Jahnke, *Nonequilibrium Carrier Dynamics in Transition Metal Dichalcogenide Semiconductors*, 2D Materials 3, 031006 (2016).
[4] M. Rösner, C. Steinke, M. Lorke, C. Gies, F. Jahnke, and T.O. Wehling, *Two-Dimensional Heterojunctions from Nonlocal Manipulations of the Interactions,* Nano Letters 16, 2322 (2016).

Quantum Photonics with Quantum Dots

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Abstract not available.

Polarization-based purification of a single photon nonlinearity

Henk Snijders,[1] J.A. Frey,[2] J. Norman,[3] M. P. Bakker,[1] E. C. Langman,[2] A. Gossard,[3] J.E. Bowers,[3] M. P. van Exter,[1] D. Bouwmeester,[1,2] and W. Löffler[1]

[1]*Huygens-Kamerlingh Onnes Laboratory, Leiden University*
[2]*Department of Physics, University of California, Santa Barbara*
[3]*Department of Electrical and Computer Engineering, University of California, Santa Barbara*

Quantum dots (QDs) in high-quality optical micropillar cavities are a promising system for nanoscale quantum optics and quantum information applications such as quantum logic gates, and as an interface between flying and solid-state qubits. To entangle the photon polarization deterministically with the QD electron spin, one needs polarization degenerate cavities, which is hard to achieve experimentally. Our QD-cavity system has the potential to generate high-fidelity spin-photon entanglement, because the cavity modes can be tuned to be polarization degenerate to a very high degree, while the QD-cavity coupling strength is close to the strong coupling regime.

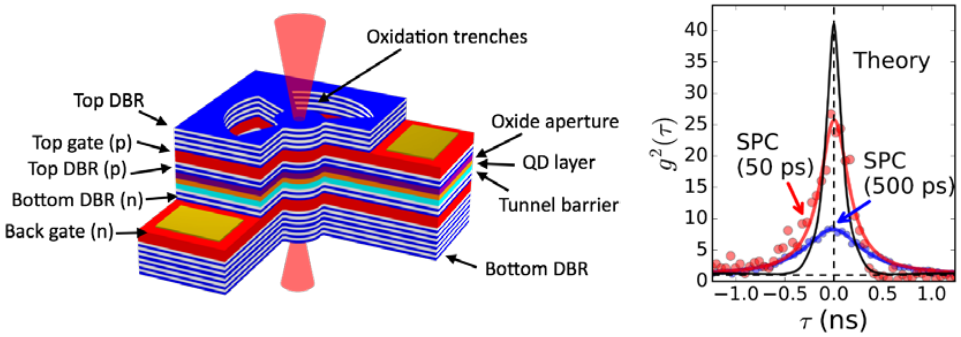

Figure 1: (left) The device structure of our polarization degenerate micropillar cavity with QDs inside. (right) Second-order correlation function for the special polarization case showing a $g^2(0) \sim 40$. We compare here theory and experiment using two different sets of single photon counters (SPCs) with different timing jitter, 50 ps and 500 ps.

The interaction of photons with the cavity-QED system is limited by a finite QD-cavity coupling strength. Here we show that, by polarization pre-and post-selection, we can restore perfect interaction in the limit of vanishing pure dephasing of the quantum dot. With this, we can transform an incident coherent light beam into a stream of strongly correlated photons with $g^2(0) \sim 40$, see Fig 1. We have developed a theoretical model that takes the (residual) polarization fine structure of both cavity and quantum dot into account, with this we obtain very good agreement between the numerical results and our experimental data. Our result brings solid-state cavity-QED in the domain of trapped ion quantum optics with much longer coherence times. By comparing the results with numerical simulations of the quantum master equation, we found first indications of photon-number sensitive Jaynes-Cummings physics in the weak coupling regime of cavity-QED [1].

[1] Henk Snijders et al. arXiv:1604.00479

Hyper-entangled photons emitted by a single semiconductor quantum dot

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[b] *Institut für Experimentalphysik, University of Innsbruck, Innsbruck, Austria*
[c] *Institute for Quantum Optics, University of Ulm, Ulm, Germany*

In the development of novel devices in the scientific fields of quantum information, quantum computing and quantum communication, semiconductor quantum dots (QD) have proven their ability to serve as bright emitters of pure, single photons [1]. Especially, with respect to realize a so-called quantum network, also the quantum mechanically concept of entanglement was demonstrated individually for the polarization [2] and for the time-bin degree of freedom [3] of photon pairs emitted by a QD. Going one step further, we report here the generation and verification of so-called hyper-entangled photon states, occupying both of the aforementioned types of entanglement. By applying a resonant and coherent two-photon [4] double pulse excitation scheme on a QD with a fine structure splitting below the natural linewidth, we create a hyper entangled biphotonic state consisting of a single exciton-biexciton photon pair from the cascaded decay of the emitter. We experimentally verify the multiple degrees of entanglement by simultaneous state tomography measurements of each subsystem. The obtained density matrices (see Fig. 1) yield the concurrence (fidelity) $C_{\mathrm{pol}} = 0.70(2)$ ($F_{\mathrm{pol}} = 0.80(2)$) of the polarization and $C_{\mathrm{tb}} = 0.76(8)$ ($F_{\mathrm{tb}} = 0.84(3)$) of the time bin entangled state. Our result paths the way for an efficient quantum network with strongly decreased error rate by exploiting high-quality hyper-entangled states emitted by a single semiconductor QD.

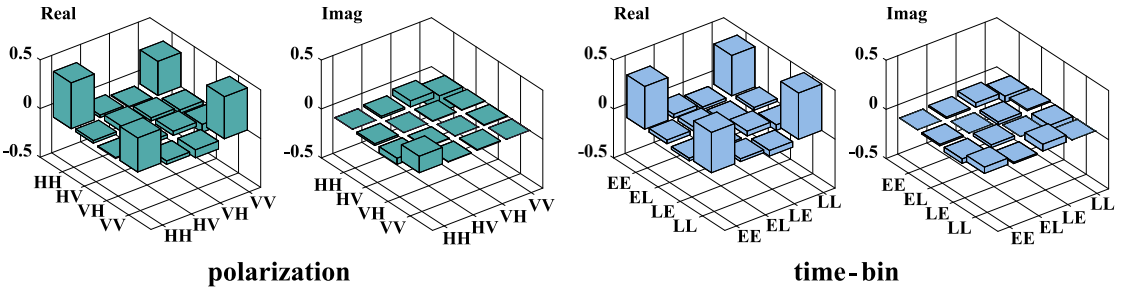

Figure 1: Reconstructed density matrices for entanglement in the polarization (green) and the time-bin (blue) degree of freedom. The expected biphotonic states $|\Phi^+\rangle_{\mathrm{pol}} = (|H\rangle_{XX}|H\rangle_X + |V\rangle_{XX}|V\rangle_X)/\sqrt{2}$ and $|\Phi^+\rangle_{\mathrm{tb}} = (|E\rangle_{XX}|E\rangle_X + |L\rangle_{XX}|L\rangle_X)/\sqrt{2}$ are represented in the basis vectors of horizontal and vertical polarization ($|H\rangle$, $|V\rangle$) and early and late time-bin ($|E\rangle$, $|L\rangle$), respectively.

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Electro-Optic Sampling of the Quantum Vacuum and Sub-Cycle Squeezing

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The quantum vacuum is one of the most fundamental states of light and matter fields. From quantum mechanics we know that the vacuum is not just empty space: E.g., in the vacuum state, even in the absence of any photons, the electromagnetic field is not strictly zero but fluctuates. Can one access these fluctuations directly? Despite many indirect measurements, this question has remained open until very recently [1].

We show that vacuum fluctuations of the electric field in free space can be directly detected using the linear electro-optic effect. For this purpose, we developed a general paraxial theory of electro-optic sampling of quantum fields [2]. Our calculations adopting a thin electro-optic crystal and stable few-femtosecond laser pulses show that nonlinear mixing of a femtosecond near-infrared probe pulse with the multi-terahertz vacuum field leads to an increase of the signal variance with respect to the shot noise level, as confirmed experimentally [1]. The detection method avoids absorption or amplification of photons of the probed quantum field. Furthermore, applying the theory to a broadband squeezed vacuum state, we predict that temporal oscillations of the electric field noise, significantly beating the bare vacuum level, can be traced with sub-cycle resolution [2]. An example of the calculated variance of the electro-optic signal from a broadband squeezed vacuum is shown in Fig. 1. In this example, each frequency mode of light in the range from 20 THz to 60 THz is squeezed independently and we have a state with a constant photon flux.

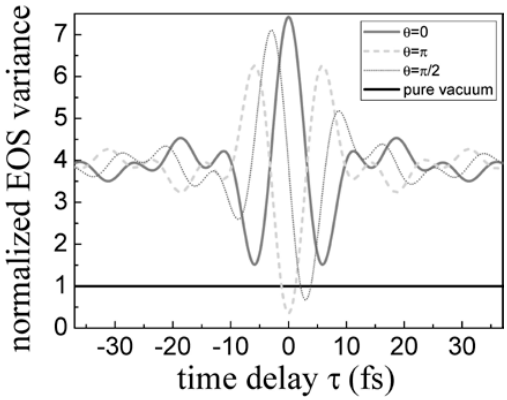

Figure 1: Variance of the electro-optical signal (EOS) in dependence on the time delay τ of the probe near-infrared pulse for the squeezed vacuum with different values of the squeezing phase θ.

We believe that our findings pave the way for an approach to quantum optics operating in an extreme time-domain limit, providing access to quantum statistics of light on a sub-cycle time scale. In line with this, we will consider theoretically two physical possibilities to generate a pulsed squeezed vacuum state out of the bare vacuum by application of a femtosecond near-infrared pump pulse: (i) via the $\chi^{(3)}$ nonlinearity of an appropriate nonlinear optical crystal (NOX) where the pump pulse itself acts on the co-propagating multi-THz vacuum state and (ii) via a cascaded $\chi^{(2)}$ process in the NOX where at first a secondary classical multi-THz field transient is created by the pump and then acts on the vacuum fluctuations present in around half the carrier frequency via broadband parametric down-conversion.

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Dispersion laws of the two-dimensional cavity magnetoexciton-polaritons

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The energy spectrum of the 2D cavity magnetoexciton-polaritons has been investigated previously, using exact solutions for the Landau quantization of conduction electrons and heavy holes provided by the Rashba method [1]. Two lowest Landau quantization levels for electrons and three lowest Landau levels for heavy-holes, lead to the construction of the six lowest magnetoexciton states. They consist of two dipole-active, two quadrupole-active, and two forbidden quantum transitions from the ground state of the crystal to the magnetoexciton states. The interaction of the four optical-active magnetoexciton states with the cavity mode photons with a given circular polarization and with well-defined incidence direction leads to the creation of five magnetoexciton-polariton branches. The fifth order dispersion equation is examined by using numerical calculations and the second order dispersion equation in the point k=0 is solved analytically, taking into account only one dipole-active magnetoexciton state. The effective polariton mass (Fig. 1) on the lower polariton branch, the Rabi frequency and the corresponding Hopfield coefficients (Fig. 2) are determined in dependence on the magnetic field strength, the Rashba spin-orbit coupling parameters and the electron and hole g-factors [2].

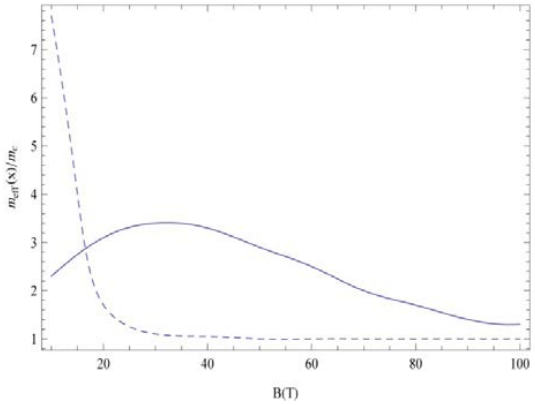

Figure 1: The dimensionless effective polariton mass $m_{\text{eff}}(0)/m_C$ in the point k=0 of the lower polariton branches in dependence on the magnetic field strength B in the presence (solid line) and in the absence (dashed line) of the Rashba spin-orbit coupling.

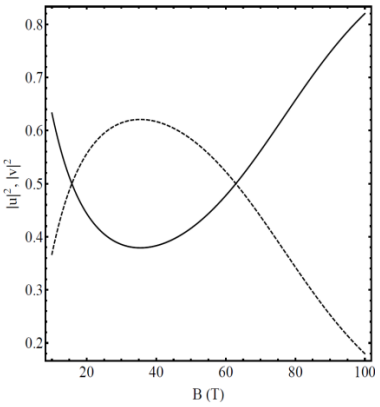

Figure 2: The dependences on the magnetic field strength B of the Hopfield coefficients square moduli $|u|^2$ (solid line) and $|v|^2$ (dashed line) in the case of magnetoexciton state F_1 interacting with the cavity photons in the presence of the Rashba spin-orbit coupling.

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Interaction of the two-dimensional magnetoexcitons under the influence of the Rashba spin-orbit coupling and Zeeman splitting effects

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The interaction between the two-dimensional magnetoexcitons with in-plane wave vector $\vec{k}_{\|} = 0$, taking into account the influence of the excited Landau levels (ELLs) and of the external perpendicular electric field parallel with the strong magnetic field were investigated. The influence of the ELLs gives rise to the overall attraction between the spinless electrons and holes lying on the lowest Landau levels (LLLs), which in the Fock approximation leads to the repulsion between the magnetoexcitons with $\vec{k}_{\|} = 0$. The interaction constant g decreases inverse proportional with the increasing magnetic field strength B (g~1/B). In the presence of the perpendicular electric field the Landau quantization of the electrons and of the holes takes place under the influence of the Rashba spin-orbit coupling (RSOC), Zeeman splitting (ZS) and nonparabolicity of the heavy-hole dispersion law. The electrons and holes are withdrawn from the LLLs and are moving with new cyclotron orbits changing their Coulomb interactions as well as the affinities of the 2D magnetoexcitons with $\vec{k}_{\|} = 0$ to interact between them. The changes of the Coulomb interactions imprinted by the electrons and by the holes moving in the new spinor states are characterized by the imprint coefficients, which in the absence of the electric field turn to be unity. The differences between the imprint coefficients of the electrons and of the holes forming the magnetoexcitons determine their affinities to the interactions. The interactions between six types of 2D magnetoexcitons F_n with n=1, 2…6 created by the combinations of two lowest electron states with three lowest heavy-hole states was studied. In these conditions 21 two-magnetoexciton pairs (F_n, F_m) can be formed. There are 6 pairs (F_i, F_i) of homogeneous magnetoexcitons with the same electron and hole states. The interaction between them is attractive, except one type of magnetoexciton with zero affinity. There are also 6 pairs of heterogeneous magnetoexcitons in which the electron and hole states are different. Two-magnetoexciton states created by four electron and hole states can be formed in two possible ways interchanging the electron and hole states. The superpositions of the two-magnetoexciton states with and without interchanging give rise to symmetric and antisymmetric states. There are also 9 semihomogeneous magnetoexciton pairs with either different electron states and with coincident hole states or vice versa. The semihomogeneous and heterogeneous magnetoexcitons forming the symmetric states attract each other, if their affinities have the same signs and undergo repulsion if their affinities have different signs. The interactions of the heterogeneous magnetoexcitons forming the antisymmetric states are of the opposite signs in comparison with the symmetric states. The interaction coefficients decrease with the increasing of the magnetic field strength B as $g \approx 1/\sqrt{B}$.

Charge Transfer or Energy Transfer between Quasi-zero-dimensional Nanostructures

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Using the nonequilibrium quantum transport theory a formula is developed for the irreversible transfer of electronic excited state (exciton), or for the transfer of an electron, or a hole particle, between two quasi-zero-dimensional nanostructures. The electron-phonon interaction is included in an approximation going beyond the limits of a finite order of the perturbation calculation. The formula is expected to be suitable for analyses of light-conversion measured data, like in the experiments on the photosynthesis. Also we show, that the application of the formula to the electric conduction of some electrically conductive polymers is rather promissing. The authors acknowledge the project LD14011 (HINT COST Action MP1202), the CSF project 16-10429J and the CAS project KONNECT-007.

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Terahertz spectroscopy of the Berry Curvature

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The Berry curvature **Ω** is an intrinsic property of crystals and is as fundamental as the effective mass. It resembles a magnetic monopole in momentum space and has important implications on many electronic properties leading to fascinating physical effects, e.g., quantum Hall, spin Hall, and anomalous Hall effects. In a semiconductor exposed to an electric field, **Ω** also leads to a macroscopic anomalous velocity $\langle v \rangle_a$ in the absence of a magnetic field. In this case, carriers with a particular spin move in a direction perpendicular to the electrical bias. This effect provides an attractive tool for the detection and detailed investigation of **Ω**. However, $\langle v \rangle_a$ may also result from carrier scattering and, so far, no straightforward distinction between **Ω** (intrinsic) and scattering (extrinsic) contributions has been achieved.

Here, we induce $\langle v \rangle_a$ in an undoped (110)-oriented GaAs quantum well (QW) sample with a well width of 28 nm on a femtosecond time scale and study its temporal evolution with sub-picosecond time resolution to distinguish among the various microscopic origins of $\langle v \rangle_a$ [1,2]. For this purpose we provide the electrical bias in the plane of the QW using free-space single-cycle THz pulses. Carriers with a certain spin orientation are excited by circularly-polarized optical femtosecond pulses in the QW. This combined optical and THz excitation induces $\langle v \rangle_a$ perpendicular to the polarization of the incident THz radiation. As a result THz radiation whose polarization is perpendicular to the polarization of the incident THz radiation is emitted. We perform a time-resolved study of this THz emission versus delay between the optical and THz excitation pulses (τ). Our measurements not only facilitate a clear identification of intrinsic and extrinsic effects but also provide access to ultrafast and coherent phenomena influencing $\langle v \rangle_a$.

In Fig. 1(a) is plotted the amplitude of the THz traces emitted from $\langle v \rangle_a$ versus τ for left- (σ-) and right-handed (σ+) circularly-polarized optical excitation. The opposite polarity of the two curves demonstrates the opposite orientation of $\langle v \rangle_a$ for the opposite spin polarization of carriers. In Fig. 1(b) is shown a contour plot with the x and y axes denoting the THz time *t* and τ. For small τ the emitted THz trace (blue curve) is phase shifted with respect to the incident THz trace (black curve). This phase shift decays to zero with a time constant of 3 ps. While at later τ the emitted THz trace (red curve) nearly follows the incident THz and its strength decays with a time constant of 10 ps.

We simulated the THz shapes emitted from the various components of $\langle v \rangle_a$ and found that THz traces linked to **Ω** will be phase shifted, while THz traces linked to scattering will have no phase shift as compared to the incident THz trace. Based upon this information we conclude that the contour plot proves the existence of **Ω**-induced effects which decay with energy relaxation in the valence band (~3 ps). Our simulations also show that the extrinsic effects result in THz radiation whose amplitude decays with both energy and spin relaxation (~10 ps) [1]. Due to the value of the involved time constants we conclude that $\langle v \rangle_a$ results mainly from the valence band. In Fig. 1(c) we plot simulations resembling Fig. 1(b). The simulations provide a ratio of Berry curvature and scattering induced contributions to $\langle v \rangle_a$ of ~0.6 showing the dominance of extrinsic over intrinsic effects in our sample.

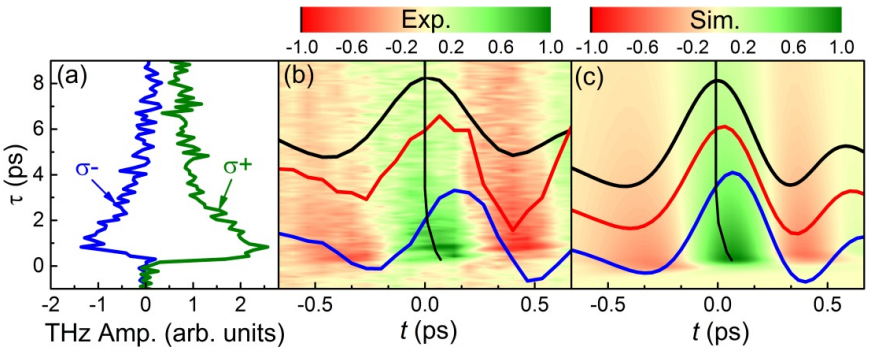

Fig. 1: (a) Amplitude of THz traces emitted from $\langle v \rangle_a$ versus τ. (b) Amplitude of THz traces emitted from $\langle v \rangle_a$ versus *t* and τ. Blue curve: THz trace at τ=0.8 ps, red curve: THz trace at τ=6.4 ps, black curve: incident THz trace. (c) Simulation of the measured contour plot.

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Excitonic spectra in high external fields

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Excitonic spectra are often described within the simple band model by a hydrogen-like series [1,2]. However, to understand and interpret excitonic absorption spectra of real semiconductors [3] it is indispensable to incorporate the complete valence band structure in a quantitative theory. We present a new method of solving the Schrödinger equation of excitons in a complete basis. This method allows us to calculate not only the excitonic absorption spectra of direct semiconductors with a complex valence band structure but also the corresponding relative oscillator strengths.

In a recent publication [4] this method has been applied to investigate the zero field splitting of states with different angular momentum in cuprous oxide (Cu_2O). Extending the method to incorporate external magnetic and electric fields and comparing the theoretical results to experimental data (Fig. 1) allows us to determine the Luttinger parameters of Cu_2O.

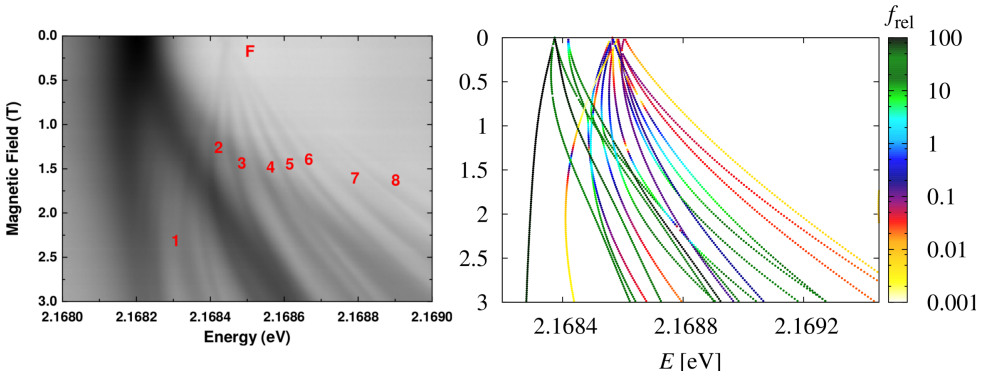

Figure 1: Spectrum of the exciton states with principal quantum number $n = 5$ in an external magnetic field B. Left: Experimental absorption spectrum from Ref. [3]. Right: Preliminary theoretical result with relative oscillator strengths f_{rel}.

Including a finite momentum $\hbar K$ of the center of mass in our calculations, we can show that a K-dependent line splitting of the exciton ground state, which has originally been attributed to an exchange interaction, is actually caused by the valence band structure of Cu_2O [4].

In the future, we will also include phonons in our theory. The investigation of the line spectrum of excitons in external fields in the presence of the exciton-phonon interaction will let us explain and understand the experimentally observed GUE statistics in excitonic spectra at high energies [5].

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Dynamics of dipolaritonic optical parametric oscillator

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Along with exciton–polaritons, a new bosonicquasi-particle (dipolariton), which is formed in coupled double quantum wells (QWs) in a microcavity, was observed for the first time in [1]. In comparison with an exciton–polariton, a dipolariton is a superposition of microcavity photon and direct and indirect excitons. Here, the direct exciton is a bound state of a pair of electron and hole from the same well, and the indirect exciton is formed by coupling an electron and a hole from neighboring wells. The coupling of microcavity photon with direct and indirect excitons leads to the formation of eigenmodes of the system with three dispersion branches: lower, intermediate, and upper dipolariton branches [2]. Due to the large dipole moment of dipolariton, the latter has been proposed as an ideal quasi-particle for generating THz radiation. However, despite the significant progress in the experimental study of dipolaritons, rigorous theoretical consideration of their physical properties is absent. Therefore, further studies in this field are urgent.

We report the results of investigation of the dynamics of dipolariton excitations in the parametric oscillator mode for the times shorter than the excitation relaxation time. The behavior of dipolaritons in the time-dependent mode, when pumping is performed by a femtosecond laser pulse, is of great interest. In this case, one can assume that ultrashort excitation pulses serve only to form initial densities of dipolaritons. Then the system is left on its own and evolves in time.

We will consider the situation in which dipolaritons with a high density are excited on the intermediate dispersion relation branch by a high-power laser pulse (pumping). As a result, parametric conversion of pump dipolaritons and generation of signal and idler dipolaritons occur. There are two conversion channels in this case [3]. One of them is the conversion of a pair of pump dipolaritons into a signal dipolariton on the lower branch and an idler dipolariton on the upper branch. The other channel is conversion of a pair of pump dipolaritons into signal and idler dipolaritons on the intermediate branch. Both conversion channels satisfy the laws of conservation of energy and momentum .

The above results indicate that pumping of the intermediate branch of the dipolariton dispersion relation under exact resonance conditions results in only aperiodic irreversible complete conversion of pump dipolaritons into idler and signal dipolaritons.

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INFLUENCE OF ELECTRON INTERFERENCE EFFECTS ON REFLECTION OF ELECTRON WAVES FROM POTENTIAL BARRIER IN 2D SEMICONDUCTOR NANOSTRUCTURES

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The influence of the interference of electron waves in the case of their reflection from potential barrier on the spatial distribution of the density of quantum-mechanical current $ej_x(x,z)$ (e – electron charge) in 2D semiconductor nanostructure which is represented by rectangular narrow ($x < 0$, QW_1) and wide ($x > 0$, QW_2) quantum wells (QWs) sequentially oriented along the direction of the propagation of electron wave has been studied theoretically. It is supposed that the wave falls from the narrow QW_1 on the semi-infinite potential barrier V_0 in height in the wide QW_2, the energy of the falling wave being less than V_0. Differing widths of QW_1 and QW_2 provide the non-orthogonality of wave functions of particles in these regions and the corresponding existence of electron interferential effects in this kind of nanostructure. In particular cases these effects lead to the appearance of spatially inhomogeneous distributions $ej_x^{(1)}(x,z)$ in QW_1 and $ej_x^{(2)}(x,z)$ in QW_2. It has been analytically demonstrated that in case of an electron wave falling along the first (lower) quantum-dimensional subband in QW_1 and its kinetic energy E_x being less than the energy positions of all the other subbands in QW_1 (*i.e.*, the undamped propagation of the wave reflected from the barrier with real quasi-momentum is possible only along this lower subband) $ej_x^{(1)}(x,z)$ and $ej_x^{(2)}(x,z)$ are equal to zero. However, if a particle has such an energy that the refection of the wave with real quasi-momenta is possible along more than one (lower) subband, then the situation completely changes due to the interference of the reflected waves. In this case the interference leads to an existence of a complicatedly oscillating spatially inhomogeneous distribution $ej_x^{(1)}(x,z)$, and under the barrier in QW_2 it provides the appearance of exponentially damped at $x \to \infty$ and possessing a coordinate dependence of leakage $ej_x^{(2)}(x,z)$ under the barrier. Besides, three regions of the symmetric along z axis propagation $ej_x^{(2)}(x,z)$ are formed under the barrier. They are the central one, in which the current is directed in axis x positive direction, and two side regions in which the current is directed in negative direction. The presence of the regions of that kind provides the charge flow from under the barrier. The numerical calculations of $ej_x^{(1)}(x,z)$ and $ej_x^{(2)}(x,z)$ have also been made taking into account 31 subbands. It should be noted that these kinds of effects have a general nature and exist in 1D and 2D nanostructures with arbitrary profiles of QWs and barriers.

Theoretical model for the operating characteristics of semiconductor quantum well lasers

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A comprehensive theoretical model for the operating characteristics of semiconductor lasers with a low-dimensional active region is developed. A particular emphasis is given to the effect of capture delay of both electrons and holes from a bulk optical confinement layer (OCL) into a quantum-confined active region and to a proper account of the condition of global electroneutrality in the laser structure.

Increasing the output optical power has been one of the most important tasks for developers of semiconductor lasers with a low-dimensional active region [1, 2]. To achieve high powers, the light-current characteristic (LCC) of a laser should remain close to linear at high levels of pumping. However, saturation of the LCC occurs at high injection currents in separate-confinement double-heterostructure lasers with a low-dimensional active region. The saturation can be due to different factors. Among them is the carrier capture from a bulk reservoir region (OCL) into a low-dimensional active region [3].

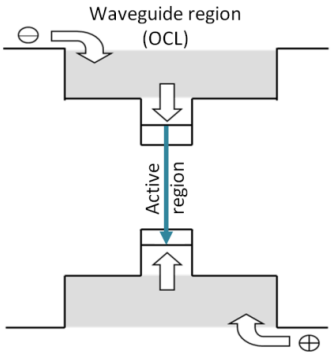

Figure 1: A schematic of a semiconductor laser with a quantum-confined active region.

Analytical model can provide insights into the processes controlling the laser performance and be used to optimize the laser structures to achieve desired operating characteristics. In this presentation, we analyze the effect of both electron and hole capture delay from the OCL into a low-dimensional active region on the operating characteristics of semiconductor lasers. We take into account the condition of global electroneutrality in the laser structure, which includes the charge carriers both in the active region [quantum wells – (QWs)] and OCL. The threshold characteristics of the laser, as well as characteristics at high pumping levels, are calculated. At the lasing threshold, the charge of each sign, both in the OCL and QW, has been shown to differ from each other; hence the electroneutrality in these layers is violated. At high pumping levels, it turns out that the charge of each sign in the OCL is significantly larger than that in the QW. As a result of this, (i) the global electroneutrality condition reduces to the condition of electroneutrality in the OCL and (ii) the local electroneutrality in the QW can be strongly violated, i.e., the 2D electron and hole densities in the QW can significantly differ from each other. The product of the 2D electron and hole densities in the QW, however, remains virtually constant with increasing injection current.

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Nuclear spin relaxation in InGaAs quantum dots under slow polarization modulation of optical excitation

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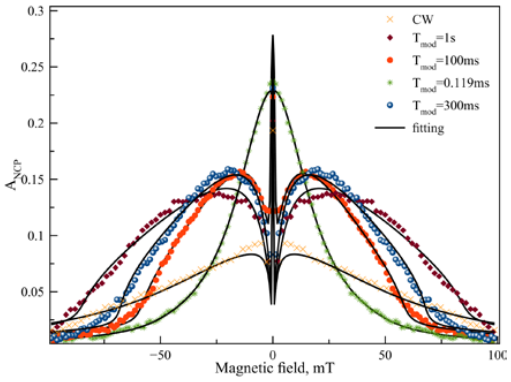
In semiconductors, the depolarizations of the electron spin in a transverse magnetic field, often referred as the Hanle effect. Particularly, the electron-nuclear interaction leads to the nuclear spin cooling initiated by the optical orientation of the electron spins under the circularly polarized excitation [1]. It results in a strong modification of the usually observed Lorentzian-like Hanle depolarization curve, namely, a W-like singularity appears around zero magnetic-field values [2].

We have measured the electron-spin Hanle depolarization curves for the InGaAs/GaAs quantum dots at different modulation frequencies of polarization of the optical pumping. Examples of such dependencies are shown in the Figure. At the continuous-wave (CW) excitation with no modulation of polarization, the clearly visible W-like structure is observed indicating the developed nuclear spin polarization. When the slow modulation of the polarization is switched on, the strong increase of the spin polarization is observed in the wide magnetic field range. At the modulation period T < 1 ms, the W-structure disappears and the Hanle curve acquires a classical Lorentz-like shape. To understand this effect, we have modeled each of the Hanle curves using the equation:



Hanle curves measured at the polarization modulation of optical excitation with different modulation periods given in the legend. The solid lines show fitting of the experimental data with the formula given in the text.

$$S_z(B) = S_0 \frac{B_{Nz}^2 + B_{fz}^2}{(B + B_{Nx})^2 + B_{Nz}^2 + B_f^2}$$

Here B is the magnitude of external magnetic field, $\mathbf{B}_N = [B_{Nx}, B_{Nz}]$ is the nuclear Overhauser field, and B_f is the field of nuclear spin fluctuations. To achieve the agreement with the experiment, we suppose that the Overhauser field consists of two components associated with dipole (±1/2) and quadrupole (±3/2, ±5/2, …) nuclear spin states. Our modeling shows that both the nuclear fields decrease with the decreasing the modulation period. The suppression of nuclear polarization occurs when the modulation frequency exceeds the inverse nuclear-spin relaxation time. The modeling allowed us to evaluate the relaxation times for each component of nuclear polarization. It is remarkable that the modulation suppresses not only the well-ordered dynamical nuclear polarization but also the randomized nuclear fluctuations. The mechanism of frequency dependence of the nuclear spin fluctuations requires further study.

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Dynamics of optically induced nuclear spin polarization in fluorine-doped ZnSe

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We study the dynamics of nuclear spin polarization induced and detected by coherently precessing optically oriented electron spins in a fluorine-doped ZnSe epilayer using time-resolved Kerr rotation (TRKR) technique in traditional and resonant spin amplification regimes. The helicity of the pump beam is changed from σ^+ to σ^- by an electro-optical modulator with the frequency f_m varied from 50 up to 1050 kHz. The degenerate pump-probe scheme was used at resonant excitation of the donor-bound heavy hole exciton ($D^0X - HH$).

The nuclear polarization in the vicinity of a fluorine donor is induced by interaction with coherently precessing electron spins in a magnetic field applied in the Voigt geometry [1]. It is detected by nuclei-induced changes in the electron spin coherence signal. This all-optical technique allows us to measure the longitudinal spin relaxation time T_1 of the ^{77}Se isotope in a magnetic field range from 10 to 130 mT under illumination. We combine the optical technique with radio frequency methods to address the coherent spin dynamics of the nuclei and measure Rabi oscillations, Ramsey fringes, and the nuclear spin echo. The inhomogeneous spin dephasing time T_2^* and the spin coherence time T_2 of the ^{77}Se isotope are measured. While the T_1 time is on the order of several milliseconds, the T_2 time is several hundred microseconds. The experimentally determined condition $T_1 >> T_2$ verifies the validity of the classical model of nuclear spin cooling for describing the optically induced nuclear spin polarization. As an example we present the results of T_1 time measurement [Fig.1].

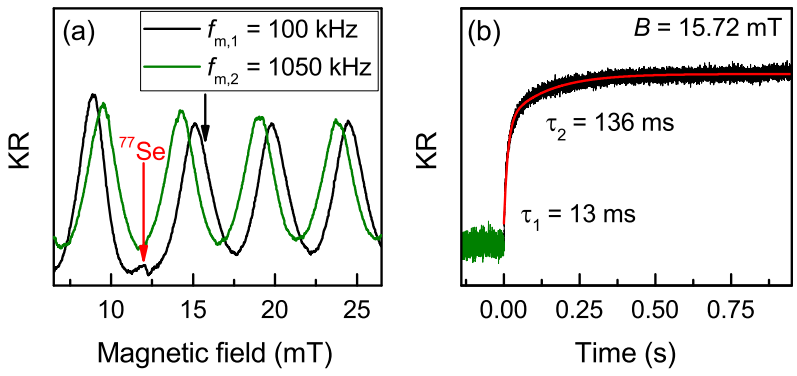

Figure 1: (a) RSA spectra measured at $f_{m,1}$ = 100 kHz. (black line) and $f_{m,2}$ = 1050 kHz (green line). The red arrow marks the optically induced NMR of the ^{77}Se isotope at $f_{m,1}$ = 100 kHz and the black arrow marks the magnetic field position (B = 15.72 mT) for the measurement shown in Fig. 1(b). (b) Change of KR amplitude at fixed magnetic field induced by switching from $f_{m,2}$ (green line) to $f_{m,1}$ (black line). The red line shows a double exponential fit to the data.

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Ultrafast response of the lower exciton-polariton branch in CdZnTe

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We investigate experimentally and theoretically the transient optical response in high-quality 200-μm-thick CdZnTe crystals. While in this material sample the pump pulse propagates nearly spectrally unchanged and creates hot carriers via two-photon absorption, the probe pulse is strongly governed by the lower exciton-polariton branch [1]. The slow light propagation leads to interesting new features in the differential transmission signal. For positive delay times, the processes are dominated by excitation-induced dephasing and show Lorentzian-type signatures. For nominally negative delay times, however, the differential transmission curves are far more complex, see Fig. 1.

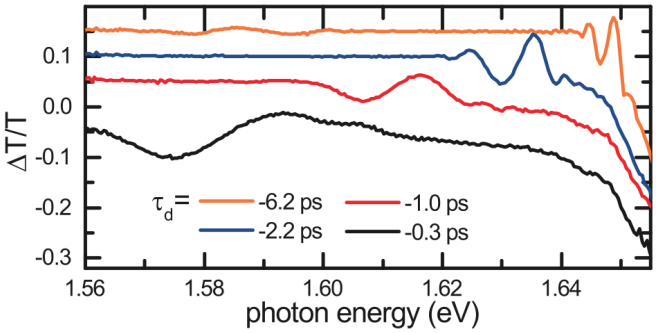

Figure 1: Spectrally resolved differential transmission for nominally negative delay times $\tau_d < 0$.

Besides a mixture of spectral oscillations and Lorentzian curves the features exist only in a specific frequency window. We suggest that particularly the slowly propagating probe components effectively get surpassed by the much faster excitation front induced by two-photon absorption of the off-resonant pump. Model simulations for the optical response taking into account the actual exciton-polariton dispersion and excitation-induced dephasing of a nonlinearly driven two-level system support this interpretation [2].

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Pump dynamics of nuclear spins in GaAs quantum wells

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Irradiating semiconductors with circularly polarized light polarizes the spins of the charge carriers due to the conservation of angular momentum. This effect is important for various applications including quantum-computing or magnetic resonance spectroscopy.

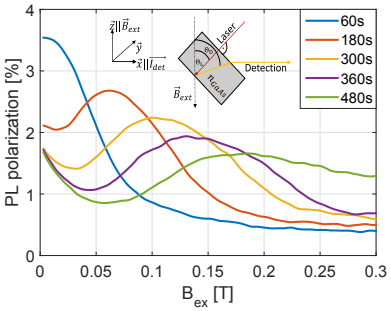

Fig.1: Experimental Hanle curves taken after different pumping times.

Here, we study the dynamics of the optical pumping process in GaAs/AlGaAs quantum wells [1] in the presence of an oblique magnetic field. We are especially interested in the polarization of the nuclear spin system, whose average hyperfine interaction generates an effective nuclear field acting on the electron spins [2,3]. We monitor the buildup of the nuclear spin polarization by measuring Hanle curves [4,5] as a function of the pumping time. Furthermore we observe the time dependence of the photoluminescence polarization [6,7]. We present a simple theoretical model for the dynamics and compare the results with experimental data.

The measurements have been performed at $T \approx 4.7\,\mathrm{K}$ using a semiconductor laser and a resistive magnet at external magnetic fields in the order of 0.5 T. To understand the process, we study the effect of the relevant parameters influencing the optical pumping rate like the intensity and detuning of the laser. Fig.1 shows measured Hanle curves, which were taken after different pumping times at $B_{ex} = 0.3\,\mathrm{T}$. Fig.2 (a) illustrates the temporal development of the nuclear magnetic field and the inlay shows the dependence of the optical pumping rate on P_{exc}, while (b) depicts the results for the time dependence of the PL polarization during optical pumping for different optical detunings.

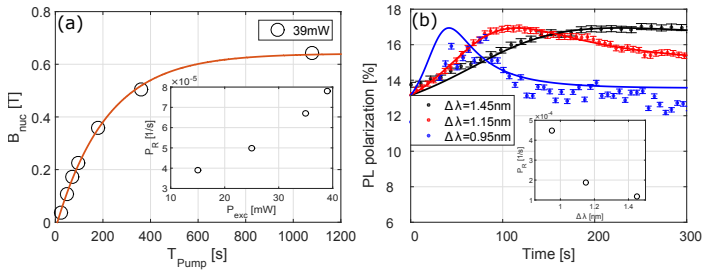

Fig.2: (a) Measured time dependence of the induced nuclear magnetic field for $P_{exc} = 39\,\mathrm{mW}$ and the dependence of the optical pumping rate P_R on P_{exc}. (b) Time dependence of the PL polarization as a function of the detuning $\Delta\lambda$ of the laser with respect to the center of the optical resonance of the quantum well.

These results indicate that we can quantitate the processes that transfer angular momentum from the electronic to the nuclear spins. Future work will attempt to improve the agreement between the model predictions and the experimental observation and lead to an optimized pumping process for magnetic resonance experiments in these systems.

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Unified Microscopic Analysis of Photocurrents using k.p-based Semiconductor Bloch Equations

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Ultrafast photocurrents appearing in the $\chi^{(2)}$ response of semiconductors and semiconductor nanostructures, i.e., injection, shift, and rectification currents [1], are analyzed using a microscopic theory that combines k.p band structure calculations with multiband semiconductor Bloch equations.[2,3,4] The extended Kane model, a 14-band k.p theory, is applied to obtain electron states of non-centrosymmetric semiconductor systems such as GaAs. Numerical solutions of the k.p based multiband semiconductor Bloch equations allow us to analyze the dynamics of the material excitations in terms of interband and intersubband polarizations/coherences and occupations non-perturbatively in the light-matter interaction. With our

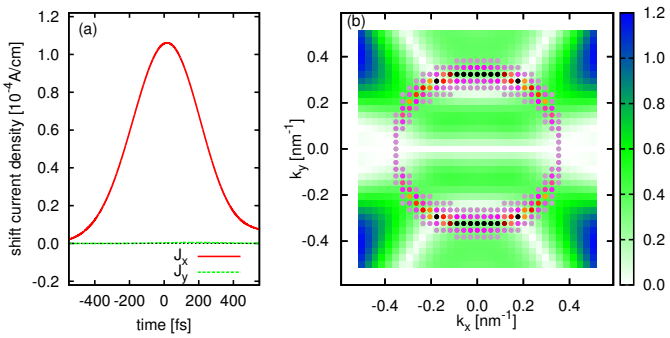

Figure 1: (a) The x- and y-components of the shift current generated in a 8 nm GaAs QW grown in (110) direction. The QW x- and y-axes correspond to the crystallographic (100) and (1-10) directions, respectively. (b) The energy difference between the highest valence bands of the QW in meV. Overlayed is the hole population in the two bands generated by the optical pulse.

microscopic approach an analysis of photocurrents is possible in the time and the frequency domains for bulk as well as quantum well and quantum wire systems with various growth directions. Theoretical results on the injection, rectification, and shift currents in bulk GaAs and GaAs-based quantum wells are presented and compared to experiment.[4]

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Many quantum dots in mesoscopic quantum optical systems: numerically exact solution for full quantum statistics and entanglement

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One of the most fundamental questions in quantum optics addresses the interaction of quantized electromagnetic field modes with optical emitters. Quantum optical emitters, like quantum dots, can be described by either two-, three or general multi-level systems (mls), which interact with a variable number of quantized electromagnetic modes. Such a general setup includes physical systems and concepts as diverse as lasers, parametric amplifiers, electromagnetically induced transparency, superradiance, entanglement, quantum information processing, etc.
In all these situations a realistic and meaningful approach must include system environment interactions, like dissipation, dephasing and pumping. Unfortunately the complexity of the corresponding equations scales exponentially with the number of quantum emitters, rendering exact solutions impossible even for moderate emitter numbers. A multitude of approximations schemes for these equations with varying sophistication have been developed in the past. However all these approximations rely on assumptions, certain limits and can always only give limited information access.

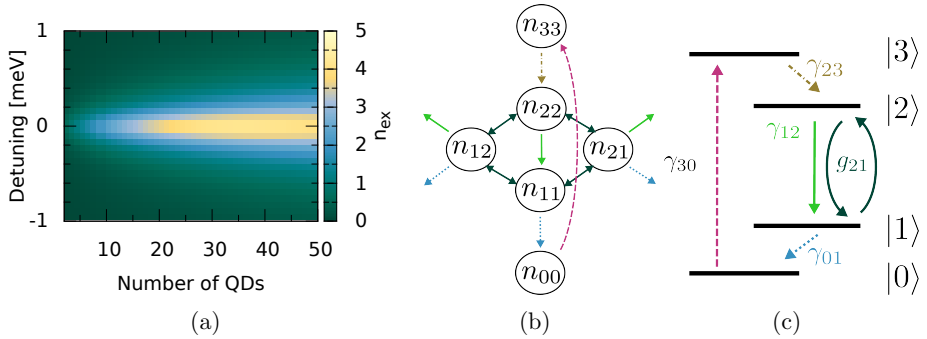

Figure 1: (a) Mean exciton occupation in a coupled plasmonic hybrid system as a function of emitter numbers and detuning of the pump (b) Sketch illustrating the working principle of the method for a collection of four-level systems. (c) The corresponding level scheme with coherent and incoherent processes.

We present an efficient and numerically exact solution for many identical multi-level systems interacting with an arbitrary number of quantized modes. The exponential complexity of the straightforward approach is reduced to polynomial scaling without using any approximations. The full, unfactorized density matrix is computed, which gives access to all observables including all quantum correlations and entanglement. The solution is especially useful in the $\sim 10^0 - 10^2$ multi-level system range, which is exactly the range of most modern semiconductor quantum optics devices like VCSELs and DBR micropillar setups. We give a detailed introduction into the new formalism and show recent results on semiconductor nanostructures.

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Quantum kinetic spin dynamics of carriers in paramagnetic II-VI diluted magnetic semiconductors with spin-orbit coupling

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We study theoretically the spin dynamics of quasi-free carriers in intrinsic diluted magnetic semiconductors (DMS) on a quantum kinetic level.[1-3] We show in which situations a description in terms of rate equations is justified and when genuine quantum kinetic corrections such as finite-memory effects become important. Apart from the usually dominant *s-d* exchange interaction (EXI) between the spins of the carriers and the magnetic impurities, we also account for an external magnetic field as well as a **k**-dependent effective magnetic field in the form of a Dresselhaus or Rashba Hamiltonian which stems from spin-orbit interaction (SOI).[4]

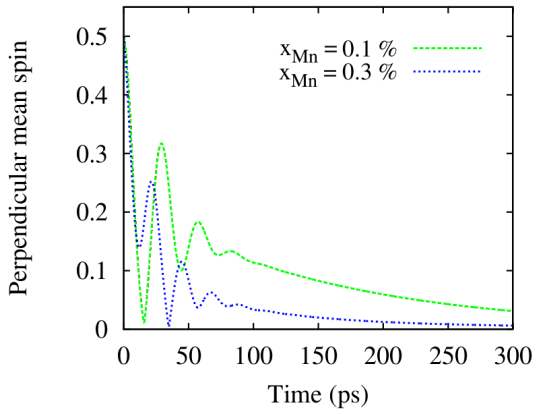

Figure 1: Time evolution of the mean electron spin component perpendicular to the Mn magnetization in a $Hg_{1-x-y}Mn_xCd_yTe$ quantum well with Rashba SOI for two different Mn doping fractions x_{Mn}. The parameters are taken from Ref. [5].

We find that, for both, three and two dimensional systems, regimes can be reached where EXI or SOI dominate the spin dynamics or are of comparable strength.

Figure 1 shows the temporal evolution of the mean electron spin component perpendicular to the average Mn magnetization in a DMS quantum well under the influence of Rashba SOI, which can be tuned via the voltage applied across the well and by varying its thickness.

We find that the SOI generally introduces oscillations of the carrier spin and can lead to a significantly faster spin decay than predicted by EXI alone. Interestingly, the frequency of these oscillations increases and their amplitude becomes smaller when increasing the Mn concentration.[5]

Furthermore, we find that the effective fields acting on the carrier and impurity spins cause a precession-like movement of the carrier-impurity correlations, which gives rise to a modification of the spin decay rates even in the Markovian limit, i.e. when finite memory effects are not important.[1,3]

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Properties of II/VI microdisk-waveguide structures grown on III/V semiconductor substrates

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Microdisk cavities of ZnSe/(Zn,Mg)Se and CdSe/ZnSe/(Zn,Mg)Se quantum well (QW) hetero-structures providing emission from the blue to the orange/red spectral range [1,2] are a versatile platform for low threshold lasers or single photon sources. A certain challenge of such microdisk resonators is the development of a suitable interface through which the microscopic field is probed and the radiation efficiently collected and accessed by macroscopic optics.

In one production flow and on the same sample chip we fabricated coupled microdisk/waveguides structures (MWS) which enable evanescent field coupling between disk and waveguide. The latter are usually free-standing due to selective removal of the in-transparent GaAs substrate below the waveguide (Fig.1), but also mechanically instable because of strain-induced bending of the waveguide. Solving this trade-off in a unique approach, we introduce a thin AlAs layer between the GaAs substrate and the epitaxially grown II/VI quantum structure. After transfer of the MWS pattern into the ZnSe/ZnMgSe the AlAs can be selectively oxidized to Al_2O_3 by a water-vapor process [3]. The transparency of the Al_2O_3 over the whole visible spectrum and it's sufficiently low refractive index makes the GaAs substrate removal and subsequent free-standing structures obsolete while simultaneously stabilizing the waveguide resting on top of the Al_2O_3/GaAs hybrid-system.

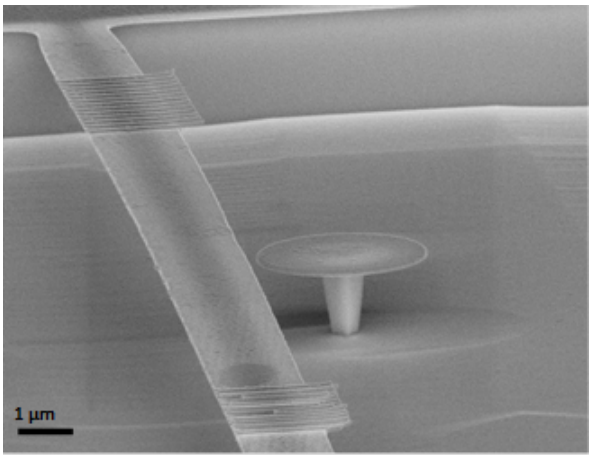

Figure 1: Scanning electron microscope image of a free-standing microdisk/waveguide system obtained from a ZnSe/ (Zn,Mg)Se quantum structure grown on GaAs substrate.

Here we report on the characteristic optical properties of MWS obtained via the free-standing and the selectively oxidation approach. Specifically important parameters such as the transfer-length and distance-dependent microdisk/waveguide coupling of the structures are extracted from spatial-resolved µ-photoluminescence measurements and quantitatively compared. Our results demonstrate that the MWS based on the Al_2O_3/GaAs hybrid-system platform provide remarkable potential for the design and realization of various integrated-optical photonic devices with II/VI semiconductor quantum structures.

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All-optical control of the spectral properties of a single photon emitted from a quantum-dot microcavity system

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In quantum-communication applications, quantum-dot microcavity systems are promising nanostructures for solid-state based on-demand generation of single photons. Commonly, the spectral properties, such as frequency and linewidth, of the emitted single photon are fixed by the characteristics of the material system, such as electronic transition energies and spectral properties of the resonator. In this contribution, we theoretically analyze the spectral properties of a single photon generated from a partly stimulated non-degenerate two-photon transition from the biexciton to the ground state [1], schematically summarized in Fig. 1. In particular, we demonstrate that frequency and linewidth of the single photon are determined by the external control beam, and thus can be all-optically controlled during the photon-creation process.

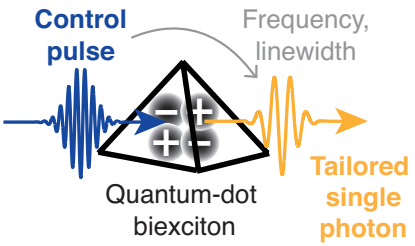

Figure 1: Scheme. An external control pulse triggers the first photon of a direct two-photon transition between biexciton and ground state. The cavity-enhanced second photon is spontaneously emitted with properties fixed by the control pulse. Control pulse and cavity are off-resonant to the biexciton-exciton cascade.

The control of the single-photon frequency is a direct consequence of energy conservation of the two-photon transition. In particular, optimum emission is achieved when the energy of the control pulse and of the cavity approximately add up to the energy difference between biexciton B and ground state G, $E_{\text{control}} + E_{\text{cavity}} \approx E_B - E_G$. We define the control detuning from this ideal two-photon resonance as $\Delta = E_{\text{control}} + E_{\text{cavity}} - (E_B - E_G)$. Figure 2 shows calculated emission spectra for a continuous-wave (CW) control beam with varying control detuning. It clearly demonstrates that the single-photon emission line can be tuned within the cavity line. Its width is tunable via the temporal width of the control field, following Fourier-transform rules. Since temporal profile and frequency of the control field can be chosen independently, this ultimately allows for all-optical spectral shaping of the single photon [2].

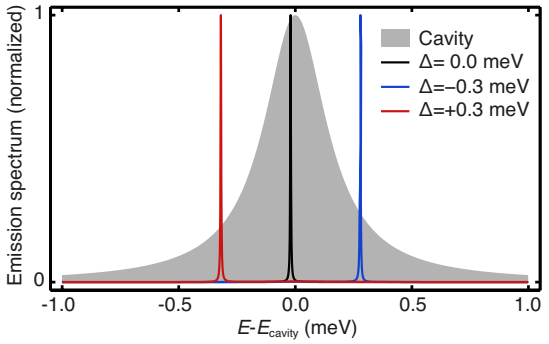

Figure 2: Control of the single photon's emission energy. Calculated emission spectra (each normalized) are shown for varying detuning Δ (i.e., varying frequency) of a CW control beam. The cavity line is shown for comparison as the shaded area. A detailed discussion is given in [2].

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Controlling the optical spin Hall effect of microcavity polaritons

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The optical spin Hall effect (OSHE) describes a spatial spin-separation of resonantly scattered exciton-polaritons in planar semiconductor microcavities [1]. This effect is based on a transverse-longitudinal cavity-mode splitting, which acts as an effective magnetic field and gives rise to a pseudo-spin orbit coupling [2]. Using a circularly polarized excitation, the OSHE results in a spatial modulation of the pseudo-spin density, represented by the first Stokes-Parameter S1 (Fig. 1a shows the k-space result highlighting the resonant nature of the scattering onto the elastic circle).

Here, we present an approach to control the OSHE using only all-optical means [3]: For a sufficiently strong cw-excitation, the effective magnetic field vector is tilted out of the cavity plane, to which it is confined in the linear optical regime. Mediated by polariton-polariton interactions, this nonlinear effect results in a significant rotation of the four-quadrant pattern in S1 (Fig. 1b).

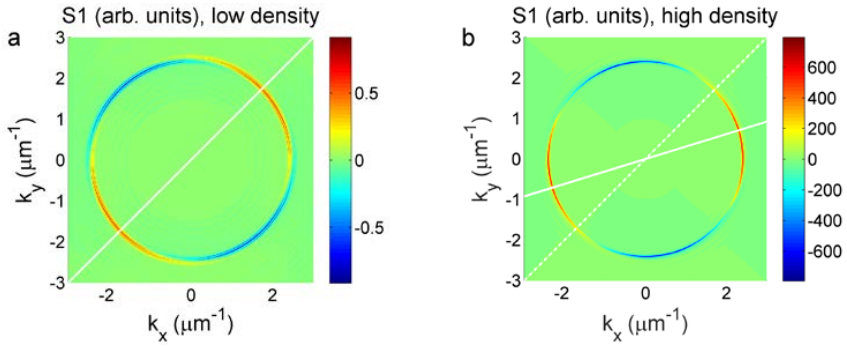

Figure 1: Shown are numerical results for the first Stokes Parameter S1 in momentum space for a low (a) and a high (b) coherent polariton density. The pattern orientation is marked by a solid line.

For an ensemble of interacting polaritons including spin-degree of freedom and all third-order nonlinearities, we derived an expression for the pattern rotation angle observed. Our analytical predictions are well confirmed by our experimental and numerical results [3].

In conclusion, we report a novel nonlinear effect, which allows the precise all-optical control of the polariton pseudo-spin and which could find its use in future spin-optotronic applications.

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Optical grating and fluxes of colloidal quantum dots

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Optical fields interacting with micro- and nanoparticles induce sizeable mechanical forces acting on the particles, which enables their optical trapping and precise manipulation [1]. Using photonic interference schemes, one can create the arrays of optical traps and form the lattices of dielectric particles [2], molecular complexes [3], biological cells [4], and metal particles [5]. Previous research in this field was focused on the study of gradient optical forces acting upon non-resonant particles.

Here, we present the theoretical study of optical forces and the optically induced motion of semiconductor quantum dots in a colloidal solution. We consider that the dielectric response of a quantum dot is caused by exciton transitions and has a resonant behavior. The optical grating is induced in the solution by two coherent laser beams. We calculate the optical force acting on the quantum dot in the spectral range of exciton resonance and analyze two orthogonal contributions to the force. The gradient contribution is determined by the real part of the susceptibility; it is directed along or oppositely to the light intensity gradient depending on the detuning between the light-field frequency and the exciton frequency. The scattering contribution determined by the imaginary part of the susceptibility reaches a maximum at the exciton frequency and directed along the line of the equal intensity of light.

In the presence of both contributions, the total mechanical force is non-conservative. Therefore, the optical grating of colloidal solutions leads not only to the formation of spatially periodic density of the quantum dots but also to the emergence of circulating fluxes of the dots. By considering the interplay of the optical forces and the processes of viscous friction and diffusion of dots, we analyze the dynamics of dots in the solution, calculate the steady-state distributions of dots density and fluxes as well as the time scales of the steady-state distribution formation.

We also analyze the optically induced distributions of dot density and fluxes in colloidal solutions with the dispersion of quantum dot sizes and, consequently, the dispersion of exciton frequencies. Since the gradient and scattering contributions to the optical force have pronounced and distinct spectral dependences, the optical grating of such solutions results in a spatial separation of quantum dots with different exciton frequencies that can be tuned by varying the light frequency.

This work was supported by FR President Grant for young scientists support MD-4550.2016.2 and the RFBR grant 16-02-00204.

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Two-level quantum dot susceptibility and polarization peculiarities caused by strong Coulomb correlations

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Recently, low-dimensional semiconductor structures with a small number of electrons attract strong attention. The reason is the progress in technological procedure that gives possibility to fabricate nanostructures with high precision [1]. Optical properties of three-dimensionally confined electrons and holes in semiconductor QDs have been extensively studied in recent years [2]. Spatial confinement and Coulomb interaction play an important role in determining the optical properties of QDs. Now a days semiconductor QDs appear as a promising candidates to achieve large susceptibilities. Moreover the dipole matrix elements in QDs can also be large, with typical dipole matrix element ranging from a fraction of a nanometer to a few nanometers. Consequently, the analysis of coupled QDs polarization is also of great interest. This work is caused by the interest in fundamental physics of finite systems and their potential as efficient nonlinear optical and laser materials [3],[4].

We consider electron tunneling through two-level QD with Coulomb correlations weakly coupled to the reservoirs. We analyzed susceptibility, polarization and electron filling numbers difference behavior in terms of pseudo operators with constraint. We revealed that susceptibility and polarization of two-level QD weakly connected to the reservoirs are not proportional to the electron filling numbers difference when strong Coulomb correlations are present. Susceptibility and polarization behavior are strongly determined by the single-electron energy levels position, applied bias voltage and Coulomb correlations values [5].

We revealed that susceptibility and polarization of two-level quantum dot (QD) with Coulomb correlations between localized electrons weakly connected to the reservoirs are not determined only by the stationary electron filling numbers difference. We demonstrated that susceptibility and polarization also depend on high-order correlation functions of electrons localized in the QD. We found that susceptibility and polarization can be controlled by applied bias voltage value, Coulomb correlations strength and Rabi frequency. We demonstrated that susceptibility and polarization amplitudes can significantly increase and even change the sign due to the tuning of the QD parameters (Fig.1).

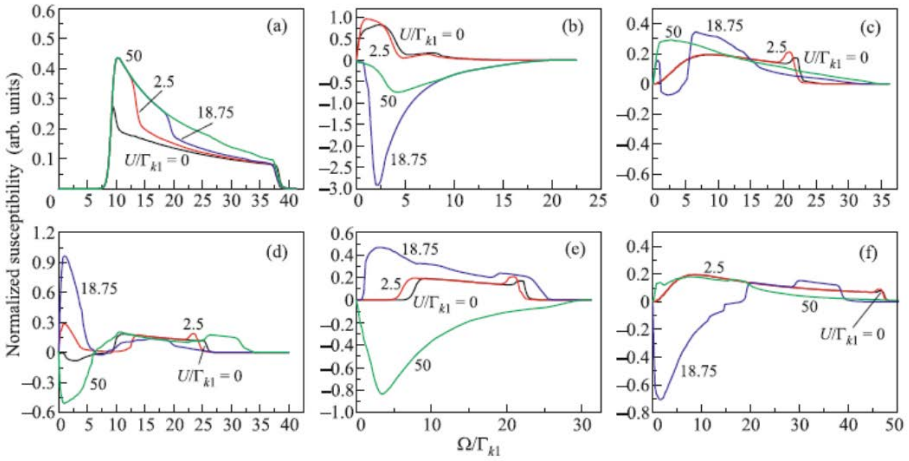

Fig.1. Normalized susceptibility as a function of Rabi frequency for different values of Coulomb correlations, applied bias voltage and energy levels position: (a) $eV/\Gamma_{k1}=50$, (b) $eV/\Gamma_{k1}=37.5$, (c) $eV/\Gamma_{k1}=-25$, (d) $eV/\Gamma_{k1}=-37.5$, (e) $eV/\Gamma_{k1}=-12.5$, (f) $eV/\Gamma_{k1}=-50$. For all the figures parameters $\Gamma_{k1}=\Gamma_{p2}=1$, $\Gamma_{k2}/\Gamma_{k1}=\Gamma_{p1}/\Gamma_{k1}=0.125$.

We would like to stress that one can tune the QD susceptibility -change it's sign and amplitude by means of system parameters changing: Rabi frequency, Coulomb correlations value, applied bias voltage and energy levels position.

This work was supported by President Grant for young scientists support MD-4550.2016.2

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Spin-photon chiral coupling in photonic crystals

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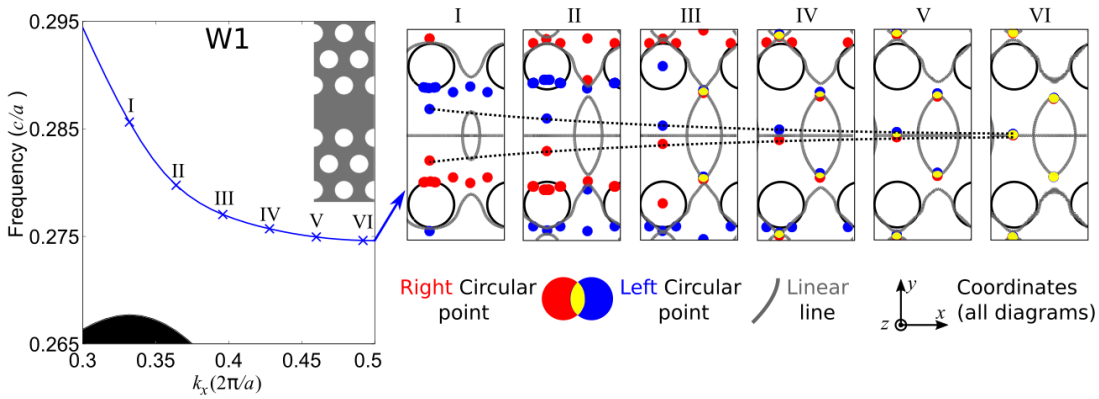
The optical modes of photonic crystal waveguides (PhCWGs) support in-plane circular polarisation. The forwards and backwards modes are related by temporal symmetry, forcing counter-propagating modes to support opposite circular polarisations.

This connection between propagation direction and polarisation results in the emission direction of photons from a quantum dot (QD) being directly controlled by the spin of the dot transition [1]. This opens up an intriguing new approach to couple the path information of photons to the spins of electrons [2].

We present a theoretical study into PhCWG designs suitable for this scheme, considering the archetypal PhCWG (w1) and a modified design (glide), introduced in [1].



At the bandedge (stopped-light) time-reversal symmetry requires either an absence of circular polarisation, or two degenerate modes supporting opposite circular polarisations. It can be seen (figure) that in the W1 the circular points (red/blue circles) annihilate in pairs. In the Glide waveguide we instead observe two guided modes becoming degenerate and everywhere-opposite in circular polarisation [3]. Thus all directional behaviour cancels out at the bandedge, as the circular points either come together in space (W1) or in frequency (glide).

Consequently, for these waveguides, operating in the fast light (weaker coupling) regime, far from the bandedge, is best for chiral interactions. Ideally stronger coupling and chiral interactions would be realised simultaneously and to this end we have explored the design parameter space for better waveguides. We have identified a “winner” with an eight-fold improvement in coupling strength at circular points.

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[3]arXiv:1601.04591 (2016)

Implementation of an electro-optical polariton transistor switch

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Exciton-polaritons have emerged as a versatile platform to study the behavior of a quantum fluid of light in a solid state environment. Due to their part-exciton nature, polaritons can interact with each other and their environment and can be conveniently manipulated. Studying the prospects of polaritons in optical on-chip logic circuits, all-optical transistors [1] and Mach-Zehnder interferometers [2] have been realized.

We study the propagation of an optically injected exciton-polariton condensate along a one-dimensional photonic wire under the influence of a local, electrical gate, cf. Fig. 1(a). Applying a gate voltage, results in a general redshift of the emission [3] along the wire superimposed by a local potential dip underneath the contact. Tuning of the trap depth and taking advantage of the detuning gradient along the wire is sufficient to block the polariton flow through the contact, Fig. 1(b)-(d). As a consequence of the switching process and increased field ionization of excitons, the device shows a negative differential resistance and features a pronounced bistability in the probed photocurrent.

The combination of lithographic and electro-optical potential landscape engineering results in a compact device. It works as a polariton transistor switch which is operated by an external electric field rather than a control laser beam. This makes the approach suitable for on-chip applications and complex polariton circuits [4].

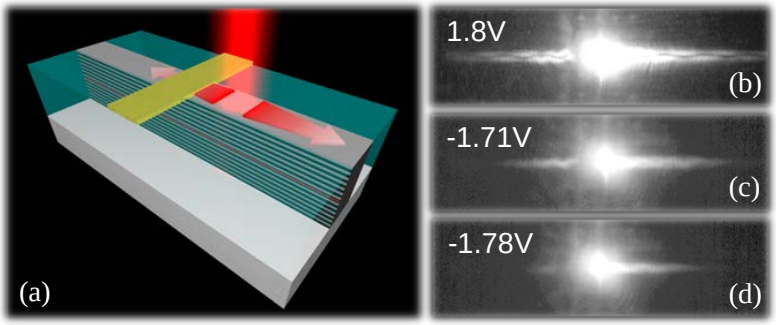

Figure 1: (a) Schematic illustration of the investigated device. (b)-(d) Real space images of the emission along the wire for different voltages. The polariton flow through the contact (flow to the left) is switched off at around -1.75V.

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Temporal shifts of photon echo from semiconductor quantum wells and quantum dots

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Manipulation of electronic states by laser pulses requires precise timing of the pulse sequence. A particular example is ultrafast coherent control of exciton complexes confined in semiconductor nanostructures which may be used for manipulating quantum states or even storing quantum information. For an inhomogeneous ensemble of two-level systems (TLS) such as quantum dots (QDs) or localized states in quantum wells (QW) the information retrieval induces echoes for the recovered signal. To be of practical use, the photon echo (PE) formation time needs to be determined with high accuracy.

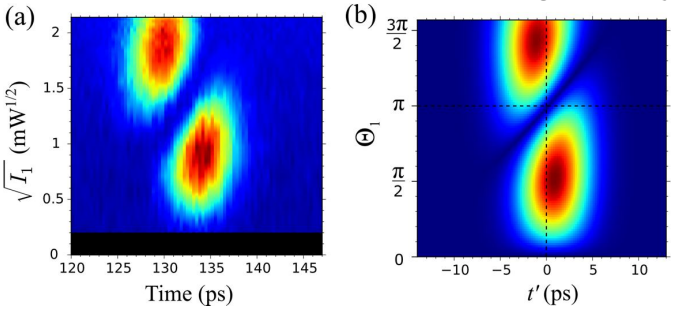

Figure 1: Experimental measurement on QDs (a) and theoretical calculation (b) of PE transient as a function of the first pulse amplitude.

Generally, it is expected that for strongly inhomogeneous TLS ensembles the PE temporal profile may undergo significant distortion compared to the standard τ_{12}–$2\tau_{12}$ sequence, showing either retarded or advanced echo pulses [1]. In this Report, we demonstrate that the PE transients are strongly influenced by the inhomogeneity of studied ensemble [2]. We study the dynamics of the PE from exctions in (In,Ga)As/GaAs QDs and trions in a CdTe single QW excited by picosecond laser pulses. By varying the amplitude of the first excitation pulse we find a complex evolution of Rabi oscillations in the amplitude of the PE, deviating strongly from the τ_{21}–$2\tau_{21}$ expectation. Namely, we observe temporal shifts of the PE pulse relative to the expected PE arrival time. We analyze the experimental results using a transparent analytical model.

Financial support by the DFG and the RFBR in the frame of the ICRC TRR 160 (RFBR proj. No. 15-52-12016 NNIO_a) as well as partial funding by RFBR (proj. 16-29-03115 ofi_m) are acknowledged.

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Simulations and design of integrated quantum optical systems

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With integrated systems containing optical waveguides and elements such as beam splitters, couplers, and polarization converters several quantum optical effects which are of great interest in fundamental physics and which have a significant potential for applications have been demonstrated.[1] Here, we focus on the $LiNbO_3$ material system in which by the indiffusion of Titanium waveguides and optical circuits can be realized. In addition, $LiNbO_3$ has a large $\chi^{(2)}$ nonlinearity which can be used for the generation of photon pairs by spontaneous parametric down conversion.[2]

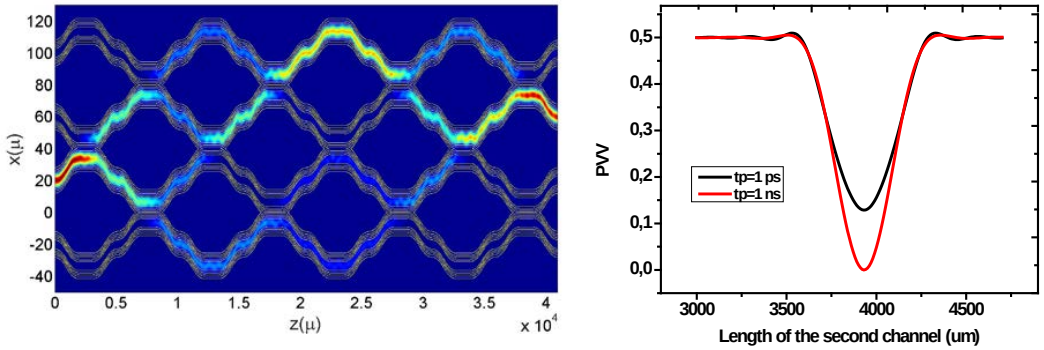

Figure 1: (left) Propagation of the TE mode in a coupled waveguide system. (right) Dependence of the coincidence probability, i.e., the HOM dip, on the length of a waveguide channel for pump pulses with two durations.

For a precise design of integrated quantum optical chips classical light propagation simulations that include integrated elements such as couplers, beam splitters, polarization beam splitters, polarization converters, etc. are a prerequisite. Such studies, see, e.g., Fig. 1(left), provide the output intensities of different channels and can be used to study the influence of imperfections related to, e.g., fabrication tolerances, index variations, bending losses, and therefore are able to provide optimized geometrical designs.

In a particular device under study we consider photon pairs generated by type-II parametric down conversion in a periodically poled Titanium indiffused $LiNbO_3$ waveguide. Using integrated optical elements the signal and idler photons can be split into different channels. By rotating the polarization in one channel the photons become indistinguishable when reaching a final beam splitter which results in two photon HOM interference.[3] The profile of the HOM deep depends on several experimental parameters and imperfections and losses of the waveguide system, see, e.g., Fig. 1(right).

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Speeding up a single quantum dot experiment

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We recently showed [1], that it is possible to measure transient reflection on single semiconductor quantum dots in the far field.

Here we discuss how to improve those measurements. The lifetime of an excited quantum dot is around of 300 ps. The time delay between two laser pulses in the old setup (repetition rate 78 MHz) is 12 ns. By changing the laser system to another one with a higher repetition rate (1 GHz) we reduce this time delay to 1 ns. This laser system consists of two independent Ti:Sapphire oscillators. The repetition rate of both oscillators is stabilized by a control loop. With these lasers, we can use different excitation wavelengths for pump and probe beam. Additionally, we also increase the spectral rate to 120 kHz. With these changes. It should be possible to decrease the necessary time by a factor up to 12 and get a higher measurement cycle.

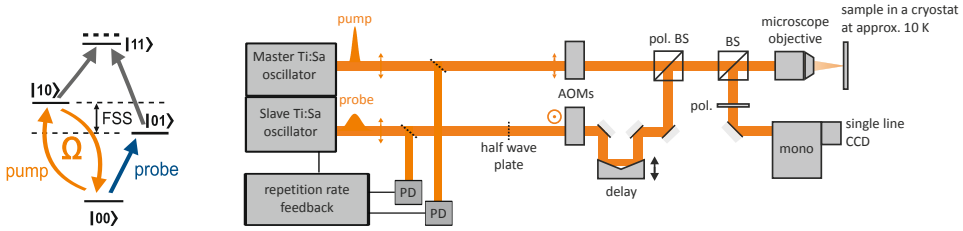

Figure 1: (left) Excitation and relaxation of quantum dots. (right) Overview over the setup.

We are interested in the characterization of a single quantum dot two-level system and its interaction with environment through transient absorption spectroscopy. We will add plasmonic structures to do antenna enhanced single quantum dot spectroscopy.

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Optical second harmonic generation on excitons in ZnSe and ZnSe-based quantum wells

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We apply a second harmonic generation (SHG) technique with femtosecond laser pulses to ZnSe bulk material and ZnSe/BeTe quantum wells. In order to investigate on excitons the laser photon energy is set at half of the structures band gap. The non-linear technique of SHG allows us to test different excitation selection rules compared to linear optical measurements. Breaking of symmetry by magnetic fields up to B = 10 T opens the opportunity to lift degenerated energy levels and induce shift and mixing of the exciton states. Despite the broad spectral bandwidth of the femtosecond laser pulses we succeed to detect narrow exciton resonances (Fig.1, left side).

For bulk ZnSe we present SHG measurements for diffrent crystal orientations and in magnetic field in Voigt geometry. Especially in magnetic field a rich spectrum of magneto-excitons arises along with exciton ground states. The polarization dependency of the SHG intensity is analysed as well.

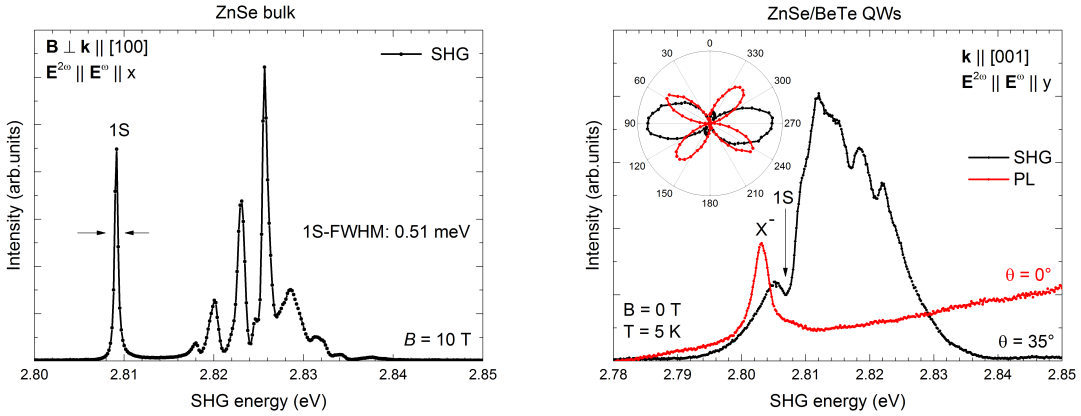

Figure 1: Left side: SHG measurement on bulk ZnSe. Right side: SHG and PL measurement on ZnSe/BeTe quantum well structure.

SHG and photoluminescence (PL) spectra on a ZnSe/BeTe heterostructure with a type-II band alignment, grown on [001]-GaAs substrate are shown on the right side of the figure. Our focus are the direct transistions within the ZnSe quantum wells (QWs). In tilted geometry ($\Theta = 35°$) without magnetic field the spectrum reveals a nonresonant second harmonic signal, generated in the GaAs substrate, wherein absroption dips due to exciton states in the ZnSe QWs are detected. For perpendicular light incidence to the sample exciton resonances from the QWs arise as a magnetic field is applied in Voigt geometry. Photoluminescence measurements show a trion state (X^-) and confirm the position of the 1S exciton state.

This work was supported by the Deutsche Forschungsgemeinschaft via Sonderforschungsbereich TRR142.

Dynamics of the dressed biexciton in a deterministically fabricated quantum dot microlens

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The dressing of the biexciton in a quantum dot (QD) through a resonant two-photon excitation gives rise to an original coupling of a laser field to a three level "ladder" system, constituted by the ground state, the exciton and the biexciton. We investigate the dynamics of such a system by correlating the photons emitted by the dressed states. The studied system is constituted by a InGaAs quantum dot embedded in a determistically processed microlens[1], allowing a good focusing of the excitation laser and a broadband extraction of the photons emitted by the different dressed states. We demonstrate that the latters emit, one after the other, single photons and that the time ordering of the photons emitted by the biexciton and the exciton usually observed under incoherent excitation is suppressed as the Rabi frequency is increased and the Jaynes-Cumming ladder is established. One can conveniently prepare a particular dressed state and change the path of the radiative cascade by tuning the laser from the two-photon resonance. Under such conditions, a time ordering of the emitted photons can be recreated and is observed in the cross-correlation function. In addition, the coherence of the system will be further discussed through the observation of the biexcitonic Rabi oscillations in the time domain.

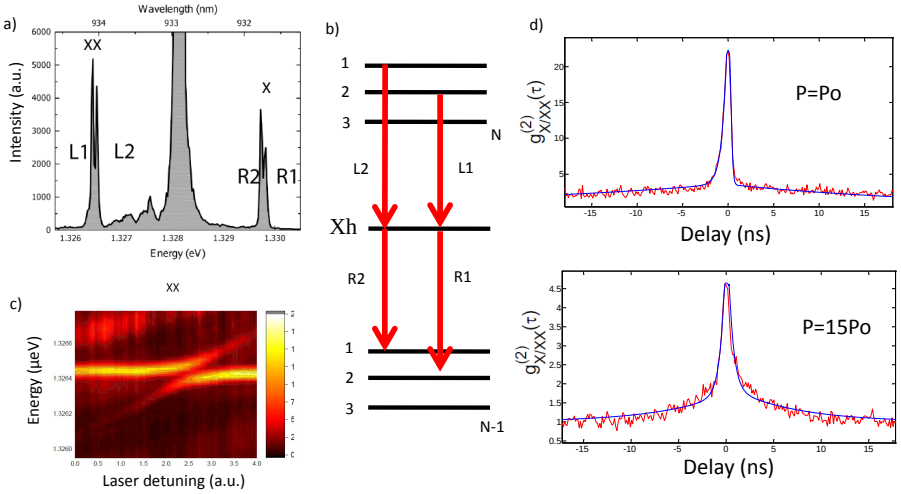

Figure 1: a) Typical spectrum of a QD-microlens resonantly excited through the continuous two-photon absorption. b) Scheme of the ladder consituted by the dressed states and the bare horizontally polarized bare exciton. c) Energies of the dressed states as a function of the Laser energy. d) Cross correlation of the photons from the dressed states and the bare exciton lines for low power P_o and high power $15P_o$.

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Fundamental limits to coherent scattering and photon coalescence from solid-state quantum emitters

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Recent efforts to suppress the detrimental effects of phonon interactions in solid-state sources have renewed interest in studying the weak (Heitler) excitation limit [1-5]. In atomic systems, this regime is dominated by elastic (coherent) scattering of photons, with the proportion of coherent emission approaching unity as the driving strength is reduced [6]. As the population excited within the emitter then becomes very small, it is expected that in solid-state systems phonon effects will be correspondingly suppressed, such that the emitted photon coherence times may become extremely long.

Here, we demonstrate that this intuition is incomplete. Phonon interactions remain a vital consideration for QDs in the weak excitation regime, despite the vanishing dot population. In fact, we show that non-Markovian relaxation of the phonon environment leads to a fundamental limit (below unity. See Fig. 1, Left) to the fraction of coherently scattered light from a solid-state emitter at weak driving. This is in clear contrast to the atomic case, and thus constitutes a novel regime of semiconductor quantum optics. Furthermore, we show that signatures of the phonon relaxation process can be even more pronounced in two-photon interference experiments, resulting in a substantial suppression of the visibility of photon coalescence on picosecond timescales, which is further exacerbated when accounting for the inevitable detector temporal response. This leads to a non-monotonic dependence of the visibility on driving strength that is unexpectedly optimised at intermediate rather than very weak excitation (Fig. 1, Right).

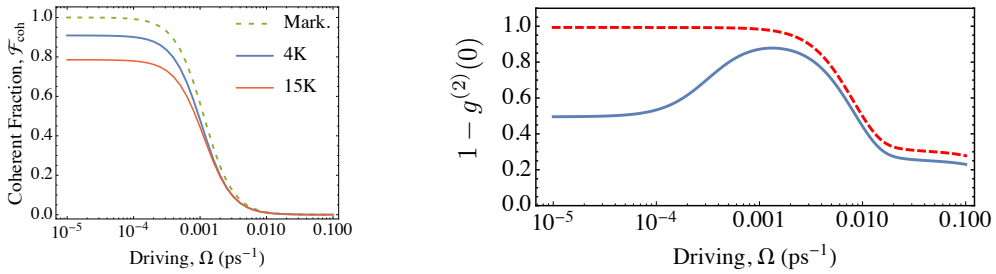

Figure 1: (Left) Fundamental limit to the fraction of coherently scattered light when non-Markovian phonon relaxation is accounted for. (Right) The visibility of the two photon interference as a function of driving strength for a realistic single photon detector.

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Drastic energy concentration in plasmonic-excitonic composite multilayered structures

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The study of light harvesting is crucial for the development of sustainable energy technologies. In particular, the concentration of harvested light energy into the photoactive part in a device is important for realizing highly efficient photonic functions. One of the promising approaches of harvesting and concentrating energy is to utilize optical antennas sustaining the surface plasmon polariton (SPP) resonance. For instance, it has been proposed that the quantum interference between the split coupled modes comprising the SPP mode and the molecular excitonic one leads to a drastic energy concentration in the molecule [1,2]. Because the fabrication and the control of parameters are not easy for such coupled systems if the fine metallic structures are used, it is highly desired to realize similar concentration effect by simpler structures such as metal-insulator composite layers [3].

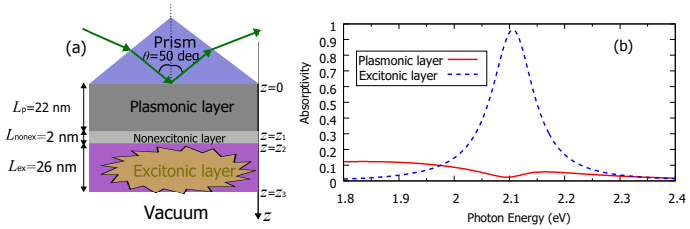

Figure 1: (a) Sketch of the prism/plasmonic layer/nonexcitonic layer/excitonic layer/vacuum structures. (b) The absorptivity spectrum of the plasmonic layer in red solid line and that of the excitonic layer in blue dashed line.

In the present contribution, we theoretically demonstrate particular parameter sets for the drastic energy concentration effect in plasmonic-excitonic multilayered structures, where the incident light is strongly concentrated in the excitonic layer as if the plasmonic layer becomes transparent. Figures 1(a) and 1(b), respectively, show the assumed sample structure and the absorptivity spectra. By appropriately controlling both the light incident angle and thickness of the plasmonic layer, we have found the condition that the absorptivity of the excitonic layer reaches 97 % whereas that of plasmonic layer becomes about only 2 %. This is because the plasmonic layer serves as an optical antenna, and the light is prominently concentrated in the excitonic layer. Furthermore, the absorptivity of the excitonic layer in the present system is near 50 times larger than that in a single excitonic layer with the same thickness. The key effect in this phenomenon is the interference between the eigenmodes of the plasmon-exciton coupled systems [1]. This result indicates the possibility to realize highly efficient photonic devices even by simpler layered structures with appropriately designed photon intake.

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[3] S. Hayashi, *et al.*, Appl. Phys. Lett. **108**, 051101 (2016).

Computer-aided cluster expansion

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We introduce a computer-aided algebraic approach for a microscopic description of open quantum systems [1,2]. The presentation combines the conceptual ideas of the computer-aided cluster expansion with the application on a current research topic - sub- and superradiance of semiconductor quantum dots.

We exploit a configuration formulation that allows for an exact treatment of a subsystem e.g. a multilevel quantum dot [2]. The fundamental object of the system is described without approximation while correlations between objects can be treated on different levels of approximation. The computer-aided cluster expansion (Fig.1 (a)) provides an efficient algebraic approach to derive equations of motion (EoM), while the user can focus on the physical modeling and conceptional questions. The routines offer a variety of different types of approximations applicable for finite systems with strong coupling as well as large systems where augmented mean-field theories apply.

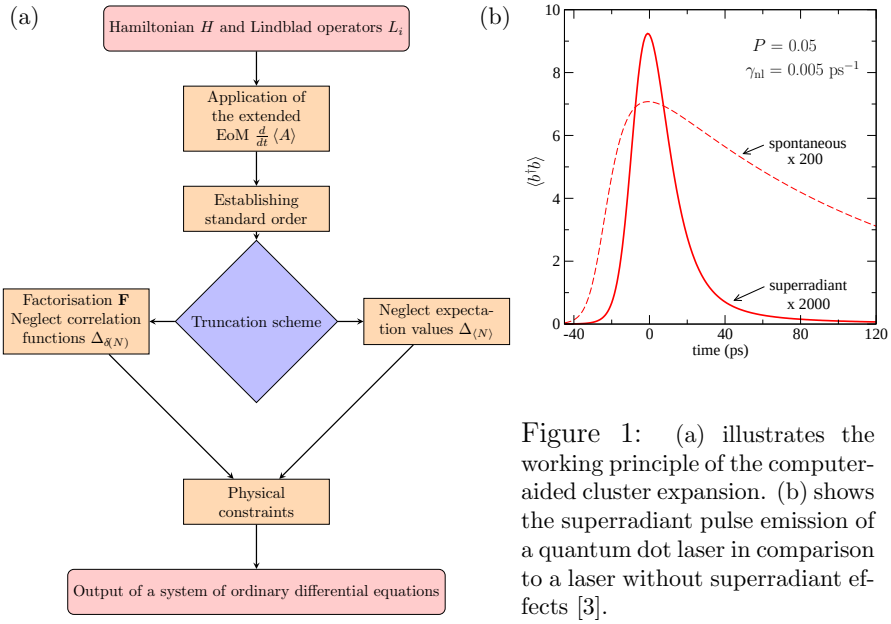

Figure 1: (a) illustrates the working principle of the computer-aided cluster expansion. (b) shows the superradiant pulse emission of a quantum dot laser in comparison to a laser without superradiant effects [3].

The method is illustrated by means of a representative example - the sub- and superradiance in state-of-the-art quantum-dot nanolasers [2,3]. In agreement with experimental results we demonstrate giant photon bunching, excitation trapping and superradiant pulse emission (Fig.1 (b)).

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[2] H.A.M. Leymann, A. Foerster, et al., Phys. Rev. Applied **4**, 044018 (2015).
[3] F. Jahnke et al., Nat. Comm. **7**, 11540 (2016).

Energy transfer in transition metal dichalcogenide heterostructures

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In recent years, layered materials beyond graphene have attracted immense interest in the scientific community. Among those, particularly the semiconducting transition metal dichalcogenides (TMDCs) in their monolayer form are in the focus of the current research due to their intriguing optical properties and their potential application in valleytronic-based devices. When thinning the material down from a bulk crystal to the monolayer limit, a changeover from an indirect to a direct optical gap in the visible and near-infrared spectral range occurs, making the materials promising candidates for future ultrathin and transparent optoelectronic devices. The optical properties are governed by excitonic features, even at room temperature. The excitons in monolayer TMDCs have unusually large binding energies due to the two-dimensional carrier confinement and weak dielectric screening.

Via a deterministic transfer process, a TMDC monolayer can be transferred onto a variety of substrates. This includes also the possibility of stacking two monolayers on top of each other. Thereby, atomically sharp interfaces can be created without the need for a match of the lattice constant or of the twist angle of the flakes. Here, we perform an optical spectroscopy study to investigate the properties of twisted artificial bi- and trilayer MoS_2 [1]. The stacking order as well as the interlayer distance in these samples differs from the common 2H stacking in TMDCs. The combination of second-harmonic-generation microscopy and photoluminescence measurements allows us to determine the degree of interlayer coupling. The PL intensity is slightly quenched due to resonant energy transfer between individual layers. The efficiency of this process depends on the interlayer distance and on the ratio of radiative and non-radiative recombination of the excitons.

Energy transfer cannot only occur in homogenous material stacks, but also between a metallic substrate and a thin TMDC sheet. We report on the electroluminescence (EL) of monolayer WSe_2 transferred onto a thin electromigrated Ag film. Under the flow of a high-frequency ac current in the silver film, the energy is directly transferred to the TMDC monolayer. This results in a bright excitonic EL spectrum of the flake without the need for a sophisticated production of a p-n-junction. Hence, resonant energy transfer represents an efficient and viable process in order to let atomically thin crystals light up.

[1] G. Plechinger, F. Mooshammer, A. Castellanos-Gomez, G. A. Steele, C. Schüller, and T. Korn, 2D Materials **2**, 034016 (2015).

ZnO-based microdisk resonators under nonlinear optical excitation

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Due its high nonlinear optical coefficients, ZnO is an attractive candidate for nonlinear device applications in the visible spectral range. However, the high intensity required for $\chi^{(2)}$- and $\chi^{(3)}$-effects still hampers applications in microstructured devices. In this work, we exploit the field enhancement provided by whispering gallery modes (WGM) in order to enhance optical nonlinear effects in the structures. We demonstrate that optical sub-bandgap excitation of ZnO microdisk resonators enables multi-photon absorption, second and third harmonic generation and efficient feeding of WGM modes.

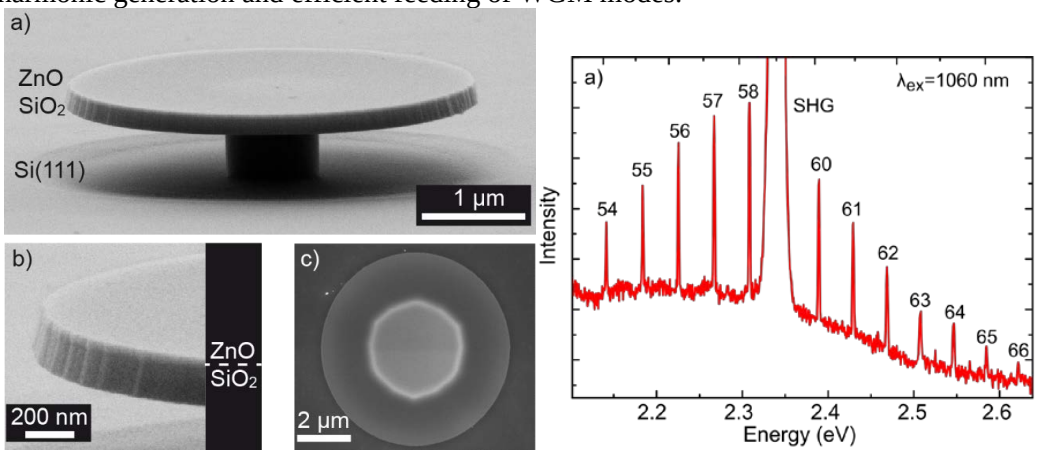

Figure 1: (a-c) Secondary electron micrographs of a ZnO-based microdisk in side (tilted) view and top-view. (d) Luminescence spectrum of a ZnO-based microdisk obtained using three-photon absorption of sub-wavelength photons. The strong peak around 2.33eV is due to second harmonic generation.

We find that the MDs exhibit strongly confined WGMs over the blue-yellow part of the visible spectrum for all excitation processes on pre-patterned ZnO/SiO_2. Quality factors as high as Q=4700 are measured, which are among the highest reported values for ZnO-based photonic resonators. From the spectroscopic data it is confirmed that the optical field is mostly confined inside the ZnO film. These results clearly show that due to the high nonlinear optical coefficients ZnO photonic micro-/nanostructure can effectively be pumped using nonlinear processes.

Noise processes in singly charged quantum dot–cavity system

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Charged quantum dot (QD) devices have many potential applications in quantum technologies; for example, by manipulating the spin degrees of freedom of such systems, a series of entangled photons may be generated [1, 2], which may then be used in quantum computing schemes. Recent experimental work has demonstrated increased decoherence of a singly charged QD in a cavity compared to its neutral counterpart, which represents a significant challenge for creation of entangled states [3].

We develop a consistent model describing a singly charged QD coupled to a cavity at the master equation level. With this model, we perform an in-depth analysis of incoherent noise processes crucial for understanding decoherence processes in such systems. This analysis shows, among other results, that the cotunneling rate, i.e. the tunneling rate of the electron out of the QD, has a significant impact on the decoherence rate of the QD dipole moment (see Fig. 1a).

Along with numerical calculations of the transmittivity of a coherent laser field through the QD–cavity system, we develop a semiclassical mean-field model in a manner similar to well-known results obtained for a single QD transition interacting with a cavity [4, 5]. However, this mean-field model is shown to break down as the coupling rate is increased above the decoherence rate due to induced light-matter correlations (see Fig. 1b).

Finally, the developed model is a promising theoretical platform for investigating other coherent and incoherent processes in charged QD–cavity systems. With the full implementation at the master equation level, the model can readily be extended to include effects such as coupling to phonons and spin rotations due to interaction with an external magnetic field.

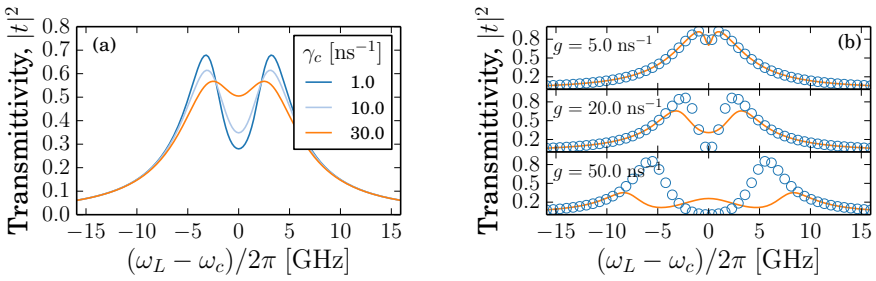

Figure 1: (a) Transmittivity through the cavity as a function of laser detuning relative to the cavity, $\omega_L - \omega_c$, for increasing cotunneling rates, γ_c. (b) Comparison of the full numerical solution (solid red lines) and a mean-field analytic expression (blue circles) of the transmittivity for increasing coupling rates, g.

[1] C. Y. Hu, W. J. Munro, and J. G. Rarity. Phys. Rev. B **78**, 125318 (2008).

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Coherent dynamics of excitons in $MoSe_2$ monolayers explored with four-wave mixing micro-spectroscopy.

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By implementing four-wave mixing (FWM) micro-spectroscopy we measure coherence and population dynamics of the exciton transitions in monolayers of $MoSe_2$ [1]. We reveal their dephasing times T_2 and radiative lifetime T_1 in a sub-picosecond (ps) range, approaching T_2=2T_1, and thus indicating radiatively limited dephasing at a temperature of 6 K. We elucidate the dephasing mechanisms by performing FWM hyperspectral imaging (Fig. 1 a) and spatially-resolved dephasing study with a sub-micron resolution. By inferring photon echoes in FWM transients (Fig. 1 b) and correlating the retrieved inhomogeneous and homogeneous broadenings, we indicate that the local disorder governs the radiative rate and thus the dephasing time T_2. With increasing the temperature (see Fig. 1 c) we observe that the dephasing accelerates owing to the phonon interaction. At 100 ps range, we observe the residual FWM produced by the incoherent excitons, which initially disperse towards the dark states, but then relax back to the optically active states within the light cone. By introducing polarization-resolved excitation, we infer inter-valley exciton dynamics, showing an initial polarization degree of around 30%, constant during the initial sub-picosecond decay, followed by the depolarization on a picosecond timescale. The FWM hyperspectral imaging reveals the doped and undoped areas of the sample, allowing to investigate the neutral exciton, the charged one or both transitions at the same time. In the latter, we observe the exciton-trion beating in the coherence evolution, indicated their coherent coupling, as confirmed by two-dimensional FWM spectroscopy.

[1] T. Jakubczyk *et al.*, resubmitted in Nano Letters (2016).

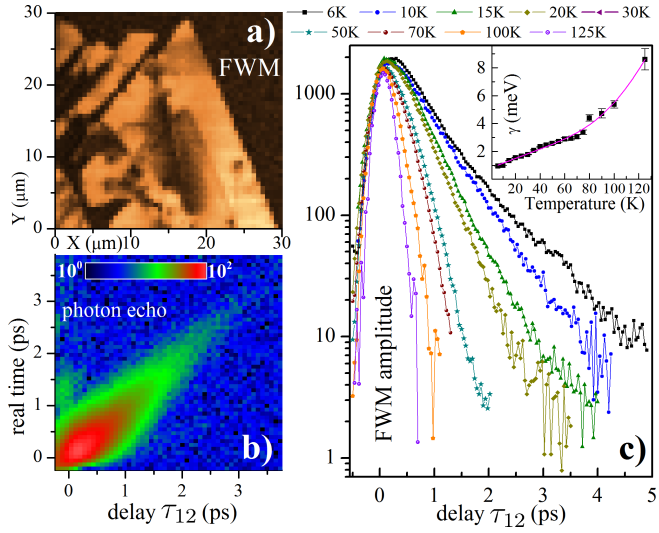

Figure 1: **Four-wave mixing micro-spectroscopy of the $MoSe_2$ monolayer.** a) FWM imaging of the flake observed at the energy of the neutral exciton ($\sim$ 1652 meV). b) The measured time-resolved FWM, exhibiting photon echo, enabling to retrieve homogenous (γ) and inhomogeneous broadenings of the exciton transition. c) Time-integrated FWM versus temperature displaying phonon-induced dephasing. The initial linear increase of γ with temperature is due interaction with acoustic phonons, followed by bosonic activation of optical phonons.

Micro-Photoluminescence Spectroscopy and Imaging of Optically Coupled Microdisk Dimers

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Semiconductor quantum dots (QDs) coupled to optical microcavities serve as ideal building blocks for the investigation of cavity quantum electrodynamics (CQED). These solid-state systems offer the possibility to explore basics of light-matter coupling [1], or to build sources of single, or indistinguishable photons and entangled photons pairs [2] for applications as quantum cryptography and quantum information processing. Qbit operations can be realized by coupling two or more QDs via the electric field of a single cavity mode [3]. However, due to the accurate alignment and addressing of individual QDs necessary for these schemes the experimental realization is still challenging. By exploiting the mode distribution of coupled cavities, so called photonic molecules [4], one can more easily address single QDs in different cavities.

We investigate two monolithically grown, adjacent GaInP microdisks (Fig. 1(a)) coupled via the evanescent field of their whispering-gallery modes. Each disk houses an active layer of self-assembled InP QDs. We present different experimental techniques to investigate and manipulate the interdisk coupling. Additionally to the already successfully established temperature tuning approach by local laser heating [5] that brings uncoupled modes into resonance, we search for disk pairs displaying already coupled modes by means of µ-photoluminescence spectroscopy scans to map the coupled mode profile applying a 4f-setup (Fig. 1(b)). Numerical FDTD simulations (Fig 1(c)) reveal opportunities to increase the coupling strengths between two disks by a factor of 4 by simply adjusting the microdisks shape. The symmetric deformation still allow for the scaling of the system to larger and more complex structures like chains and arrays [6].

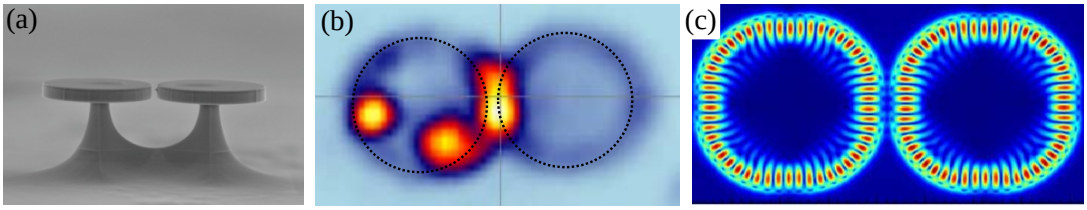

Figure 1: (a) SEM image of photonic molecule consisting of two AlGaInP microdisks with single disk diameter of 2.12 mm and an interdisk spacing of nominal 100 nm. (b) Colorscale photoluminescence map of a microdisk dimer, which is excited at the center. Quantum dots are located at the bright spots, while scattered light of WGM modes is visible at the disks surrounding. (c) FDTD simulation of a deformed pair of coupled microdisks.

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[3] A. Imamoglu, et al., Phys. Rev. Lett. **83**, 4204 (1999). A. Laucht, et al., Phys. Rev. B **82**, 075305 (2010).
[4] M. Bayer, et al., Phys. Rev. Lett. **81**, 2582 (1999). A. Dousse, et al., Nature **466**, 217-220 (2010).
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Magnetic-Field-Induced Third and Second Harmonic Generation on Exciton-Polariton in GaAs

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GaAs has the noncentrosymmetric crystallographic structure of zinc blend type in which nonlinear optical process of third harmonic generation (THG) is allowed and second harmonic generation (SHG) is forbidden in the electric-dipole approximation. A resonance in the THG and SHG spectra of GaAs is observed in the vicinity of the 1s-exciton energy. An external magnetic field of 10 T gives rise to a giant enhancement of the THG intensity by a huge factor of hundred. The effect is attributed to spatial dispersion of exciton-polaritons and its modification in magnetic field caused by mixing of dark and bright 1s-exciton states. Magnetic field and rotational anisotropy dependencies allowed us to unambiguously confirm the microscopic mechanism of the magnetic-field induced THG.

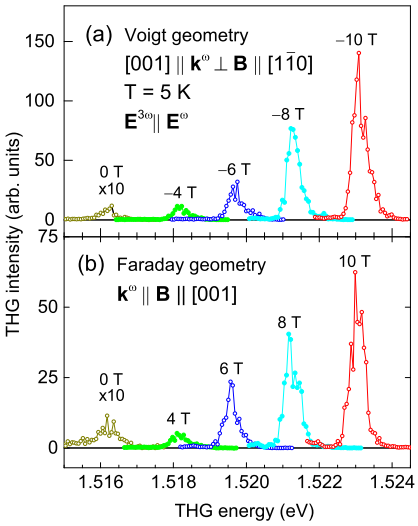

Figure 1: THG spectra measured in $E^{3\omega} \parallel E^{\omega} \parallel [010]$ geometry in the vicinity of the 1s-exciton resonance for different magnetic fields. (a) Voigt geometry (b) Faraday geometry.

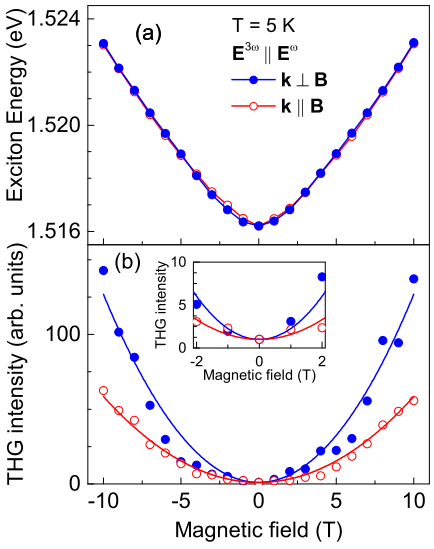

Figure 2: (a) Exciton energy of THG resonance as a function of magnetic field (b) THG intensity as a function of the magnetic field. Lines are interpolation with $\propto (1 + a \cdot B^2)$ dependence. THG amplitude at $B = 0$ is normalized to unit. Insert shows a zooming part close to the zero magnetic field. One has to note that THG signal at $B = 0$ is finite.

Nonlinear excitation of fully undercut ZnO-based photonic crystal membranes with 3D optical confinement

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For studying nonlinear photonics, a highly controllable emission of photons with specific properties is essential. Two-dimensional photonic crystals (PhCs) have proven to be an excellent candidate for manipulating photon emission due to resonator-based effects. Additionally, zinc oxide (ZnO), along with emission in the UV regime, has high susceptibility coefficients and therefore shows pronounced nonlinear effects. However, in order to fabricate such a cavity, a fully undercut ZnO membrane is required, which is a challenging problem due to poor selectivity of the known etching chemistry for typical substrates such as sapphire or ZnO. We demonstrate and characterize fully undercut photonic crystal membranes based on a thin ZnO film sandwiched between two layers of silicon dioxide (SiO_2) on silicon substrates. The ZnO is grown by plasma assisted molecular beam epitaxy (PA-MBE) on a dry oxidized SiO_2 layer on top of a Si(111) substrate and is subsequently covered with SiO_2 via chemical vapor deposition (CVD). Thereafter, the heterostructure is patterned by electron beam lithography and reactive ion etching. Additionally, high temperature rapid thermal annealing (RTA) is used in order to enhance the photoluminescence (PL) of the ZnO layer. This process leads to a fully undercut ZnO-based membrane with adjustable optical confinement in all three dimensions (see Fig. 1(b)).

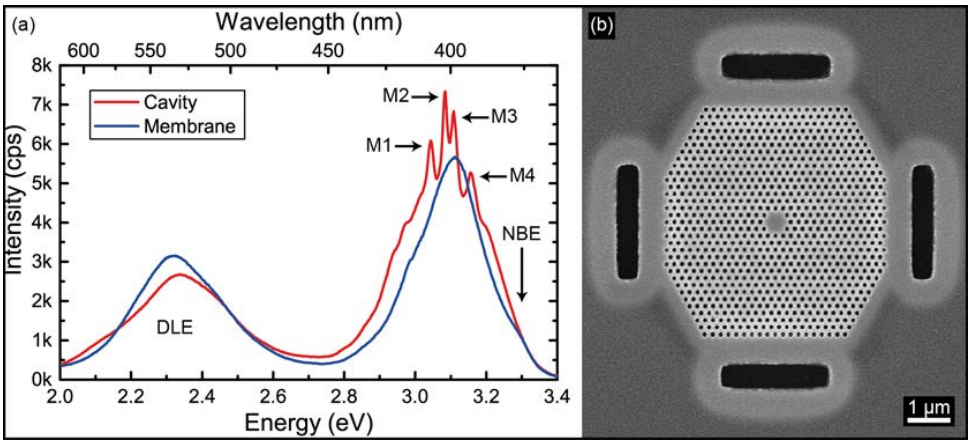

Figure 1: (a) Photoluminescence measurements of a PhC at the H2 cavity and non-patterned SiO_2-ZnO-SiO_2 membrane in a continuous-wave setup with constant excitation power of 5 mW. M1-M4 are corresponding to photonic resonances within the photonic band gap. (b) SEM micrograph of a completely fabricated ZnO-based PhC. The separation from the Si substrate can be observed as a brighter area around the holes and the four rectangular openings.

For characterization, photoluminescence measurements of different cavities with continuous-wave excitation as well as two-photon absorption were performed. They result in resonances within the tailored photonic band gap for TE-polarization (see Fig. 1(a)). The presented approach enables a variety of photon based resonator structures in the UV regime for studying nonlinear effects, including photon-exciton coupling and all-optical switching.

Robustness of photon indistinguishability versus temporal delay and temperature for a quantum dot in a cavity

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A fundamental building block in the architecture of photonic quantum networks is a true single-photon source generating pure indistinguishable photons. We recently reported on such sources [1], fabricated by deterministically inserting quantum dots in electrically controlled micropillar cavities [2], see a schematic representation of the device in Fig. 1(a).

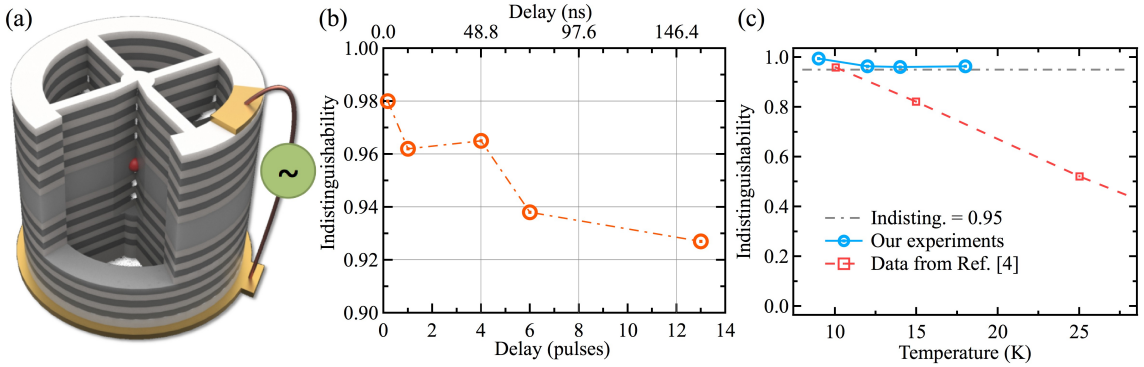

Figure 1: (a) Sketch of the quantum dot-micropillar cavity device, with electric contacts to apply a bias voltage on the quantum dot. (b) Indistinguishability versus temporal delay (in laser pulses, bottom axis, or in nanoseconds, top axis) between the two interfered photons. (c) Indistinguishability of the zero phonon line versus temperature in our experiments (blue circles, 12 ns delay), compared to data from Ref. [4] (red squares, 2 ns delay).

We first experimentally study the robustness of the high photon indistinguishability versus the time-delay between two photons [3] to estimate how many identical photons can be generated by a single source. In Fig. 1(b) we show that the photon indistinguishability is almost independent of the time delay between the two excitation pulses, going from 0.98 at 2.2 ns to 0.92 at 150 ns delay. This result shows that one could use a 1 GHz laser excitation rate and generate a train of more than 100 single-photons with an indistinguishability exceeding 90%.

Then we also study the dependence of the indistinguishability of the zero phonon line versus temperature in a regime of strong Purcell effect. The bias voltage tuning allows keeping the quantum dot in resonance with the cavity for all the measured temperatures. We observe an almost negligible decrease of the indistinguishability with temperature up to 20 K [Fig. 1(c)]. Our results show that the strong Purcell effect cancels the influence of pure dephasing of the zero phonon line.

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Enhancement of second harmonic generation by plasmonic nanoantennas

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The light-matter interaction for nonlinear processes is known to be rather weak. Consequently, high excitation powers are required for efficient second harmonic generation (SHG). Plasmonic nanostructures are a promising approach to achieve strong near-field enhancement. This work focuses on the investigation of resonances of nanorod antennas with respect to lattice periodicity and geometry, as well as their efficiency for second harmonic generation of light.

Optimized plasmonic nanostructures result in highly amplified electromagnetic fields and sharp plasmonic resonances. Two major absorbance peaks can be identified from the transmission spectra, resulting from the excitation of localized surface plasmon polaritons (LSPPs) and from the lattice diffraction, which is given by the periodical arrangement of the antennas within each array. For a superposition of both peaks, the local electric field is strongly enhanced, which is due to the light being diffracted by the grating like antenna array within the dielectric surface.

This effect can be utilized to increase the efficiency of second harmonic generation from the substrate. Since SHG is mostly generated at the surface of the substrate, thin ZnO films with periodically arranged nanoantennas show highly amplified SHG signals. This effect can be further increased by using double resonant nanoantennas with a second plasmonic resonance for the SHG signal, resulting in a strongly improved far field interaction.

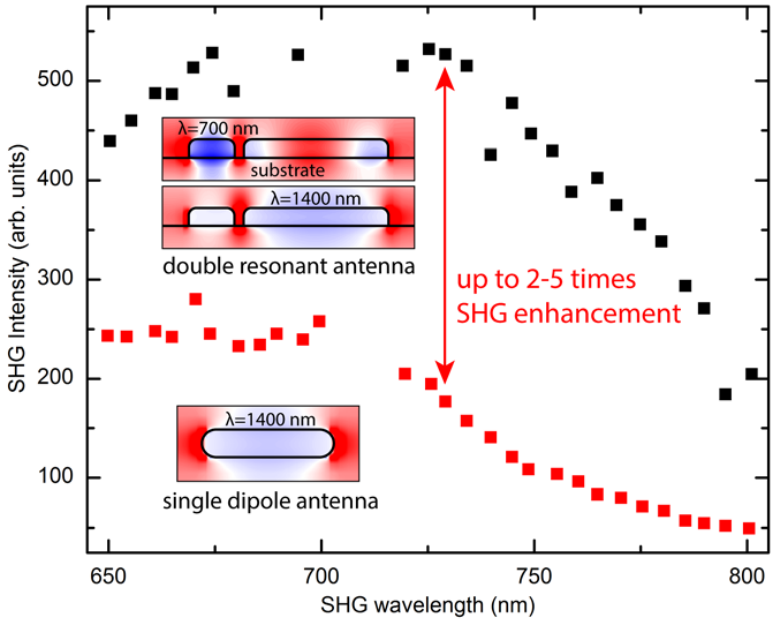

Figure 1: Wavelength-dependent SHG signals of dual resonant nanoantennas compared to single dipole antennas. The second resonance is tuned to match the SHG wavelength of the large antenna, enabling higher far field interaction.

Tamm plasmons and exciton polaritons in hybrid microcavities

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In recent years researchers have drawn their attention to cavity-exciton polaritons considering not only questions arising from fundamental research but also from the viewpoint of optoelectronic applications. Tamm plasmons [1] have been discussed as a new tool for tailoring light-matter interactions. They can be formed at the interface between a metallic layer and a DBR. Such a concept can be integrated into well established microcavity structures in order to manipulate the light-matter interaction. In addition, strong coupling between Tamm plasmon modes and quantum well excitons has experimentally been demonstrated [2].
We present evidence for the existence of a hybrid state of Tamm-plasmon exciton-polaritons in a ZnSe-based microcavity sample covered with an Ag metal layer. The eigenenergy of the Tamm plasmon resonance can be altered by varying the thickness of either the top DBR layer or the metal layer. However, increasing the metal layer thickness would diminish the transmission of the Tamm plasmon resonance. Hence changing the thickness of the top layer of the DBR would be advantageous in order to vary the Tamm plasmon eigenenergy. A thickness gradient for the top DBR layer was realized by etching with a shadow mask. Finally, a 40 nm thick Ag layer was deposited by electron-beam physical vapor deposition on top of the sample surface. In microreflectivity measurements performed for different detunings between the Tamm plasmon and the cavity mode the bare cavity mode shows a characteristic anticrossing with the Tamm-plasmon mode. If the Tamm-plasmon mode is in resonance with the cavity polariton four hybrid eigenstates will be observed due to the coupling of the cavity-photon mode, the Tamm-plasmon mode, and the heavy- and light-hole excitons. If the bare Tamm-plasmon mode is tuned, these resonances will exhibit three anticrossings. Experimental results are in good agreement with calculations based on the transfer matrix method as well as on the coupled-oscillators model. The lowest hybrid eigenstate is observed to be red shifted by about 13 meV with respect to the lower cavity polariton state when the Tamm plasmon is resonantly coupled with the cavity polariton. This spectral shift which is caused by the metal layer can be used to create a trapping potential for the polaritons. We anticipate that such a concept for the lateral confinement of the lower polariton eigenstate may be important for manipulating, shaping, and directing the flow of polaritons. Additionally, a possibility for electrical tuning could be established.

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Study of electron and spin transport in p-type $Al_xGa_{1-x}As$ layers by optical orientation

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Many pioneering works on optical orientation of electron spins in semiconductors were carried out on a wide application $A^{III}B^{V}$ solid solutions and heterostructures [1,2]. It was revealed, when using this new method, that heterogeneity of recombination conditions in the bulk and on the surface, at the interface as well as the distribution of spin density from the surface of the optical excitation to the bulk influence the relaxation lifetimes of electrons and their mean spin.
Different mechanisms of spin relaxation were theoretically predicted, and experiments basically confirmed these predictions [3], despite the fact that the above stipulations were not taken into account.
Here we report the results of experiments on optical orientation of electron spins where the electron lifetimes and spin relaxation times were determined. Measurements were carried out over a wide temperature range for various AlGaAs heterostructures, with layers having different thicknesses *d*, from small, of the order of the electron diffusion length, up to large ones, when $d>>L$. Temperature dependence of measured times considering electrons transport, their spin and recombination-relaxation processes at interfaces were analyzed.

Comparison with the results available in the literature is also disclosed.

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Valley Zeeman splitting and valley polarization in monolayer $MoTe_2$ at high magnetic fields

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Atomically thin layers of semiconducting transition metal dichalcogenides (TMDCs) give rise to fascinating phenomena on the quantum scale due to their thickness below a nanometer. Application of an external magnetic field leads to valley Zeeman splitting and magnetic-field-induced valley polarization in TMDC monolayers.[1] However, the only telluride member of the family, $MoTe_2$, which extends the spectral range of TMDCs to the infrared region, has not been studied in high magnetic fields so far.

Here, we present helicity-resolved magneto-photoluminescence (MPL) and magneto-reflectance contrast (MRC) spectroscopy measurements of 2H-$MoTe_2$ monolayers under external magnetic fields of up to 29 T, applied in Faraday geometry and at cryogenic temperature (Fig. 1(a)).[2]

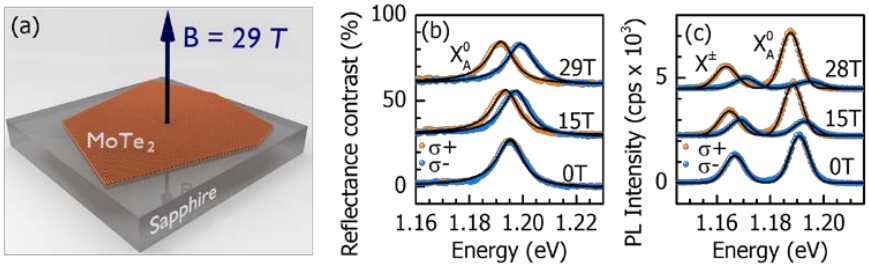

Figure 1 (a) Sample geometry, (b) helicity-resolved micro-reflectance contrast spectra, and (c) micro-photoluminescence spectra of a $MoTe_2$ monolayer in a magnetic field.

Valley Zeeman splittings for the neutral A and B excitons (X_A^0 and X_B^0) are resolved using MRC (Fig. 1(b)), whereas the neutral and charged A excitons ($X^{\pm}$) are measured using MPL (Fig. 1(c)). The effective g-factors for X_A^0, X_B^0, and $X^{\pm}$ are determined to be -4.6 ± 0.2, -3.8 ± 0.6, and -4.5 ± 0.3, respectively. These values are comparable to those observed in other TMDC monolayers and can be understood on the basis of a tight binding model. Furthermore, the magnetic field induces strong valley polarization, which reaches 78% and 36% for the X_A^0 and $X^{\pm}$ transitions at a magnetic field of 28 T (Fig. 1c). These are the highest reported values on any TMDC monolayer till date.

Our results represent the first magneto-optical study performed on an atomically thin transition metal dichalcogenide based on tellurium and will light the way to new spin- and valleytronic devices operating in the infrared spectral region.

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Theory of 2D spectroscopy of dynamics of localized excitons in disordered Quantum wells

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Dynamics and transport of optically created excitons in disordered quantum wells is important for many applications in optoelectronic devices. Multidimensional coherent spectroscopies like 2D photon echo spectroscopy can show the exciton localization dynamics after optical excitation. In this work, we calculate the dynamics of the 1s exciton of a quantum well in a disordered potential under the influence of exciton phonon coupling and compare to experimental data. We use a sum over states approach for calculating the spectra [1] using Green's functions for the relaxation process. The exciton-phonon interaction leads to a redistribution of oscillator strength, visible in changes of the exciton resonance shape (see Figs. 1 a)-b)). The higher oscillator strength of the localized states below the mobility edge compared the delocalized states above is crucial for understating the spectral shape during the exciton phonon relaxation.

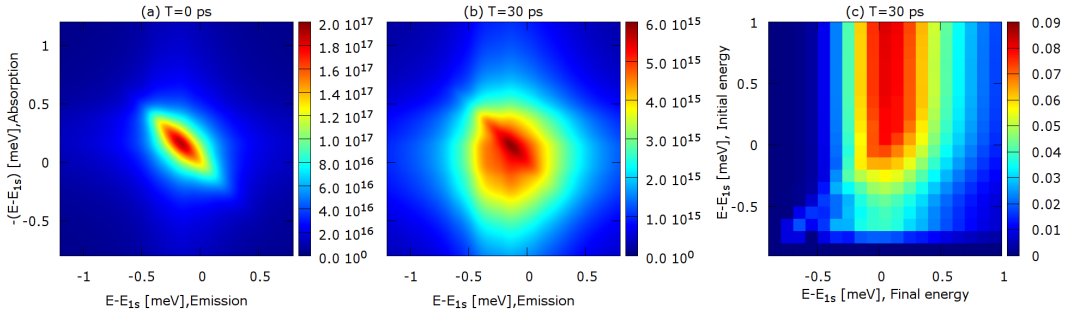

Figure 1: (a) and (b) 2D photon echo of the 1s exciton resonance of a 2D quantum well at 5K for a delay time of 0ps and 30ps between the second and third pulse (Energy is given as tuning relative to the 1s exciton energy E_{1s}). (c) A plot of the Green's function $G(\omega_1, \omega_2)$, which is the probability, that an exciton with initial energy $\hbar\omega_1$ is after $T = 30$ps in a state with energy $\hbar\omega_2$.

This work also hints at, how in general a theoretical model and the solution of inverse mathematical problems can be used to obtain additional information about homogeneous and inhomogeneous dephasing from experimental data. Specifically information about relaxation dynamic can be obtained after eliminating the effects of homogeneous broadening for a direct comparison to the theoretical calculated exciton density matrix dynamics using a Green's function (Fig. 1c)).

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Robust trion emission in two-dimensional $Mo(S_xSe_{1-x})_2$ alloys

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Transition metal dichalcogenides (TMDCs) have attracted significant attention due to the discovery of the indirect-to-direct bandgap transition and the coupling of the spin and valley degrees of freedom when reducing thickness to one monolayer. Due to the strong confinement to single layer, the TMDC excitons have very high binding energies of a few hundreds of meV. In optical spectra of $MoSe_2$ and WSe_2 well-resolved exciton and charged exciton transitions were detected. The strong spin-orbit coupling in these materials leads to the spin splitting of A-exciton between the dark and bright states, approximately equal to the splitting of the conduction band Δ^{cb}_{so}. As predicted in theoretical calculations, Δ^{cb}_{so} for WSe_2 is negative, whereas for $MoSe_2$ it is positive. This mainly results in the contrasting lowest energy exciton sub-bands: dark in WSe_2 and bright in $MoSe_2$. Furthermore, monolayers of these semoconductors possess charged exciton binding energies equal to 30 meV, which are nearly resonant with corresponding optical phonon energies. This results in a unique resonant condition.

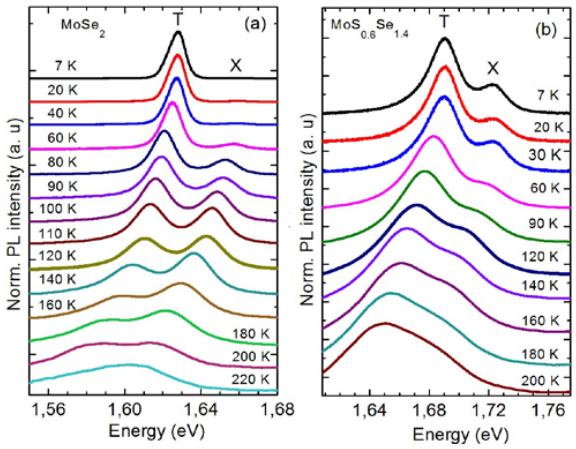

Figure 1: The temperature-evolution of the PL for (a) $MoSe_2$ and (b) $Mo(S_{0.3}Se_{0.7})_2$

Here, we employ a temperature-dependent micro-photoluminescence (μ-PL) spectroscopy to probe variation in the relative intensity ratio between the neutral and charged excitons in $Mo(S_xSe_{1-x})_2$ for the small sulfur content x ($0.1<x<0.3$). We have found that in contrast to binary $MoSe_2$, for all ternary samples with small sulfur admixture, the trion emission intensity exceeds exciton intensity in the entire temperature range from T = 7 K to 280 K, what is shown in Fig.1 (a) and (b), for $MoSe_2$ and $Mo(S_{0.3}Se_{0.7})_2$, respectively. Moreover, this intensity ratio between charged (T) and neutral exitons (X) in two dimensional $Mo(S_xSe_{1-x})_2$ layers can be continously tuned as a function of the composition x. Additionally, we present a complementary, helicity-resolved ($\sigma^+\sigma^+$, $\sigma^+\sigma^-$) micro-Raman scattering measurements performed at T = 300 K in backscattering geometry. As the composition x slightly increases, we observe the characteristic splitting of the out-of plane vibration A'_1 into two phonon branches. They evolve in different manner as a function of the composition x, and they are likely related to the different distribution of the chalcogenide atoms within the $Mo(S_xSe_{1-x})_2$ layers (Se-Se and Se-S pairs). Interestingly, the trion binding energy, determined from PL spectra, takes the value accurately from the middle of the frequency range definite by corresponding phonon branches. This leads to distinctive resonant condition that makes these 2D semiconductors an excellent platform to study exiton-phonon interaction. We attribute the robust thermal trion emission in $Mo(S_xSe_{1-x})_2$ alloys with small sulfur content to strong increase of trion-exciton coupling mediated by resonant optical phonons.

Nanowire Crystal Phase Quantum Dots

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Solid state quantum systems, such as quantum dots, have great potentials as building blocks of advanced quantum devices. They are flexible in design and can be integrated into complex structures. However, up-scaling is a serious hurdle, that halts any practical attempts to use quantum dots in multi-qubit systems. Here we show a feasible approach to an unprecedented control in the design of quantum dots, exploiting the unique property of semiconductor nanowires – the possibility of two crystal phases (zincblende and wurtzite) to coexist in the same nanowire. In principle, this enables to control the quantum dot geometry on the atomistic level, due to the monolayer sharp zincblende / wurtzite interface, as shown in the transmission electron microscopy image in Fig.1 a). The confinement is created by the band alignment of the two crystal phases, resulting in non-alloyed and intermixing free quantum dots [1]. We perform a comprehensive experimental and theoretical study of the optical properties of single crystal phase quantum dots in InP nanowires. We demonstrate that crystal phase quantum dots are a source of pure single-photons and cascaded photon-pairs from type II transitions with excellent optical properties [2], as shown in Fig.1 b). Our results open the way for more complex device fabrication using identical or different-by-design quantum dots. Crystal phase quantum dots offer a practical way to realize complex solid-state quantum systems, such as quantum registers, quantum networks, and quantum simulators.

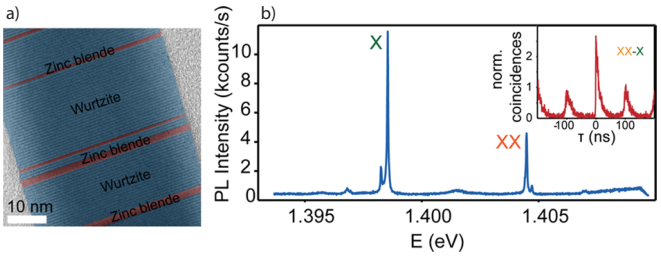

Figure 1: a) Transmission electron microscopy of an InP nanowire. b) Single InP crystal phase quantum dot spectroscopy. The inset shows second-order cross-correlation measurements, revealing a two-photon cascade.

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The role of spatial non-locality of the dielectric response for surface plasmon-polaritons.

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We investigate effects related to the non-locality in the dielectric response on the dynamics and propagation of surface plasmon-polaritons (SPP). In particular we calculate the time evolution of a quantum dot placed near a metal surface [1]. The dot dynamics is induced by the electromagnetic interactions with the quantized surface plasmon-polariton excitations. The calculations are done using a continuous media model for a metal with with a linear non-local electromagnetic response, modeled by a Lindhard-type permittivity function which is modified compared to its bulk form to account for the geometry of the system.

The analysis reveals that the non-locality modifies SPP excitations considerably. In particular, the frequency dispersion changes such that a plasmon wave packet can have two group velocities. It is also demonstrated that a large contribution to the damping of SPP modes is provided by the Landau damping mechanism, in agreement with the earlier works [2,3]. The time dependence of the dot coupled to SPP states is found to proceed in two distinct phases: rapidly decaying oscillations at short times that are followed by a much slower monotonic decay. The existence of two different relaxation times is another consequence of the non-locality. We also demonstrate that the two-velocity dispersion law gives rise to two types of plasmon wave-packages, narrow and wide, that propagate at different velocities.

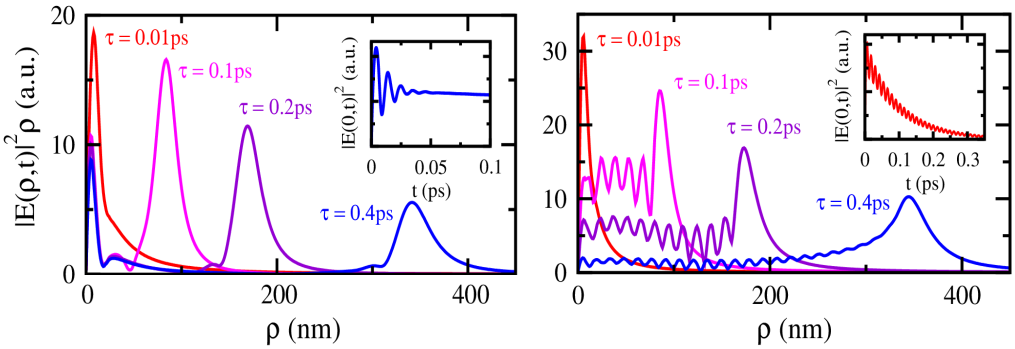

Figure 1: Propagation of surface plasmon-polariton wave packets (the spatial distribution of the electric field intensity is plotted at different delay times τ after the initial excitation). Left panel: when Rabi oscillations are suppressed, right panel: when Rabi oscillations are enhanced at longer times. Insets show the dynamics of the standing (not propagating) part of the plasmon excitation.

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Kinetic of spin-lattice relaxation and energy transfer in II-VI DMS nanostructures

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Strong enhancement of integral exciton photoluminescence (PL) in II-Mn-VI DMS nanostructures in magnetic fields was observed together with quenching of intra-shell Mn^{2+} emission. This phenomenon has been reported recently [1,2], but its origin was not clarified. Two mechanisms have been under consideration: (i) spin dependent direct transfer between excitons and $3d^5$-shell of Mn^{2+} ions and (ii) spin dependent Auger recombination of excitons, mediated by population of excited states of Mn^{2+} ions.

In this communication we summarize the results of comprehensive studies of spin-dependent energy transfer processes between excitons and *3d*-shell levels of Mn^{2+} ions in quantum well (QW) structures of (Zn,Mn)Se/(Zn,Be)Se, (Zn,Mn)Te/(Zn,Mg)Te and (Cd,Mn)Te/(Cd,Mg)Te with Mn^{2+} content varied from x=0.004 to x=0.12. Dependencies of intensities of exciton photoluminescence and intra-shell Mn^{2+} PL on magnetic field, as well as, PL excitation (PLE) spectra and kinetics of both emission processes were studied. Optically detected magnetic resonance (ODMR) spectra were monitored by studying intensity changes and energy shift of exciton PL and intensity change of Mn^{2+} PL.

In the ODMR experiments we observed a strong decrease of an integral exciton intensity against an increase of Mn^{2+} intra-shell emission under the electron spin resonance condition, i.e., at the magnetic resonance of Mn^{2+} ions in the ground state. Under the same conditions the spin-lattice relaxation (SLR) time, measured by time-resolved ODMR technique, decreases, as well as decay time of Mn^{2+} ions intra-shell emission. At the same time, exciton PL decay time was not affected by magnetic field. It is important to note that, PLE spectra of excitons and Mn^{2+} intra-shell emission are matched basically and determined by exciton absorption in QW and barrier.

Results of comprehensive studies of the above-mentioned effects show, that simple mechanism of resonant excitation transfer could not be used for their explanation. Otherwise, mechanism of Auger-recombination suppression in magnetic field [2,3] or/and mechanism of exchange scattering of carriers on the Mn^{2+} localized spins [4] looks to be available. The absences of magnetic field influence to exciton radiative life time and polarization dependence of ODMR spectra are evident on the strong effects of exchange scattering.

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Second-order coherence of radiation field from population-inverted two-level systems with frequency up-conversion

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Coherent light sources, such as lasers, require population inversion, which is usually realized by cascade transition processes in multilevel systems e.g. three- or four-level systems. Recent theoretical studies, however, have revealed that the population inversion can be occurred even for a single two-level system with an axillary system such as a microcavity and a localized surface plasmon-polariton (LSPP) [1-3]. The key element of these schemes is the Mollow triplet [4]. One scheme involves the implementation of a large contrast between the spontaneous emission rates at the lower and higher Mollow sidebands, of which the microcavity is tuned to resonance with one [1]. Another scheme we have proposed employs a single two-level system where the Mollow sideband of the LSPP is tuned to resonate with a transition energy [2,3]. A unique feature of our scheme is that both an up-converted photoemission and the population inversion occur together [3]. Thus, our scheme has considerable potential for application in a novel type of up-conversion coherent light source.

In this study, we discuss second-order coherence of the radiation field for the system of multiple two-level atoms extending our previous model with a single two-level system [3]. We consider the two-level atoms in the gap between gold nano-particles sustaining LSPP, which is driven by an intense laser. We model the LSPP as a two-level system because of the anharmonic behavior reported in an experiment [6] and thus, the LSPP level forms the usual Mollow triplet. Its dynamics is described by a Markovian master equation. All two-level atoms reside in a volume that is sufficiently smaller than the atomic resonant wavelength. Thus, the correlation between atomic excitations arises via spontaneous emission light. We numerically calculate the stationary photoemission properties for multiple two-level atoms within the second-order cluster approximation [5] by making use of the result from the input-output theory for the two-level atoms.

We find that the output light with up-conversion from a number of two-level atoms exhibits almost coherent statistics. We investigate how many atoms affect the coherence of the output field and the optimum condition for realizing the effective up-conversion coherent light sources.

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Radiative coupling of free and bound excitons

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The correlation between the free and bound excitons has been poorly discussed so far because they are usually treated independently due to the energy separation and the orthogonality of their wave functions. However, in a nano-to-bulk crossover size regime, a large coherence volume of the free exciton drastically changes this situation. In this size regime, the enhanced coherence volume leads to an increase in the radiative level shift and the band width by several tens of meV[1]. Moreover, not only the light–exciton coupling but also the exciton–exciton coupling via radiation is enhanced[2]. Such coupling exists between the free and bound excitons, and an energy concentration of light into the bound state through the free excitons is expected, which is a good analogy of the energy transparency in the plasmonic nanostructures[3].

In this work, we demonstrate the light-induced coupling between bound and free excitons in a single semiconductor thin film. As a calculation model, we consider a planar defect positioned at the center of the film which acts as a potential well for the translational motion of excitons and allows to provide a bound state. As a result, we find that the absorption peak of the bound state is strongly enhanced at a 200-nm-thick film as compared with the case where only a bound state is excited as shown in Fig. 1 (a). This can be explained by Figs. 1(b)-(d). The Fig. 1(b) shows the energy level scheme of excitons without light coupling where the bound level appears lower than the transverse exciton energy at bulk limit E_T by the binding energy, while the energy quantization of free states occurs owing to the quantum confinement of the translational motions. The light-induced coupling drastically changes the mode structures as shown in Figs. 1(c) and (d). A noteworthy point is that the low energy shifts and the radiative width of particular free excitonic states exceed the binding energy at around 200 nm. In consequence, the energy concentration occurs through the interference between the coupled modes comprising the bound and free excitons as demonstrated in Fig. 1(a). This result stimulates us to control the bound state absorption by the film thickness.

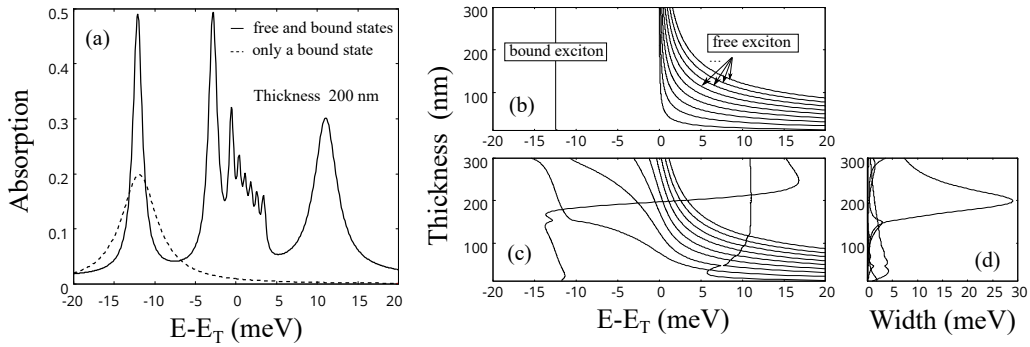

Figure 1: (a)Absorption spectra around an excitonic resonance in a 200-nm-thick film. Thickness-dependent energy structures of (b) bare excitonic system, and (c) light–exciton coupled system. (d) Thickness-dependent radiative widths of light–exciton coupled system.

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Thermal lasing in nanoscopic quantum systems - challenges and recent results

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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 or phonons.

We study a theoretical concept of a 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 temperatures of the baths impose 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 the coupling to the lasing electromagnetic or lattice displacement 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.

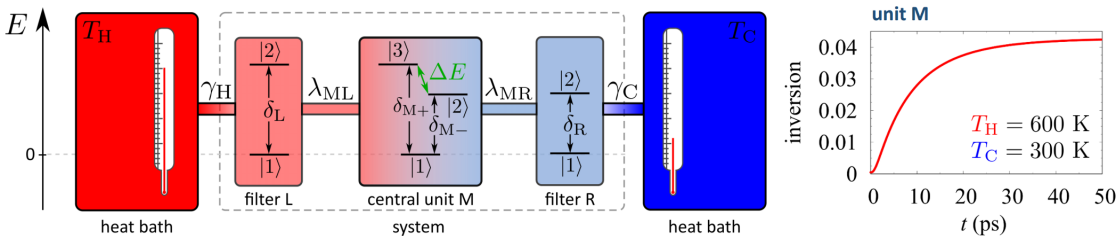

Figure 1: The model system and the evolution of positive inversion - a larger occupation of the higher energy level in comparison to the lower one - in the central unit M.

Photon emission statistics and dynamics of a trion confined in an InAs/InGaAlAs/InP quantum dash – temperature dependence study

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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, which is 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 the 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 has been 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 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) [3]. 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 experiments were performed for 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 of 1.55 ns. 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 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 the abovementioned 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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Nonlinear optical properties of dynamic one-dimensional photonic crystals in colloidal solution of quantum dots

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Theoretical and experimental study of dynamic photonic crystals properties has been realized. One-dimensional dynamic photonic crystals was formed by a periodic spatial modulation of dielectric permittivity induced by the two ultrashort laser pulses interference in semiconductor quantum dots CdSe/ZnS (QDs) colloidal solution intersecting at angle θ. The possibility of controlled dynamic change of the optical transmission spectra of colloidal quantum dots by creating dynamic photonic crystals were discussed.

Dynamic one-dimensional and two-dimensional photonic crystals are the most interesting to study as sources of exactly soluble models. Dynamic band gap of one-dimensional photonic crystal theoretically formes for an arbitrarily small difference in the dielectric constants ((|ε_1-ε_2|). Pseudo-localization is realizable for small refractive index ratio of the two dielectric media, and in this case, the band gap is called the stop-band.

The fundamental differences of dynamic photonic crystals from static one which determine the properties of these transient structures are the following. I. Dynamic photonic crystals lifetimes is determined by the nature of nonlinear changes of dielectric permittivity. II. The refractive index change is determined by the intensity of the induced standing wave maxima and nonlinear susceptibility of the sample.

Preliminary results of experiments which utilized the developed pump and probe method and theoretical foundations of the dynamic photonic crystal creation, allow us to conclude of the dynamic stop-band formation at the wavelength $\lambda_{st\text{-}b}$ expressed by the formula: $\lambda_{st-b} = \frac{\lambda_{ex} n}{sin\frac{\theta}{2}}$ (where n – refractive index, λ_{ex} – laser wavelength).

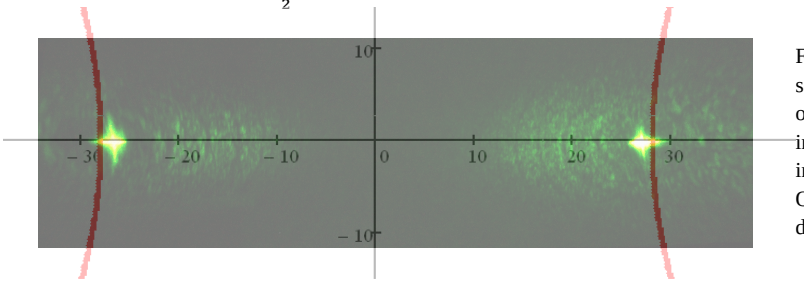

Figure 1. Experimentally measured self-diffraction pattern from dynamic one-dimensional photonic crystal induced by two laser pulses interference in colloidal solution of QDs CdSe/ZnS and calculated self-diffraction pattern.

According to Laue theory input beam $\overrightarrow{K_1}$ diffracts on the chain of atoms and diffracted maximum occurs if $\vec{K}$ is such that: $(\overrightarrow{K_1} - \vec{K})\vec{a} = m$. Parts of hyperbolas has been experimentally discovered (Fig. 1) which coincide with that calculated. It can be explained by one-dimensional dynamic photonic crystals formation under the influence of two intersecting laser beams.

Acknowledgment

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Reflected degenerate four-wave mixing on colloidal solution of CdSe/ZnS quantum dots

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Reflected degenerate four-wave mixing has been discovered in the case of one-photon resonant excitation of the excitons (electron – hole transitions) in quantum dots (QDs) CdSe/ZnS (highly absorbing colloidal solution) by powerful beams of mode-locked laser with picosecond pulse duration. Formation of the beams in forward direction can be explained both self-diffraction of the input beams on the induced one-dimensional photonic crystal (induced diffraction grating) and by degenerate four-wave mixing. Backward direction beams formation can be explained only by degenerate four-wave mixing.

Along with two beams at the output of the cell with colloidal QDs, which retained the propagation directions of the two input beams I_0 crossed in the cell at an angle θ, we discovered beams with intensity $I_{\pm1}$ in forward direction and $I_{\pm2}$ in backward direction for one-photon resonant excitation of the fundamental exciton transition in CdSe/ZnS QDs (Fig.1).

The self-diffraction of the beams I_0 occurs on induced dynamic photon crystal (transient diffraction grating), whose period is $\Lambda = \frac{\lambda}{2\sin(\theta/2)} \approx 884{,}5nm$, (θ=35°). The beams $I_{\pm2}$ are formed due to four-wave mixing in backward direction [1].

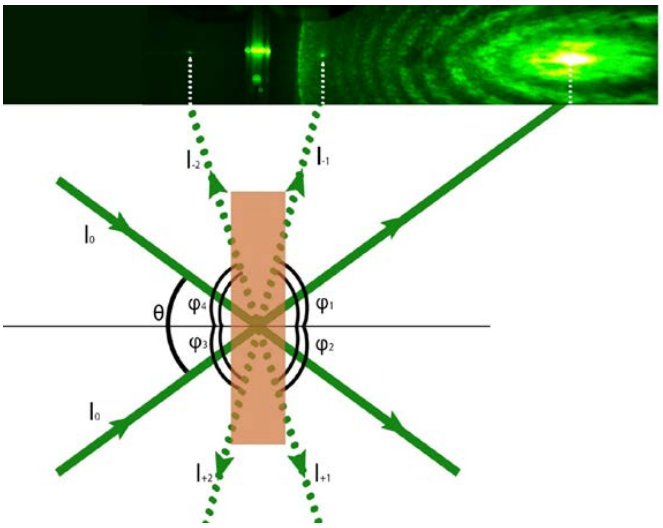

Figure 1. Scheme of the exciting beams and the generated signals. of degenerate four-wave mixing in forward and backward direction on colloidal solution of QDs CdSe/ZnS and the photograph of the generated beams cross-section.

The angles in forward direction ($I_{\pm1}$) and backward direction ($I_{\pm2}$) beams were calculated ($\varphi_1=\varphi_2=\varphi_3=\varphi_4\approx64°$).

Passed through the highly absorbing colloidal solution of QDs CdSe/ZnS (Fig. 1) laser beams holding the direction of their propagation created typically for Fresnel diffraction at a circular aperture the diffraction rings. The observed diffraction rings can be explained by self-diffraction of laser pulses from their induced transparency channels [2].

Acknowledgment

This work was partly supported by the Russian Foundation for Basic Research, Russian Federation President grant for the Young scientists MD-4550.2016.2.

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Frenkel excitons in zero-dimensional photonic structures

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Nowadays, photonic and optoelectronic devices such as light emitting diodes and lasers have to fulfill more and more requirements: on the one hand they need to satisfy the rapidly increasing demand for higher performance and advanced functionality but on the other hand have to comply with challenges regarding miniaturization and cost effectiveness. Especially, the increasing interest for immediate and on-demand fabrication of complex photonic structures (such as photonic interconnects, waveguides or cavities) on semiconductor chips is a strong driving force in current photonics research. Owing to their high versatility and flexibility, organic materials have proven to match these requirements excellently. This has strongly driven rapidly emerging research fields such as direct laser-writing by two-photon polymerization or direct circuit printing.

Here, we present different approaches capable of tailoring the in-plane confinement in planar optical microcavities filled with an active organic layer and thus creating three-dimensionally confined microstructures. The respective confinement affects both the photonic and excitonic part of the microcavity and has therefore direct influence on weak [1] and strong light-matter interactions [2]. The approaches include: (i) organic imprint lithography (see C) , (ii) direct lasing writing above bleaching threshold (A,B) and (iii) hemispherical mirrors in open microcavities. For all different techniques, we achieve confinement potentials on the order of several meV up to several tens of meV. The zero-dimensionality of the observed confined modes is evidenced by the evolvement of dispersion-less trans-verse mode patterns and drastically reduced lasing thresholds (compared to planar structures).

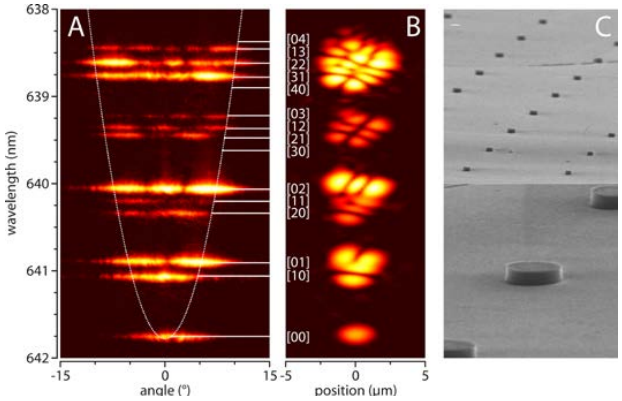

Figure: Angle-resolved (A) and real space (B) images of the laser emission from a laser-written circular trap. (C) SEM images of imprinted organic micropillars.

The variety, versatility and moreover the compatibility of the applied techniques gives us the opportunity to tailor the photonic and excitonic part of organic cavities jointly and individually and paves the way towards PT-symmetric systems or complex photonic structures such as photonic chains and lattices.

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Highly indistinguishable on-demand resonance fluorescence photons from quantum dots

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For the implementation of bright and coherent solid state quantum light sources both a high purity of the single photon emission and a high degree of indistinguishability is essential. The combination of these two key prerequisites in a single, potentially scalable device is a major challenge, despite enormous efforts for more than 15 years. We report on the observation of bright single photon emission generated via pulsed, resonance fluorescence conditions from a single quantum dot (QD) deterministically centered in a micropillar cavity device via cryogenic optical lithography. The brightness of the QD fluorescence is strongly enhanced on resonance with the fundamental mode of the pillar, leading to an overall device efficiency of $\eta = (74 \pm 4)$ for a single photon emission as pure as $g^{(2)} = 0.0092 \pm 0.0004$. The combination of large Purcell enhancement and resonant pumping conditions allows us to observe a two-photon wave packet overlap up to $\nu = (88 \pm 3)\,\%$.[1]

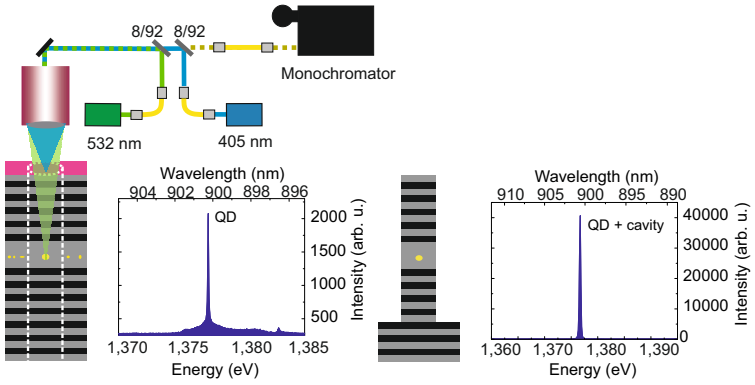

Figure 1: Sketch of the deterministic device fabrication

Furthermore a study of the influence of temperature and exciting laser pulse distance on the degree of indistinguishability is presented. For this purpose, a bright and high purity single photon emitting QD in a quasi-planar microcavity with $g^{(2)} = 0.0194 \pm 0.0007$ has been investigated, leading to a corrected Hong-Ou-Mandel (HOM) interference visibility of $\nu = (99.8 \pm 0.2)\,\%$ at a pulse distance of 2 ns.

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Temperature dependent two-photon-coalescence probability in quantum dot single photon sources

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A single quantum dot (QD) constitutes a dissipative quantum system coupled to its surrounding solid-state environment, meaning the phonon reservoir and the fluctuating electrostatic environment. This has important consequences on the coherence properties of the electronic system and the QD is a probe to study fundamental interactions.

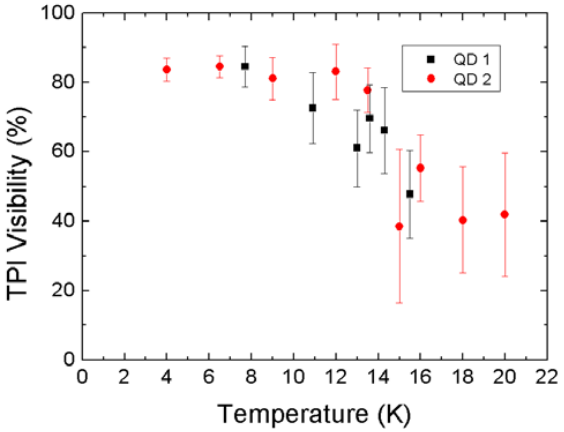

Figure 1: 1 Two-photon interferences visibility at zero delay extracted from HOM experiments as a function of temperature. Experimental data for two different QDs are presented: QD 1 (black squares) and QD 2 (red dots).

We have demonstrated the possibility to address and coherently control a single exciton state in InAs/GaAs self-assembled QDs embedded in a one-dimensional waveguide with a strictly resonant pulsed laser excitation [1]. Performing Hong-Ou-Mandel experiments [2], two-photon interferences (TPI) with high visibilities have been demonstrated very recently without any spectral filtering of the QD fluorescence. In resonant HOM experiments, the main dephasing process is related to phonon coupling, since charge noise occurs on time scales much longer than the characteristic time of TPI measurements, on µs and ns range respectively. Temperature dependent TPI experiments are well suited to probe the interaction with the phonon bath. We show that the indistinguishability is preserved with a constant TPI visibility around 85 %, followed by a rapid loss of coherence above 13 K. These new results are consistent with recent theoretical studies [3] where a fully microscopic model treating on an equal footing the electron-phonon and electron-photon interaction is used to explain decoherence.

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[2] L. Monniello et al, Phys Rev B, 041303(R) (2014)
[3] P. Kaer, and J. Mork, Phys. Rev. B90, 035312 (2014)

Exciton spin relaxation in InAs quantum dash emitting at 1.55 μm

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Recently, the InAs on InP 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 telecommunication wavelengths, essential for e.g. quantum repeater technology. Since epitaxial nanostructures as 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 and constitute the spin memory element.

We demonstrate an impact of different spin-injection scenarios on the possibility to read-out the written exciton/electron spin state confined in a QDash. The spin initialization as well as read-out processes are realized by all-optical means. A properly polarized train of femtosecond or picosecond laser pulses creates the spin excitation in a QDash, whereas analysis of the photoluminescence signal (degree of polarization-DOP as a function of time or averaged in time) provides information about the confined spin state, e.g. existence of the spin memory and its storage time. First, we have focused on the possibility to observe an exciton spin memory (ESM) under non-resonant photo-injection. This revealed existence of a strong DOP "background" of ~27% that is not connected to population of a spin state but it is due to intrinsic properties of QDashes. The ESM is observed after the spin injection into the wetting layer as indicated by enhanced DOP in respect to the intrinsic one. This result shows partial preservation of the exciton spin state after relaxation process down to the QDash ground state, with the further possibilities to be recovered in the emission. The most pronounced ESM is obtained by utilizing a single longitudinal optical phonon-mediated process for the spin injection scheme. This led to further increase in the contrast between the "background" DOP and the actual one by ~35%, i.e. indicates on easy recovery of the spin memory state. Despite existence of the ESM effect the measured spin relaxation time reaches 1.7 ns that is comparable to the exciton decay time. It raises 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 into such large nanostructures made of InAs on InP(001). In order to omit the above-mentioned limitation we propose to use a spin state of a resident electron that is addressed by utilizing the intermediate trion state. Initial results show a long spin memory effect that overcomes significantly the exciton spin lifetime.

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Optical Absorption and Emission Properties of Single Solid State Defect Centers

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We study the emission and absorption properties of single solid-state defect centers, in particular point defect centers in wide band-gap semiconductors. Such defect centers emit single photons at room temperature with high rate and high purity, with emission linewidths down to their intrinsic lifetime-limit. This makes them promising resources for quantum cryptography and quantum information processing based on indistinguishable photons such as boson sampling. Furthermore, some of these defects feature optically accessible spin states with long spin coherence times. Recently, quantum entanglement and teleportation have been shown between two nitrogen-vacancy defect centers (NV) in diamond [1]. Despite its excellent spin properties, its optical properties are suffering strongly from surrounding bulk and surface defects, in particular leading to instability of its emission wavelength over time caused by local electric field fluctuations [2], presently preventing the integration into nanostructures [3] for enhanced light matter interaction [4]. Alternatively to the NV, the silicon vacancy defect center (SiV) in diamond as well as defect centers in other materials are promising for quantum cryptography and information [5].

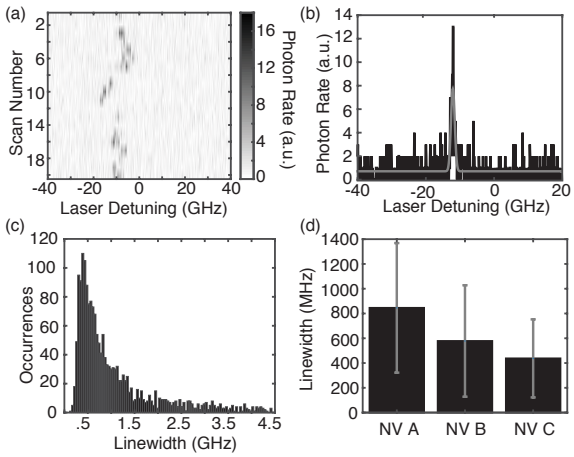

Figure 1: A typical multiscan measurement of a single, spectrometer-limited nitrogen-vacancy defect center in a diamond nanostructure with resonant excitation and collection of the phonon side band at cryogenic temperatures (18K). (b) A single scan with a Gaussian fit showing a linewidth of 918 MHz. (c) The distribution of measured single scan linewidths of NV C, with a maximally occurring linewidth of 393MHz. (d) Mean and standard deviation of measured single scan linewidths for 3 NVs in individual nanostuctures.

Here we investigate the emission properties of NVs, SiVs, and defect centers in SiC and GaN. We systematically study their optical emission properties and the influence of surface termination and reactive ion etching during nanofabrication. Finally, we analyze the properties of emitted photons in Hong-Ou-Mandel two photon quantum interference experiments.

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[5] J. R. Weber et al., PNAS **107**, 8513 (2010).

Cooperative fluorescence of optical emitters exposed by whispering gallery modes

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When excited optical emitters are integrated in small region, they virtually exchange the radiation photons and exhibit a cooperative fluorescence (superfluorescence). Although such fluorescence has been observed in atomic gasses and color centers in solids, recent experiments reported similar phenomena in semiconductor quantum dots and quantum wells [1,2]. The cooperative phenomena in artificial structures are huge step that promise to both fundamental many-body studies and applications. However, in theoretical aspects, the practical approach to treat with the radiation filed in designed systems has not been established.

In this study, we develop a new technique that numerically demonstrates the cooperative fluorescence from two-level emitters disposed in an arbitrary system. For example, we consider the case where the emitters are randomly positioned on a polystyrene sphere (Fig. 1(a)). The time evolution of the fluorescent intensity is shown in Fig. 1 (b). Cooperative phenomena like superfluorescence typically require high-density emitters that make the phase shift during the photon propagation negligible. However our result indicates that the considerable cooperation can appear even in the low-density emitters of which mean separation exceeds the wavelength of the radiation photon. Thus, it can be interpreted that the whispering gallery modes (WGMs) in the microsphere exposes the emitter-emitter cooperation. In the presentation, we report the details of the calculation and mechanism under the demonstrated fluorescent dynamics.

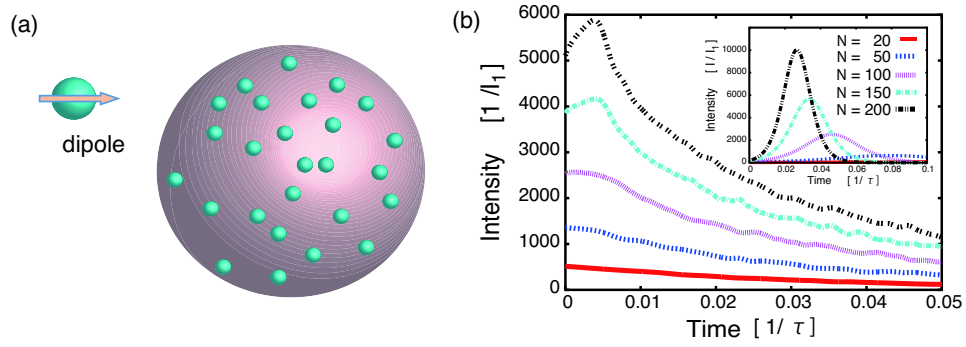

Figure 1: (a) Schematic view of the system under consideration. Excited optical emitters are randomly positioned on a polystyrene sphere (relative permittivity $\epsilon = 2.5$). All the dipoles of the emitters are aligned in one direction. (b) Fluorescent dynamics are plotted when $r_s/\lambda = 2.461$ with r_s being the sphere radius. In inset, we also plot the dynamics when all the emitters are closed packed in vacuum as a reference. Here τ is the radiation decay time of the emitters and $I_1 = 1/\tau$ is the fluorescent intensity of one emitter in vacuum.

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Polarization noise of polariton laser emission

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The term "laser" is usually applied to any device producing coherent, monochromatic and unidirectional light via stimulated emission of radiation. However, *polariton lasers* emit light spontaneously by a condensate of bosonic quasiparticles, exciton-polaritons, accumulated in a single quantum state [1]. Their emission is spontaneous; however, the light going out has all properties of a laser light: It is coherent, monochromatic, polarized and unidirectional.

In our work we study the polariton emission (PE) noise in a quantum-well microcavity below and above the polariton lasing threshold under continuous wave (*cw*) excitation. In contrast to standard measurements in spin noise spectroscopy (see, e.g., Ref. [2]), in this work we analyzed polarization fluctuations of secondary emission, rather than of a probe beam.

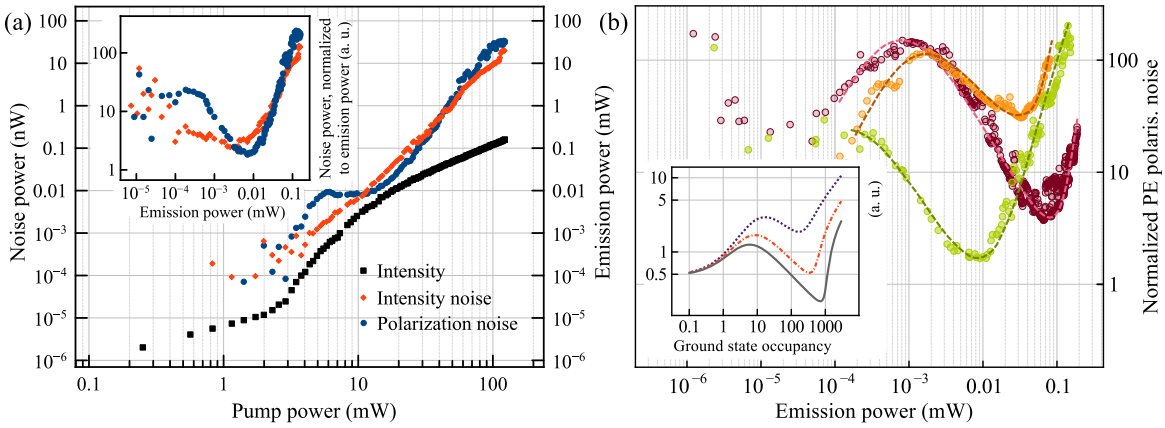

Figure 1: The dependences of polariton laser polarization and intensity noise power and emission power on pump power (a) and normalized dependences of polarization noise on polariton emission power (b).

The PE polarization noise substantially exceeded in magnitude the shot noise level and, in the studied frequency range had a flat spectrum. We analyzed the dependence of the integrated polarization noise power on pump and emission power. Figure 1 represents the key result of our work. We have found that the polarization and intensity noise dependences on the pump power are strongly different. This difference is ascribed to the bosonic stimulation effect in spin-dependent scattering of the polaritons to the condensate. A theoretical model describing the observed peculiarity of the PE polarization noise is proposed.

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Quantum state reconstruction and photon statistics for coherent states interacting with quantum dot ensembles

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Mesoscopic ensembles of emitters coupled to a cavity can exhibit rich quantum-optical emission patterns, such as super- and sub-radiance or nonclassical two- or three-photon states [1-3]. To characterize the quantum optical properties of emitters, intensity autocorrelation is a well-known technique. The correlation function $g^{(2)}$ allows to distinguish between single photon, coherent and thermal emission and thus serves as a characterization tool for single photon emitters. However, a more complete picture of the quantum state of light is lost due to the fact that the phase information of the electric field is unobtainable in an intensity autocorrelation measurement.

Quantum state tomography is a technique to reconstruct the full state from the quantum statistical measurement of the field fluctuations. One can access the complete photon statistics and quantum mechanical correlations contained in the diagonal and off-diagonal elements of the state's density matrix. Contrary to intensity autocorrelation, both quadrature components $X_1 = a^\dagger + a$ and $X_2 = i(a^\dagger - a)$ are measured and thus both the amplitude and phase information is retrieved. By sweeping the optical phase, the full quantum statistics is measured and the state's Wigner function in the optical phase space can be reconstructed [4,5].

Complementary to this, the method of photon number sampling has been developed to directly derive the individual elements of a state's density matrix [4]. We demonstrate both techniques for the interaction of a coherent state with an ensemble of quantum dots by investigating how a femtosecond laser pulse propagates through a quantum dot optical amplifier. Using a balanced detection scheme in a self-heterodyning setup, we achieve precise measurements of the quadrature components and their fluctuations at the quantum noise limit. By employing both techniques, we reconstruct the Wigner function and the photon statistics of the coherent input state before and after propagation through the amplifier with very high temporal resolution. We also combine the techniques with a pump-probe setup, which allows us to directly manipulate the state inside the amplifier at a picosecond timescale.

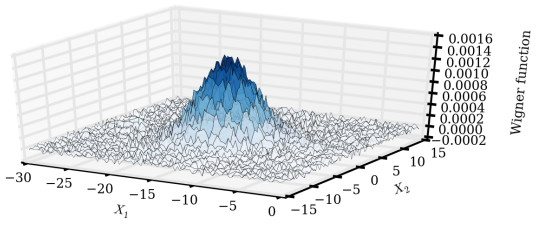

Figure 1: Wigner function of a coherent state after propagation through a quantum dot optical amplifier.

[1] V. V. Temnov and U. Woggon, *Phys. Rev. Lett.* **95**, 243602 (2005).
[2] H. A. M. Leymann et.al., *Phys. Rev. Applied* **4**, 044018 (2015).
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Non-linear two-photon resonance fluorescence of a single artificial atom

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Resonance fluorescence that arises from the interaction of a coherent light field with a two level system, has led to the development of numerous physical breakthroughs in atomic quantum optics. Increasing the complexity of the physical systems, first predictions for a non-linear counterpart of resonance fluorescence were made theoretically already 30 years ago [1].

In this contribution, we present non-linear resonance fluorescence studies for the two-photon excitation [2, 3] of individual semiconductor quantum dots. Upon monitoring the population evolution for increasing Rabi frequencies we observe an s-shaped behavior as a clear signature of the non-linear excitation process. We model the non-linearly driven artificial atom as a 4-level system resonantly excited on a two-photon resonance and find excellent agreement between experiment and theory. The simulations reveal the crucial role of the environmental coupling to LA-phonons of the system leading to a redistribution of the population between the levels. Finally, we directly measure the formation of dressed states in the non-linearly driven system that emerge from the resonant two-photon interaction between the coherent light field and the 4-level artificial atom, the hallmark of two-photon resonance fluorescence [4]. The formation of dressed states from a two photon resonance is schematically illustrated in figure 1 together with a simulation of the emission spectrum around the transition energy of X_0. Our results open the route for investigating a range of optical phenomena from entangled photon pairs to photon bundles resulting from the coherent non-linear interaction in two-photon resonance fluorescence [5].

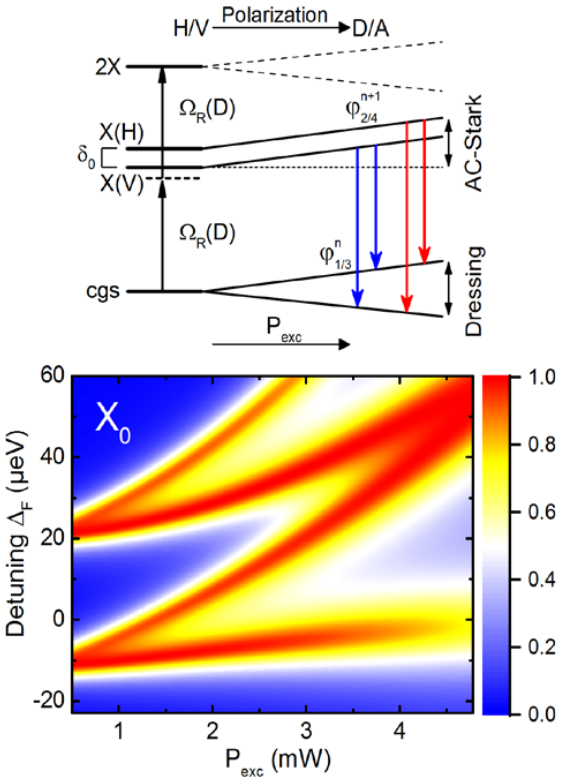

Figure 1: (Top) Schematic illustration of the formation of dressed states under resonant excitation of a two-photon transition. (Bottom) Simulation of the emission spectrum around the energy of X_0.

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Long-lived quantum emitters in hBN/WSe_2 van-der-Waals heterostructures

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We present detailed investigations of the optical properties of single photon emitters that form in 2D hBN/WSe_2/hBN van-der-Waals (vdW) heterostructures and demonstrate the potential of hBN as a high quality environment for vdW heterostructure devices.

The samples investigated are mechanically exfoliated monolayer WSe_2 crystals that are fully encapsulated within multi-layer hBN crystals using viscoelastic stamping techniques [1]. By capping the WSe_2 with hBN we symmetrize the dielectric environment of the semiconducting crystal and observe a reduction of the bulk WSe_2 exciton linewidth to ~4 meV for both X^0 and X^- transitions, a reduction of 50% compared to the linewidths of WSe_2 placed directly on Si/SiO_2 substrates. Similar effects have been interpreted as arising from suppressed non-radiative decay channels due to the hBN encapsulation of the semiconductor [2]. For low excitation power densities ($P < 2$ W/cm²), the emission spectrum is dominated by localized sharp (FWHM < 1 meV) emission lines redshifted by ~100 meV with respect to the exciton PL energies.

Second-order photon correlation measurements performed on the sharp-line emission reveal clear photon anti-bunching and allow us to identify the emission from the localized centers as arising from single luminescent quantum emitters in the WSe_2. Time-resolved PL measurements reveal a mono-exponential decay transient characterised by a very long lifetime of ~25 ns, 10-fold longer than reported in recent works [3-4]. To analyse the temporal stability of the emitters we analyse their frequency jitter and observe a 1/f frequency behaviour, which we attribute to the thermally fluctuating charge environment. Polarization-resolved experiments reveal a significant fine structure splitting of single emission lines ranging from 0.5 meV to 1 meV. Finally, we will report measurements performed for hBN-WSe2 heterostructures prepared on a ZrO_2 solid immersion lens (SIL). Hereby, we enhance the spatial resolution of our optical excitation by a factor of ~5x and determine an upper bound of the spatial extent of the localized emitters to be ~250 nm. Our results demonstrate the potential of employing hBN as a high quality substrate for optimized optical properties of delocalized and localized emission of excitons in WSe_2.

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Carrier dynamics in InAs/InP coupled Quantum Well - Quantum Dot system

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The concept of a coupled quantum well - quantum dot/dash system (QW-QD/QDash) remains a challenging issue in the context of its band structure engineering desired for specific applications. In the case of QW-QD/QDash-based lasers one of the problems is to preserve a quasi-0D-like character of the gain medium that results from a full 3D confinement of carriers. However, in the case of some QD/QDash memory applications there is required a weaker confinement in the dot allowing out tunneling of carriers into the neighboring QW. In this work we investigate a system based on InP substrate in which both scenarios can be realized by tailoring the well width (d_{well}).

The system under study consists of $In_{0.53}Ga_{0.47}As$ QW separated from a layer of InAs QDashes by 1.7-nm-wide InAlAs barrier. Four structures were investigated with d_{well} equal 4.5, 5.5 and 6.5 nm, and a reference structure with QDashes only. In all cases, the ground state (GS) emission of the entire system occurs at 1.55 μm. The electronic coupling is examined at T=5K by combination of various optical spectroscopy techniques, with the major role of time-resolved photoluminescence, supported by eight-band $k \cdot p$ calculations of the coupled system band structure. The experimental results show that with increasing d_{well} the electronic coupling between the QW and QDash parts at the GS increases considerably, as it is viewed by elongation of the PL lifetime (τ_{PL}). For d_{well}=4.5 nm the $\tau_{PL} = 1.8ns$ is comparable with the one registered for the reference structure that resembles the Coulomb-correlated electron-hole recombination lifetime in quasi-0D confinement of a QDash. However, when the d_{well} increases to 5.5 nm, and 6.5 nm, the τ_{PL} increases up to 4.9 ns, and 9.7 ns, respectively. This indicates an extension of the GS of either electrons or holes from QDashes to the well. A similar effect has been observed in (In,Ga)As/GaAs coupled QW-QDs system [1] where mainly electrons have tendency to be smeared over QW and QD potential. For the system under study a reversed trend is expected as confirmed by the theoretical calculations: the electrons are strongly confined in dash whereas the holes are leaking out into the well.

This experimental founding opens the rout towards exploration of an electron spin memory in a coupled system at 1.55 μm where initially addressed electron spin state through creation of a positively charged exciton can be left in the dash while holes can be removed away due to their tunneling into a QW.

The work has been supported by National Science Center of Poland within grant No. 2013/10/M/ST3/00636

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Reversible uniaxial strain tuning in monolayer WSe_2

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Single layers of transition metal dichalcogenides represent a new class of direct band gap semiconductors, which renders them promising for novel atomic-scale physics and devices. Strain engineering allows for tuning their optical transitions in a wide range of ≈100 meV. Recently, single-photon emitters have been discovered in monolayer WSe_2 and related to local strain potentials in the monolayer [1]. However, in contrast to other 2D materials such as MoS_2, $MoSe_2$, or WS_2 no reliable calibration of the exciton shifts under applied strain exists so far.

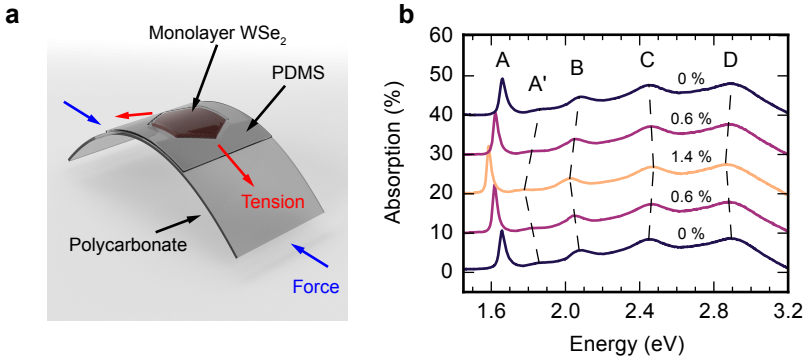

Figure 1: (a) Sample geometry. (b) Absorption spectra of monolayer WSe_2 for different levels of tensile strain.

By bending a monolayer of WSe_2 on a flexible polycarbonate substrate and covering it with PDMS, we apply reversible uniaxial strain (Fig. 1(a)) [2]. We measure the strain-dependent energy shifts of the exciton resonances in absorption. The spectral positions of the resonances before and after applying strain are the same, i.e. there is no hysteresis (Fig. 1(b)). We derive gauge factors of $-54\,\mathrm{meV/\%}$, $-50\,\mathrm{meV/\%}$, $17\,\mathrm{meV/\%}$, and $-22\,\mathrm{meV/\%}$ for the A, B, C and D exciton, respectively. A comparison with ab-initio GW-BSE calculations shows an excellent agreement with the experimental data for all resonances. Furthermore, we examine the spatial strain distribution in the WSe_2 monolayer at different applied strain levels. We find that the size of the monolayer is crucial for an efficient transfer of strain from the substrate to the monolayer. Our measurements in monolayer WSe_2 light the way to strain engineering in atomically thin semiconductor.

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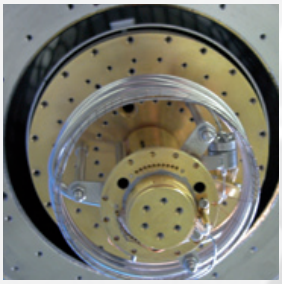

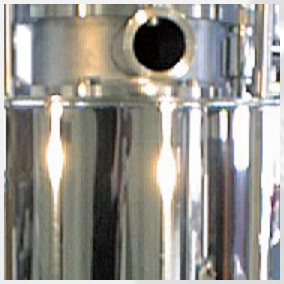

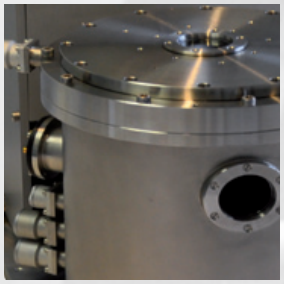

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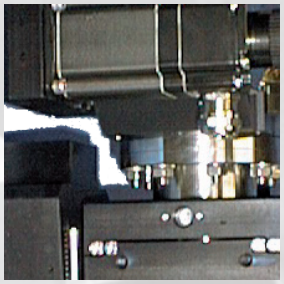

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Tuesday, 11.10.2016

Session Tu1: 09:00 - 10:30 (Novel Light Sources)

Session Tu2: 11:00 - 12:30 (Quantum Dots 1)

Session Tu3: 14:00 - 15:30 (Ultrafast Nonlinear Optics)

Poster Session P2: 15:30 - 18:00

Bosonic Cascade Lasers

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[b]*Spin Optical Laboratory, State University of St-Petersburg, 1, Ulianovskaya, St-Petersburg, 198504, Russia*

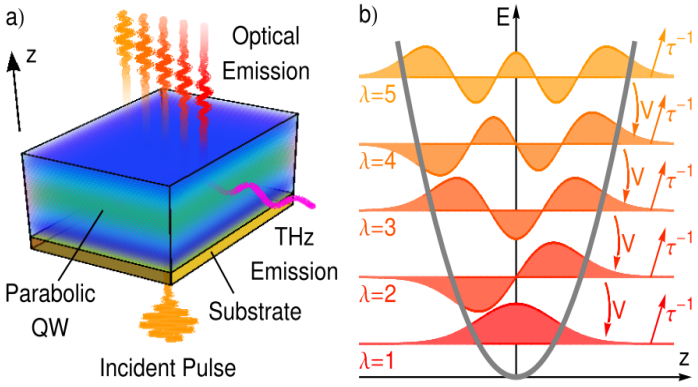

Figure 1: The schematic of a bosonic cascade laser (a). The stimulated coherent terahertz emission is generated due to the cascade of radiative transition between exciton states confined in a parabolic quantum well (b) embedded in a semiconductor microcavity. The final state of the cascade is a condensate of exciton-polaritons maintained by optical pumping. It provides the bosonic amplification factor of the terahertz generation of the order of 10^5.

In this presentation I will overview the recent progress in realization of bosonic cascade lasers (BCLs). The concept of this new type of a laser has been proposed in 2013 [1]. It is based on the stimulation of terahertz emission processes by a final state occupation number, with a final state being the polariton laser mode. Cascades of terahertz photons are emitted due to the excitonic transitions in a sequence of equidistant quantum states confined in a parabolic quantum well. The double stimulation effect may be achieved if the microcavity is embedded in a lateral terahertz cavity. The quantum efficiency of BCLs is expected to be significantly higher than 100% due to the cascade action. Recently, the dynamics of polariton relaxation and optical lasing have been demonstrated in microcavities with embedded parabolic wells designed for realization of bosonic cascades [2]. In the pump-probe experiments with pulsed excitation, the optical signal oscillating with the frequencies of 0.9, 2.9, and 4.5 THz has been detected [3]. Theoretically, it has been demonstrated that in addition to the coherent terahertz radiation, bosonic cascade lasers might emit the superbunched visible light [4]. Bosonic cascade lasers offer a valuable alternative to quantum cascade lasers and represent an attractive playground for studies of light-matter condensates.

[1] T.C.H. Liew, M.M. Glazov, K.V. Kavokin, I.A. Shelykh, M.A. Kaliteevski, and A.V.Kavokin, *Proposal for a Bosonic Cascade Laser*, Phys. Rev. Letters, **110**, 047402 (2013).
[2] A. V. Trifonov, E. D. Cherotchenko, J. L. Carthy, I. V. Ignatiev, A. Tzimis, S. Tsintzos, Z. Hatzopoulos, P. G. Savvidis, and A. V. Kavokin, *Dynamics of the energy relaxation in a parabolic quantum well laser*, Phys. Rev. B **93**, 125304 (2016).
[3] A.Tzimis, A. Trifonov, G. Christmann, S.I. Tsintzos, Z. Hatzopoulos, I. Ignatiev, A.V. Kavokin, P.G. Savvidis, *Strong coupling and stimulated emission in single parabolic quantum well microcavity for terahertz cascade*, Appl. Phys. Lett. **107**, 101101 (2015).
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Quantum Light Sources based on Two-Photon Emission from a Quantum – Dot Biexciton

Dirk Heinze[a], Dominik Breddermann[a], Artur Zrenner[a], and Stefan Schumacher[a]

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In this work we study the possibilities of using a quantum dot biexciton as a source of quantum light. The two-photon emission from the biexciton is used to either create two degenerate and entangled photons or a single photon with tailored properties.

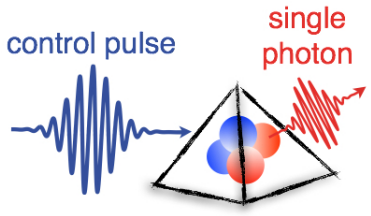

Figure 1: Schematic illustration of the recently proposed optically controlled single photon emission via a two-photon process from a quantum dot

In a first step we explore the two-photon resonance in a scenario in which a high-Q cavity is used to enhance the spontaneous emission from an initially prepared biexciton, which decays by emitting two polarization-entangled photon pairs [1]. We show that this process is robust against phonon-assisted cavity feeding at low temperatures and is insensitive to the fine-structure splitting of the excitons due to the nature of the two-photon process.

Building on these previous results we further study a partly-stimulated partly-spontaneous two-photon emission from the biexciton. This process is used to emit a single photon with properties, such as time of emission, spectral shape and polarization that can be tailored all-optically [2,3]. Here, the first photon in the two-photon process is triggered by a classical light field. The second photon is spontaneously emitted when the system relaxes to the ground state (via a virtual intermediate state), as shown in figure 2. All the important properties of the single photon can be controlled optically by the control laser pulse (cf. figure 1). Again, a cavity can be used to enhance the probability of emitting the single photon, however the general scheme does not rely on the cavity enhancement.

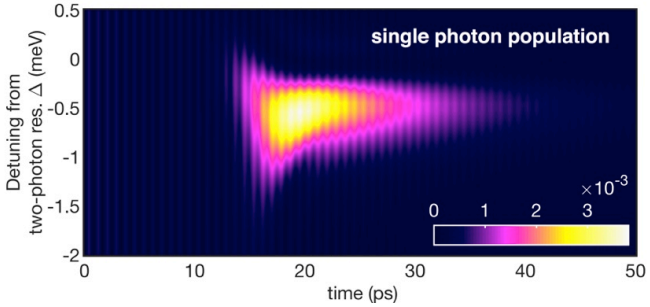

Figure 2: Single photon emission from a quantum dot biexciton triggered by a Gaussian pulse centered at 15 ps for various detunings from the ideal two-photon resonance.

In this contribution, we demonstrate that two-photon processes from a quantum dot biexciton are a versatile source for the generation of quantum light, as needed in future quantum communication applications.

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Nonequilibrium thermodynamics of quantum fluids of polaritons

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In the last two decades exciton-polaritons have attracted considerable interest since they allowed for fundamental understandings of the physics of nonequilibrium quantum fluids such as polariton Bose-Einstein condensation and superfluidity [1]. At high density, microcavity-polaritons constitute indeed a driven dissipative quantum fluid of half-light half-matter integer spin quasi-particles, which is embedded in a solid-state crystalline environment.
So far, the thermodynamic properties of polariton fluids have been mostly overlooked. An intriguing specificity of polariton condensates and superfluids is their contact with three different reservoirs: the thermal phonon bath, the exciton bath and the electromagnetic vacuum. A first interesting question is whether heat can be transferred from the phonon bath to the nonequilibrium polariton fluid.
To study polariton thermodynamics, we use high-quality ZnSe-based microcavities, since they provide a large Rabi splitting $\hbar\Omega_R$=29meV, low local disorder, a Q-factor of Q~5600, and allow for access to a high temperature phonon bath (up to T=270K) interacting with stable microcavity-polaritons.
We show experimentally and theoretically that indeed thermal phonons can be efficiently absorbed by inelastic scattering with polaritons. In this context we present a Raman spectroscopy based technique using anti-Stokes fluorescence (ASF) [2]. Resonant excitation of ground state polaritons ($k_{||}$ = 0, $\hbar\omega_0$) and subsequent phonon absorption is used to optically extract thermal energy out of the system and thus cool it down. Owing to polariton's cavity-like dispersion, Stokes fluorescence (phonon emission) is fully inhibited while ASF is permitted and enhanced by the polariton's excitonic fraction. By carrying out angle-resolved Raman spectroscopy, we measured the cooling power generated by polariton ASF. We determine the temperature and laser power range where a net cooling rate is achievable. Our experiments show that the highest cooling power is achieved at an initial temperature of only 50K [3].
We also studied the interaction of polaritons in the condensate state, at temperatures up to T=270K, with the thermal phonon baths [4]. For the first time we can (i) controllably tune and measure in a non-ambiguous way the amount of thermal equilibration of a polariton condensate, using near-room temperature phonons as a thermal bath, and (ii) observe directly its effect on the coherence properties of a nonequilibrium condensate.

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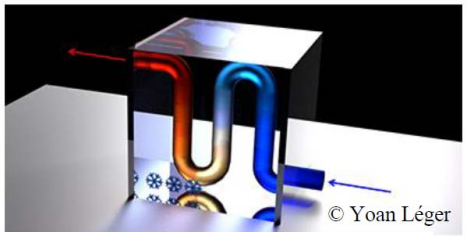

Fig. 1: Polariton cavity cooling scheme.

Directional white-light generation in $[(RSn)_4S_6]$-Cluster Molecules

Nils W. Rosemann[a,b], Jens P. Eußner[b,c], Andreas Beyer[a,b], Kerstin Volz[a,b], Stefanie Dehnen[a,c], and Sangam Chatterjee[a,b,d]

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Nanostructures based on at least one element of the chalcogenide family exhibit a large variety of physical properties and are hence used for a wide range of applications. For instance, $Cd(S_xSe_{1-x})$ quantum dots (QD) are extensively studied over the last decades. Their optical properties are tuned by changing the size-distribution or the composition of the QDs. Controlling and adapting these distributions enables a broad range of applications ranging from active material in LEDs, absorbers in photovoltaic cells or as markers in the medical sector. In particular, the latter uses are commonly achieved through functionalizing the QDs with organic ligands of the purely inorganic semiconductor compound.

Here, we study a series of chalcogenide-based cluster molecules, which inherently exhibit both, a defined composition and size in addition the possibility of controlled functionalization through organic ligands. This enables control of their properties and, in particular, the tailoring of their nonlinear optical response. In particular, we study the diamondoid cluster compounds $[(RSn)_4S_6]$ featuring four identical organic ligand groups, e.g., R=4-$(CH_2$=CH)-C_6H_4 [1]. The substance is synthesized as white powder without long-range order. This lack of crystallinity enables intriguing nonlinear optical properties: a directional, i.e., spatially coherent, white-light continuum emission is observed upon irradiation with low-power steady-state near-infrared radiation. This white-light emission is distinctively different from photoluminescence; its spectral bandwidth appears to be limited by the transition into the first molecular electronic state, cf. Fig. 1. The vast optical nonlinearity is tentatively attributed to the acceleration of π-electrons supplied by the aromatic organic ligands as confirmed by experiments on accordingly substituted cluster molecules. Furthermore, varying the degree of crystallinity by either changing the core composition or substituting the ligands appropriately confirms the relation between structural arrangement of the individual molecular nanostructures and the nonlinear optical response. An inharmonic harmonic oscillator model based on all these observation captures the experimental observations. Finally, the integration potential and applications are discussed.

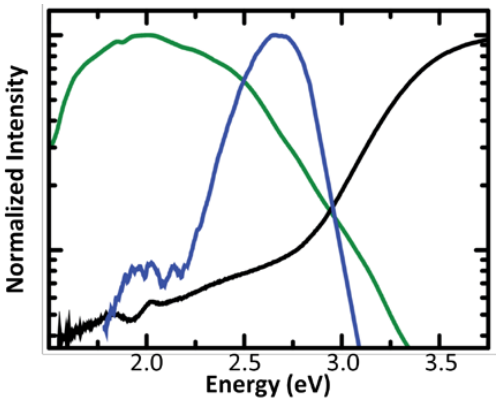

Figure 1: Normalized linear absorption spectrum (black), spontaneous emission for UV excitation above the fundamental electronic transition energy (blue) and white-light emission spectrum (green) for the driving IR laser on a semi-logarithmic scale.

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Quantum Dots–On-Demand Sources for Long Strings of Entangled Photons and Photonic Custer States

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We report on deterministic generation of long strings and cluster states of polarization entangled photons, highly resilient to qubit losses [1]. As such they are important resources for quantum information processing [1] and for quantum communication [2].

We practically realize a concept outlined in Ref [3]. The spin of an optically inactive electron-hole pair – a dark exciton (DE) – confined in a quantum dot (QD) acts as entangler for generating the emitted photonic strings. The DE is a long-lived matter spin qubit [4-5]. We initialize it in a coherent superposition of its two non-degenerate eigenstates [6], and its spin precesses with a time period of about 3 ns [4-5], which is much shorter than the qubit decoherence time (~ 100 ns [5]). Using repeated resonant excitation of the DE, every three quarters of its precession period, we coherently convert the DE population into a biexciton population. The biexciton decays radiatively within 0.33 ns, which is considerably shorter than the biexciton (~6 ns) and the DE precession times. Therefore, the recombination entangles the remaining DE spin with the polarization of the emitted photon. By repeating this procedure at rates which can exceed 1 GHz, robust, deterministic entanglement between the polarization states of hundreds of photons can be achieved.

Using polarization tomography combined with temporally resolved intensity correlation measurements of two and three sequential photon events, we unambiguously demonstrate the deterministic generation of entangled photon strings and cluster states. Our achievement may greatly reduce the resources needed for quantum information processing.

* Work done in collaboration with I. Schwartz, D. Cogan, E.R. Schmidgall, Y. Don, L. Gantz, O. Kenneth, and N. Lindner [7]

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Probing nuclear spin dynamics of a quantum dot using nuclear magnetic resonance (NMR)

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Quantum dots (QDs) in III-V semiconductors offer a unique platform for building quantum networks with optical interconnections. However, interaction between electron and nuclear spins results in electron spin decoherence and poses a major problem. In self-assembled dots large inhomogeneous strain-induced nuclear quadrupolar effects [1] complicate the picture further: recent studies [2, 3] have shown reduction of electron coherence down to sub-microsecond regime, especially in low magnetic fields. Thus deep understanding of the nuclear spin bath dynamics is crucial for achieving long coherence times in electron/hole spin qubit in III-V QDs.

Here I report on experimental studies of the nuclear spin system in neutral quantum dots. Using magnetic resonance spectroscopy, it is shown that when nuclear spin bath is taken out of equilibrium with a strong radio-frequency pulse, its typical transverse spin-echo relaxation time is 1-4 milliseconds [4]. This is a factor of 3-4 longer than in strain-free structures – such extension is attributed to inhomogeneous quadrupolar effects. Probing equilibrium nuclear spin dynamics is of even greater interest for qubit applications but is a lot more challenging since can not be achieved with spin echo spectroscopy. In order to address this problem magnetic resonance technique that utilizes low-power noise-like radio-frequency waves is developed. Such non-invasive probing reveals surprisingly long correlation times of the nuclear spin fluctuations, exceeding 1 second [5].

The striking six orders of magnitude gap in the timescales of electron and nuclear spin relaxation suggests that the qubit coherence is determined by the mutual electron-nuclear spin dynamics. Understanding how optical manipulation of the electron spin affects the nuclear spin bath is crucial in establishing a complete picture of the quantum dot spin physics. Meanwhile, several approaches to circumventing the impact of quadurpolar interactions on electron spin coherence can be considered. In particular, the use of different III-V QD system is reported here: nano-hole etched GaAs/AlGaAs QDs have excellent optical quality comparable to self-assembled dots, but with strain three orders of magnitude smaller [6], offering an attractive alternative to the widely used self-assembled InAs/GaAs QDs.

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Direct preparation of the dark exciton in a quantum dot by a chirped laser pulse

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The ultrafast optical control of excitons in semiconductor quantum dots (QDs) is an important step towards their usage in quantum information technology. The optical activity of the exciton is determined by its spin combination: In the typical case of heavy-hole excitons the exciton is optically accessible or bright for antiparallel spins of electron and hole, while for parallel spins the exciton is optically inactive or dark. Due to its optical inactivity the dark exciton is much more difficult to access. For the same reason, its lifetime exceeds the one of the bright by far, allowing for a longer time for manipulations. We propose a new method to optically access the dark exciton using the combination of a chirped laser pulse and a tilted magnetic field [1].

When the QD is excited with a chirped laser pulse, the adiabatic rapid passage (ARP) effect leads to a population inversion between ground and bright exciton state. If additionally an inplane magnetic field is applied, such that bright and dark exciton are coupled, during the chirped pulse, the dark exciton can be directly prepared. The strength of the magnetic field is chosen such that without the laser pulse the coupling between bright and dark exciton is negligible. We discuss the dependence of this excitation scheme on the sign of the chirp and show that only for positive chirps a high fidelity preparation of the dark exciton is possible (see Fig. 1).

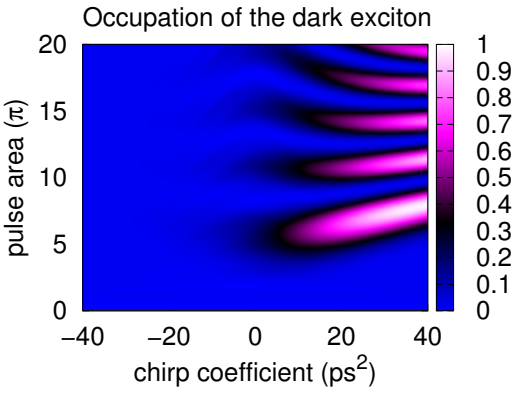

Figure 1: Final occupation of the dark exciton state after excitation with a single chirped laser pulse without exciton-phonon interaction.

Because the QD is embedded in the semiconductor host matrix, the electron-phonon interaction is always present and plays a crucial role in the optical state preparation [2]. During the ARP phonons can be either emitted or absorbed. In the case of low temperatures, where phonon absorption is suppressed, this leads to an asymmetry of preparation fidelity regarding the sign of the chirp. For the preparation of the dark exciton proposed by our scheme only phonon absorption processes can deteriorate the preparation, hence, at low temperatures this mechanism is almost unaffected by phonons. In contrast, for negative signs of the chirp phonon emission occurs. Interestingly, this results in a new way of preparing the dark exciton and for sufficiently strong exciton-phonon coupling the final occupation of the dark exciton becomes symmetric with respect to the sign of the chirp. This makes our preparation scheme and, consequently, dark excitons even more attractive for applications.

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Optical coherent control of lattice-defect spins in SiC device structures

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Divacancy defects in silicon carbide have long-lived electronic spin states and sharp optical transitions, with properties that are similar to the nitrogen-vacancy defect in diamond, but with better links to mature semiconductor device technology and optical communication at near-telecom wavelengths [1]. We report experiments on 4H-SiC that investigate all-optical addressing of these spin states with the zero-phonon-line transitions, and our results demonstrate all-optical control of coherent quantum states of spin ensembles via two-laser coherent population trapping. For quantum-memory applications, the coherent population trapping must be studied in transmission with an extended medium (giving electromagnetically induced transparency, EIT). We demonstrate EIT with this material system, thereby demonstrating how EIT can be implemented for electronic systems with a spin S=1 (instead of the more convenient S=1/2) ground state, and while the electronic systems have a very significant inhomogenous broadening for the optical transitions. Further, we will link these results to prospects for integrated quantum-optical devices in SiC.

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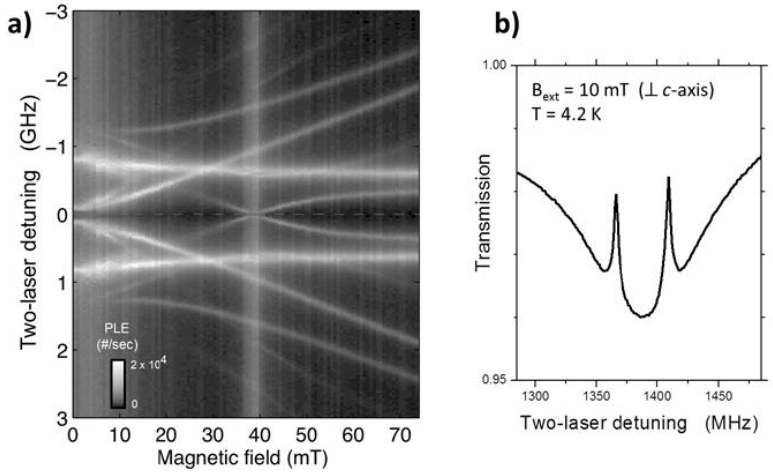

Figure 1: **a)** Photo-luminescence signals from two-laser magneto-spectroscopy reveal the homogeneous optical linewidth of spin-selective transitions and the structure of the spin S=1 Hamiltonians (for ground state and excited state). **b)** Two EIT peaks (from two different combinations of ground-state spin levels) observed in the transmission of a probe laser in two-laser spectroscopy. Tuning of the strength and direction of the weak magnetic field can give a single EIT peak with near unity transmission.

A New Understanding of Nonlinear Light Scattering from Gold Nanoparticles

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Chemically synthesized or self-organized metallic nanostructures such as gold nanorods have been investigated widely for potential applications in plasmonics. Gold nanorods (AuNRs) typically exhibit high crystallinity and structural uniformity and symmetry. As a result, it is generally assumed that the optical and electronic properties reflect the same symmetry. Through a number of experimental approaches, including state-of-the-art electron holography in a TEM, we have found that AuNRs with perfect structural symmetry nevertheless almost always are electrically asymmetric, i.e. they have a static dipole moment. This dipole arises from a static charge asymmetry, and this has highly significant consequences for the optical response; by removing the inversion symmetry, the second order optical response becomes dominant.

We have performed a detailed and comprehensive study of the nonlinear light scattering from AuNRs designed so that the excitation wavelength is resonant with the longitudinal surface plasmon mode at 800 nm. 50-fs pulses from a Ti:sapphire laser are incident on a dilute solution of AuNRs in water, and the scattered light spectrum is measured at 90 degrees direction from the incident beam. Both second and third harmonic hyper-Rayleigh scattering signals are measured, as well as a broad-band component that has been attributed in the literature to multiphoton luminescence involving d-band holes.

We show in this work that the scaling of the second and third harmonic signals with excitation power does not follow the expected quadratic and cubic behavior, but exhibits unexpected scaling that can be quantitatively understood in a Fermi liquid model as plasmon damping via hot electrons. Through detailed studies of the spectral dependence of the scaling across the broadband feature, we show that the “luminescence” in fact arises from second order light scattering enabled by the broken symmetry, and is not in fact luminescence dependent on the band structure. The spectra and the spectral dependence of the intensity scaling of both the “luminescence” and the 2ω and 3ω signals are self-consistently and quantitatively understood though a Fermi liquid model.

Revealing and characterizing dark excitons in semiconductor quantum wells with coherent multidimensional spectroscopy

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Dark excitons are of fundamental importance in a broad range of contexts, but are difficult to study using conventional optical spectroscopy due to their weak interaction with light. We show how coherent multidimensional spectroscopy [1,2] can reveal and characterize dark states. Using this approach, we identify different types of dark excitons in InGaAs/GaAs quantum wells and determine details regarding lifetimes, homogeneous and inhomogeneous linewidths, broadening mechanisms and coupling strengths [3].

Specifically, we identify and characterize three types of nominally dark excitons: parity forbidden transitions, spatially indirect excitons with hole in the barrier and electron in the well and excitons with electron in the barrier and hole in the well. In the 3D spectrum shown in Fig. 1 these dark states become evident as cross-peaks that arise due to the strong coupling of the dark and bright exciton states.

In region above the diagonal there are many cross-peaks observed, both at $E_2 = 0$ and away from this plane, indicating the presence of coherent superpositions of dark states and bright exciton states. Calculations of the energy for each of the individual carrier states are used to help confirm the identity of each dark exciton transition, with excellent matches to the experimental values found.

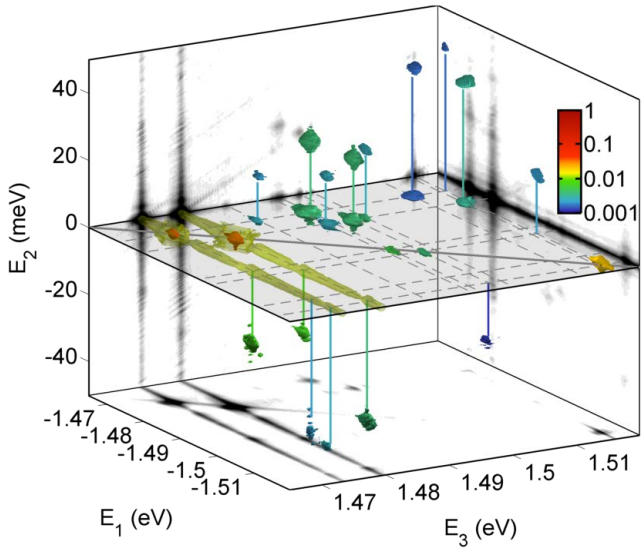

Figure 1 .The 3D spectrum from an InGaAs/GaAs double quantum well reveals strong diagonal peaks for each of the bright transitions as well as coherence cross peaks indicating coherent coupling between the bright exciton and several different dark excitons.

The ability to isolate these peaks in 3D frequency space allows further analysis of the peak shapes and peak amplitudes, which enables detailed characterization of the dark states.

This approach, based on CMDS, allows us to reveal and characterize the rich structure of dark states that is otherwise hidden and can open the door to previously unexplored physics in a variety of excitonic systems.

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Single solid-state quantum emitters for plasmonics

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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
Finally, we will present a hybrid approach combining a dielectric and a plasmonic waveguide to optimize coupling of a quantum dot to a propagating plasmonic mode.

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Transient Excitonic Tweezing in Quantum Wells

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The use of a gradient force induced by a focused laser on a dipole in the Rayleigh regime (much smaller than the wavelength of light) was proposed by Ashkin, et al. [1]. When used to trap and move particles, this phenomena is called optical tweezing [2]. The tweezing force is proportional to the gradient of the electric field and particle's dipole moment.

We use spatially resolved transient-absorption spectroscopy to measure tweezing of excitons, correlated electron-hole pairs, on a sub-picosecond time scale. We observe a transient decrease in the size of a sub-micron excitation spot created in a 10 quantum-well gallium arsenide sample, as shown in Figure 1a. The 120 fs pump (excitation) and probe pulses are resonant with the exciton transition. The excitation-spot size decreases for 3 ps, which is approximately the excitonic coherence time. We thus attribute the spot-size decrease to a gradient force exerted by the excitonic polarization.

To check for consistency with a tweezing force that is proportional to the electric field gradient, we measure the radiated polarization field as a function of time, plotted in the inset of Figure 1a. Careful analysis shows that the dipole moment of a single electron-hole pair is insufficient to account for the measured tweezing. We solve the spatially inhomogeneous semiconductor Bloch equations [3] and show that the Coulomb renormalization to the field gradient enhances tweezing by orders of magnitude. We show that this enhancement is largely due to the many-body interactions known to be the dominant source of nonlinear signals in semiconductors [4]. This enhancement explains why the direct tweezing contribution alone is insufficient. Results of this theoretical analysis are plotted in figure 1b.

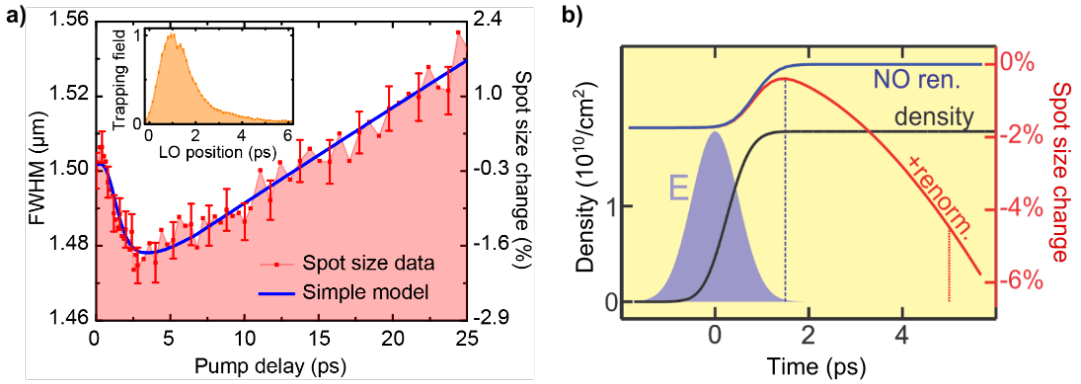

Figure 1: Comparison of experimental and computed excitation-spot size during tweezing. **a)** A pump pulse creates a localized region of excitonic polarization with an initial full width at half maximum (FWHM) of about 1.5 μm, the temporal dynamics of which are plotted in the inset. The measured spot decreases by approximately 2% before diffusion dominates the width dynamics. **b)** Computed spot-size decrease during tweezing explains experiment only when the Coulomb renormalization to the gradient term is included.

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[4] J. M. Shacklette and S. T. Cundiff, *J. Opt. Soc. Am. B* **20**, 764-769 (2003).

Towards deterministic high-efficiency single photon sources based on quantum dots in circular Bragg grating cavities

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Growing interest in quantum information processing and secure communication requires the realization of efficient single photon sources (SPS). Moreover, the reliable implementation of advanced quantum protocols requires networks of identical SPSs which makes deterministic fabrication technologies desirable. Cathodoluminescence lithography (CLL) based on deterministic positioning of the photonic nanostructure with respect to the emitter has been proven very powerful and allows for the realization of nanostructure designs optimized for a preregistered emitter [1]. A further important requirement is maximizing the extraction efficiency of QDs for which circular Bragg grating cavities (CBGC) have been proposed [2,3]. Within this work we develop a technology platform to deterministically integrate single QDs into CBGCs. We present results based on the modelling of GaAs/air CBGCs (Fig 1a) using a finite element method (JCMsuite solver [4]) which allows us to optimize the cavity design parameters for maximum extraction efficiency (Fig 1b). For this purpose, a detailed knowledge of the influence of cavity geometry on the electro-magnetic field distribution (Fig 1b), mode energy, cavity quality factor and optimal position of the QD in the cavity is indispensable. Within the optimization procedure two families of modes with advantageous properties were identified: i) with electromagnetic field distribution forming a standing wave within radial direction of the cavity utilizing interference effects to provide extraction efficiency above 80% into 0.2 numerical aperture (beneficial for application relevant single mode fiber incoupling) (Fig 1b - left), and ii) strongly localized within the central region of the cavity providing strong emission enhancement with Purcell factors up to 8.6 (Fig 1b - right). Optimized design parameters are used to realize CBGCs with In(Ga)As QDs embedded by combining cathodoluminescence spectroscopy and in-situ electron-beam lithography (Fig 1c).

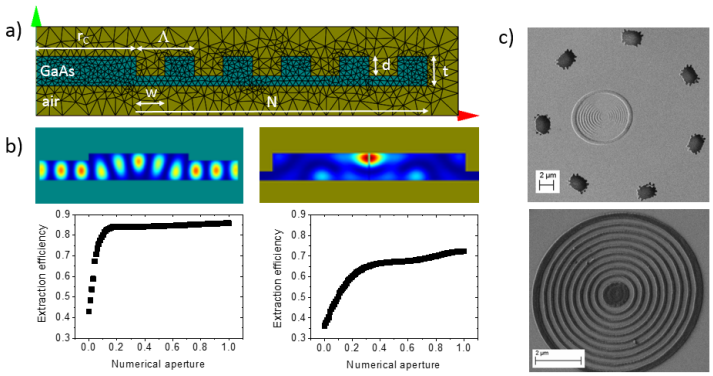

Figure 1: a) geometry parameters of CBGC and discretization used in simulations; b) exemplary distributions of electric field within the cavity for two modes together with the extraction efficiency dependence on the numerical aperture of collection optics (below); c) CBGC realized using CLL technique.

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Resonantly-driven mutually strongly-coupled coherent optical field-quantum dot-microcavity systems

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In this contribution we focus on experimental and theoretical (based on the Fourier-transformed first-order autocorrelation function including multi-photon scattering) description of quantum dot exciton strongly-coupled to the microcavity mode under coherent excitation with emphasis on the regime when amplitude of the driving optical field is comparable to light-matter coupling strength. In our configuration exciton is driven directly which allows for wavelength-independent efficient excitation crucial for characterization of mutually-coupled system. We distinguish the different excitation regimes via the energy shift of the incoherent response of the exciton-cavity mode system under resonant (quantum dot bare state) excitation, following the laser energy. The investigated system exhibits dramatically different character depending on the amplitude of the external laser with vacuum Rabi split doublet resulting from exciton-cavity mode coupling when the system is only weakly probed and laser-dressed polariton states with Mollow Triplet-like behavior being the limiting cases. Interestingly, in the intermediate pumping regime a unique scenario of hybrid system with two photons coupled strongly to a quantum dot exciton is realized. The signature of this transition regime is a clear maximum in the intensity of the optical response under resonant driving and zero exciton-cavity mode detuning for the laser amplitude equal to the strength of light-matter coupling.

Three-stage decoherence dynamics of an electron spin qubit in an optically active quantum dot

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The control of solid-state qubits for quantum information processing requires a detailed understanding of the coupling mechanisms responsible for decoherence. For electron spins in quantum dots (QDs), considerable progress has been achieved in this field for qubit dynamics in strong external magnetic fields; however, decoherence at very low magnetic fields remains puzzling when the magnitude of the Zeeman energy becomes comparable with intrinsic couplings. Phenomenological models of decoherence currently recognize two basic types of spin relaxation; fast ensemble dephasing due to the coherent precession of spin qubits around nearly static but randomly distributed hyperfine fields (~2ns) and a much slower process (>1μs) of irreversible monotonic relaxation of the spin qubit polarization due to nuclear spin co-flips with the central spin or due to other complex many-body interaction effects [1]. In this contribution, we demonstrate experimentally and theoretically that not only two but three distinct stages of decoherence can be identified in the relaxation of a QD electron spin qubit.

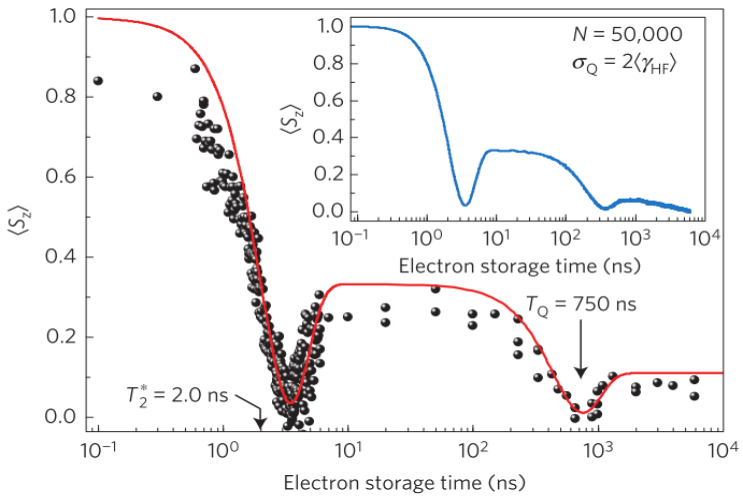

Fig. 1: **Dynamics of the electron spin relaxation.** Experimental data reveals a fast inhomogeneous electron spin dephasing. The quadrupolar coupling of nuclear spins induces oscillatory fluctuations of the Overhauser field at TQ. The inset shows a numerical simulation based on the theoretical model of central spin decoherence by a nuclear spin bath. The long relaxation tail at longer times (>1μs) is due to combined effects of hyperfine and quadrupolar

Experiments and simulations (figure1) of the spin projection without an external field clearly reveal an additional decoherence stage at intermediate timescales [2]. The additional stage corresponds to the effect of coherent dephasing processes that occur in the nuclear spin bath itself induced by quadrupolar coupling of nuclear spins to strain driven electric field gradients, which leads to a relatively fast but incomplete non-monotonic relaxation of the central spin polarization at intermediate (~750ns) timescales.

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[2] A. Bechtold et al., Nature Physics 11, 1005–1008 (2015)

Inhomogeneous nuclear spin polarization induced by helicity-modulated optical excitation of fluorine-bound electron spins in ZnSe

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Optically-induced nuclear spin polarization in a fluorine-doped ZnSe epilayer is studied by time-resolved Kerr rotation using resonant excitation of donor-bound excitons [1]. Excitation with helicity-modulated laser pulses results in a transverse nuclear spin polarization, which is detected as a change of the Larmor precession frequency of the donor-bound electron spins. The

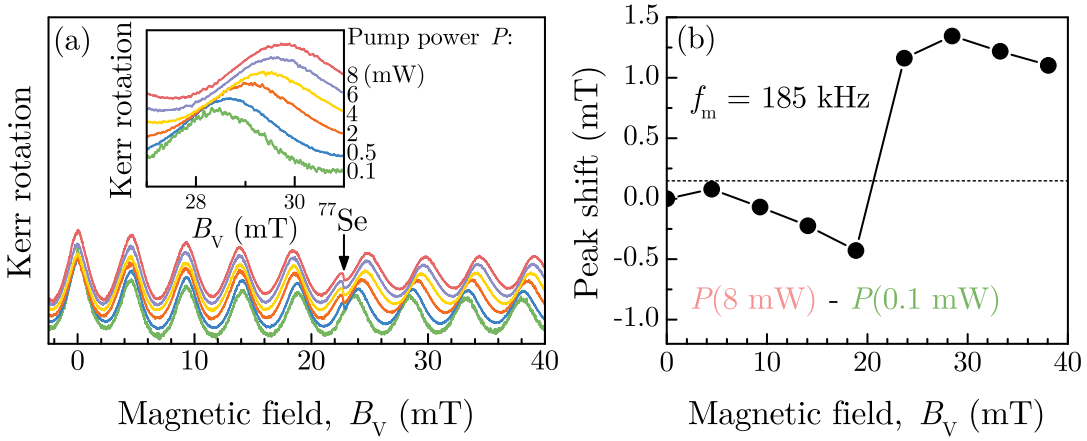

Figure 1: (a) Normalized RSA spectra measured at $T = 1.8\,\mathrm{K}$ and a helicity modulation frequency $f_\mathrm{m} = 185\,\mathrm{kHz}$ at different pump power P_pump. The arrow marks the resonance of the ^{77}Se isotope at $f_\mathrm{NMR} = f_\mathrm{m}$. (b) Difference of the peak positions at $P_\mathrm{pump} = 8\,\mathrm{mW}$ (light red line) and $P_\mathrm{pump} = 0.1\,\mathrm{mW}$ (green line) in dependence on the magnetic field (peak position at low power).

frequency shift in dependence on the transverse magnetic field exhibits a pronounced dispersion-like shape (see. Fig. 1(b)) with resonances at the fields of nuclear magnetic resonance of the constituent zinc and selenium isotopes. It is studied as a function of external parameters, particularly of constant and radio frequency external magnetic fields. The width of the resonance and its shape indicate a strong spatial inhomogeneity of the nuclear spin polarization in the vicinity of a fluorine donor. A mechanism of optically-induced nuclear spin polarization is suggested based on the concept of resonant nuclear spin cooling in the inhomogeneous Knight field of the donor-bound electron.

[1]F. Heisterkamp, A. Greilich, E. A. Zhukov, E. Kirstein, T. Kazimierczuk, V. L. Korenev, I. A. Yugova, D. R. Yakovlev, A. Pawlis, and M. Bayer, *Phys. Rev. B* **92**, 245441(2015).

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Optical Transitions in Type-II Heterostructures

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Inorganic semiconductor heterostructures are the heart of today's advanced opto-electronic devices. Conventional, type-I band alignments for direct-gap material are considered optimal for active devices such as semiconductor lasers. Increasing the emission wavelength into the infrared regime causes significant challenges regarding inherent loss mechanism such as intersubband absorption or enhanced Auger losses. An alternate extreme promising concept to circumvent many of these challenges is the combination of multiple type-II transitions to form a so called "W"-laser structure. The individual layers have large band gaps suppressing the loss channels[1]; nevertheless, such structures offer significant oscillator strength and hence gain at energies below the fundamental band gap of the individual layers despite the local type-II character. Here, the overall band alignment of the complex heterostructures needs to be considered. While the prototypical type-II heterointerfaces are GaAs/(Al,Ga)As superlattices, advanced combinations of inorganic III-V semiconductor compounds allow pushing the emission wavelength towards the mid-infrared.[2]

We study a series of MOVPE grown (Ga,In)As/Ga(As,Sb) "W"-multi quantum well heterostructures targeted as gain media in future laser applications. Those structures are investigated by modulation and photoluminescence spectroscopy to characterize the electronic transitions and explain the complex structure of electron and hole states. Further a fully microscopic theory is applied to identify the character of the observed transitions.[3]

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[2] S. Tarucha et al., Jpn. J. Appl. Phys. **22** (1983).
[3] S.Gies et al., Appl. Phys. Lett. **107**, 182104 (2015).

Towards linearly polarized quantum emitter and entangled photon pairs at telecommunication wavelengths utilizing InAs-InP based nanostructures

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Linearly polarized single photon source and entangled photon pair generation are both relevant elements for quantum communication protocols of secure data transmission (BB84, Ekert92). In this context, a deterministic quantum emitter based on a semiconductor platform and operating at telecommunication wavelengths of fiber-based transmission systems is strongly desired.

Hereby, we have investigated InAs/InGaAlAs/InP quantum dashes (QDashes) that emission wavelength overlaps with the 2nd and 3rd low-loss windows of silica fibers. Their application potential as non-classical emitters operated on both charged and neutral exciton and as a source of classically correlated photons from biexciton-exciton cascade has been demonstrated recently [1,2].

Optical properties of such nanostructures have been studied systematically by μPL showing their intrinsic properties like significant degree of linear polarization (DOLP) of emission and fine structure splitting (FSS) depending on the structures' morphology. The asymmetric confinement potential of QDashes involves both the valence band mixing and strong exchange interactions which give rise to well separated linearly polarized exciton transitions of unequal intensities. Further enhancement of DOLP up to 80% can be realized by a post-growth modification of the dielectric environment and by forming asymmetric mesa structures. On the other hand, the exciton FSS tuning is feasible by the in-plane magnetic field in a range of ~300 μeV using 5 Tesla, reducing its value below zero. Thus, the exciton bright-state crossing has been achieved in the range of 2-4 Tesla. Such tuning knob has a practical importance for possible use in a source of polarization-entangled photons, as it was shown for inverted InAs/GaAs quantum dots [3]. The experimental data on high DOLP and reduced FSS has been collected for a number of QDashes in a broad spectral range from below 1.3 μm to above 1.55 μm, and it appeared they are typical properties of such nanostructures. It allows to consider the single InAs QDashes as an active element of the future non-classical emission nanophotonic devices.

[1] Ł. Dusanowski, M. Syperek, P. Mrowiński, W. Rudno-Rudziński, J. Misiewicz, A. Somers, S. Höfling, M. Kamp, J. P. Reithmaier, and G. Sęk, Appl. Phys. Lett., 105, 021909 (2014);

[2] Ł. Dusanowski, M. Syperek, W. Rudno-Rudziński, P. Mrowiński, G. Sęk, J. Misiewicz, A. Somers, J. P. Reithmaier, S. Höfling, A. Forchel, Appl. Phys. Lett., 103, 253113 (2013)

[3] A. J. Hudson, R. M. Stevenson, A. J. Bennett, R. J. Young, C. A. Nicoll, P. Atkinson, K. Cooper, D. A. Ritchie, and A. J. Shields Phys. Rev. Lett. 993, 266802 (2007)

Coherent 2D excitons in disordered quantum wells

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It is well established that the oscillator strength of excitons in 2D systems is directly proportional to the area of the exciton in the plane of the 2D material [1,2]. Recent observations have confirmed this relationship in nanoplatelets where the spatial extent of the excitons can be well controlled [3]. In semiconductor quantum wells, the spatial extent or coherence area is limited by exciton-exciton scattering [1]. Interfacial fluctuations also play a role in determining the size of the excitons [4], but as we show here, at low exciton densities the effect of interfacial fluctuations is more relevant to the linewidths and coherent dynamics.

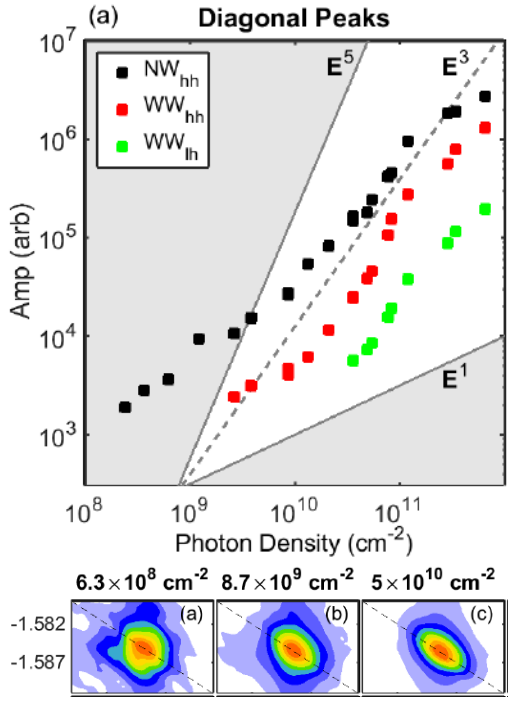

Figure 1. shows (I) the dependence of the signal electric field amplitude and (II) the 2D diagonal peak for a QW exciton as a function of the photon density. At low densities the signal amplitude scales linearly with incident field and the homogeneous linewidth increases due to the larger coherence area of the excitons.

We use an extremely sensitive coherent multidimensional spectroscopy experiment [5] to measure the coherent dynamics of excitons in GaAs/AlGaAs and InGaAs/GaAs QWs as a function of exciton density, down to average densities of ~5×10^6 cm^{-2}, corresponding to an average exciton-exciton separation of several µm.

At exciton densities <10^8 cm^{-2} we see the electric field amplitude of the 3rd order signal go from scaling with the expected 3rd power of the incident filed amplitude to scaling linearly with the incident field amplitude. We attribute this to the increasing coherence area of the excitons, which is facilitated by the reduced exciton density and hence reduced exciton-exciton scattering. The transition dipole strength which varies linearly with exciton coherence area, thus increases with the inverse 2nd order of the exciton density (and thus incident field amplitude). The combination of the total effective transition dipole strength going as E^{-2} and third order signal going as E^3 is that the signal scales linearly with E.

This intensity dependence is seen in several different QW samples. In the case where disorder is significant, the homogeneous linewidth also begins to increase as the excitation density decreases. This increase is attributed to the exciton having a coherence area larger than the characteristic scale for the interfacial fluctuations. The disorder leads to faster decoherence and a homogeneous linewidth that matches the inhomogeneous linewidth and which is governed by disorder.

[1] J Feldman, Phys Rev. Lett **59**, 2337 (1987).
[2] J Kasprzak, Nature Photonics **5**, 57 (2011).
[3] A. Naeem, et al., Phys. Rev. B **91**, 121302 (2015).
[4] V. Savona and W. Langbein, Phys Rev B **74**, 075311 (2006).
[5] J.O. Tollerud et al., Optics Express **22**, 6719 (2014)

Influence of excited carriers on the optical properties of monolayer transition metal dichalcogenides

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We address the question how the optical properties of monolayer transition metal dichalcogenide (TMD) semiconductors are modified by excited carriers, which can be either generated by optical excitation or by doping of the material with a certain carrier species.

Under photoexcitation of carrier densities up to 10^{13} cm^{-2}, absorption spectra reveal a redshift and mild bleaching of the excitonic ground state resonance, whereas higher excitonic lines are found to disappear successively due to Coulomb-induced band-gap shrinkage of more than 500 meV and binding-energy reduction. [1] The results are obtained by solving the semiconductor Bloch equations using band structures and Coulomb interaction matrix elements determined from ab-initio calculations. Our method includes material and structure-specific information on the accuracy of a G_0W_0 calculation, including the full Brillouin zone to take into account excited carriers in the different conduction- and valence-band valleys.

Complementary information about the system is obtained from photoluminescence (PL) spectra, which are calculated in the same spirit of combining an accurate ground-state description with systematic many-particle theory. [2] We show that the presence of several band-structure valleys in close energetic vicinity manifests itself in a strongly carrier-density- and strain-dependent emission intensity yield. The direct band gap, for which monolayer MoS_2 is well regarded, disappears due to band-gap renormalizations already at moderate excitation levels, which suppresses the emission especially under electrical or above-band-gap excitation of electrons and holes. On the other hand, we conclude from theory and experiment that excitation with wave lengths above and within the single-particle band gap lead to fundamentally different carrier distributions and resulting PL. Within the band gap, excitonic resonances are coherently driven and the resulting PL yield is less sensitive to the local band-structure landscape. Emission strongly exceeding that following above-band-gap or electrical excitation is expected especially in the presence of an indirect band gap, such as in multi-layer TMDs or compressively strained monolayer TMDs.

Besides excitonic features, signatures of trions appear in optical spectra if one carrier species (electrons or holes) is injected into the material, for example via chemical doping by a substrate, or if electrons and holes are excited simultaneously. Linear absorption spectra including trionic effects are presented and the doping dependence of trion oscillator strength and binding energies for different TMD materials is discussed.

[1] A. Steinhoff, M. Rösner et al., Nano Lett. **14**, 3743 (2014)
[2] A. Steinhoff, J. H. Kim et al., Nano Lett. **15**, 6841 (2015).

Atomic-vapor-enabled variable optical delay for triggered single-photons from a semiconductor quantum dot

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Quantum dots (QDs) are bright sources of single photons. Beside their enormous flux, they allow for high photon indistinguishability and photonic entanglement generation, and their use as "flying qubits" for the quantum communication of the future. One limitation of QDs is the missing long lasting quantum memory. This may be overcome by the highly coherent properties of atoms. Subsequently, quantum hybrid systems, which realize spectral superposition of QDs and atoms, have been recently attracting a lot of attention. Key steps are the efficient filtering and the slowing down of triggered single-photons emitted by QDs by means of atomic transitions [1, 2]. In a previous work we demonstrated the possibility of simultaneously filter two single photons emitted by the Mollow triplet sidebands, using a Faraday anomalous dispersion optical filter (FADOF) [3]. Here, we focus on the approach of storing light in a cesium (Cs)-vapor by slowing down single photons.

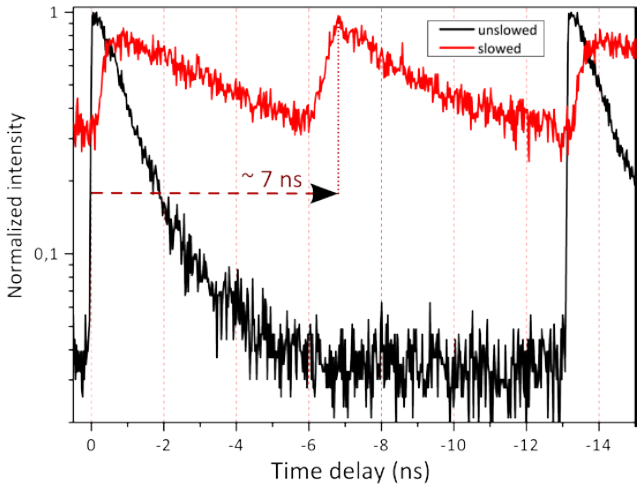

Figure 1: Measured lifetimes for slowed and unslowed photons measured via time-correlated photon counting. The black curve is taken for the QD emission detuned from the high dispersion region. The red curve is measured for the QD emission spectrum centered in between the Cs hyperfine resonances, with a delay of about ~ 7 ns.

High dispersion between ground-state hyperfine resonances of Cs-vapors enables lower group velocities, while maintaining transmission. Using a Cs-vapor as slow light-medium, we present a variable delay up to 10 ns for photons from a resonantly excited QD. As the sample is glued on a piezo, we can tune the spectrum of the QD along the atomic resonances and we investigate the spectral tuning dependency on the delay. Increasing the temperature in the vapor changes the Cs-spectral dependence and though the dispersion, which allows us to control the amount of delay experienced by the photons. Thus we demonstrate a spectrally selective and tunable delay line for single photons emitted by quantum dots.

[1] N. Akopian, *et al*. Nat. Photonics **5**, 230-233 (2011).
[2] J. S. Wildmann, *et al*. Phys. Rev. B **92**, 235306 (2015).
[3] S. L. Portalupi, *et al*. submitted (2016).

Distinct valley dynamics associated with intra-valley trions in monolayer WSe_2

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Transition metal dichalcogenides (TMDs) support very stable optical excitations, such as excitons and trions. The high binding energies for these excitations in TMDs have triggered fundamental research into their applicability in spin- and valley-tronics.

We investigate the valley polarization dynamics associated with resonantly excited trions in monolayer tungsten diselenide (WSe_2). Excitons and trions form at the hexagonal Brillouin zone boundaries at the K (K') points. For excitons, sub-picosecond valley scattering has been demonstrated, which causes a rapid loss of the excitation polarization along with the valley index [1]. We show that if trions are excited via the exciton, the trions inherit this rapid loss of polarization.

By the respective valleys occupied by the carriers constituting a trion, trions can form as inter-valley trions or intra-valley trions (Fig. 1). Recently, it has been proposed that the two different trions have a difference in their energy of about 6 meV, energetically favoring the intra-valley trion in WSe_2 [2]. In polarization-resolved pump-probe experiments pumping resonantly at the trion energy, we confirm this observation, and we demonstrate that the two types of trions display distinct valley dynamics (Fig. 2). If exciting the inter-valley trion, we find a rapid valley depolarization, fully analoguous with the observations on excitons. Intra-valley trions, on the other hand, exhibit a long lived circular polarization under resonant excitation conditions.

[1] A. A. Mitioglu et al., *arXiv preprint* arXiv: 1507.00496 (2015).
[2] A. M. Jones et al., *Nat. Phys.* **12**, 323 (2016).

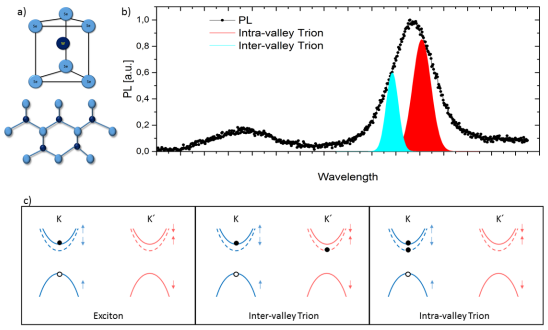

Figure 1: (a) The unit cell and top view of WSe_2 monolayer. (b) PL w.r.t. wavelength including a schematic localization of the inter-and intra-valley trion. (c) Schematic drawing of the band structure of excition, inter-and intra-valley trion.

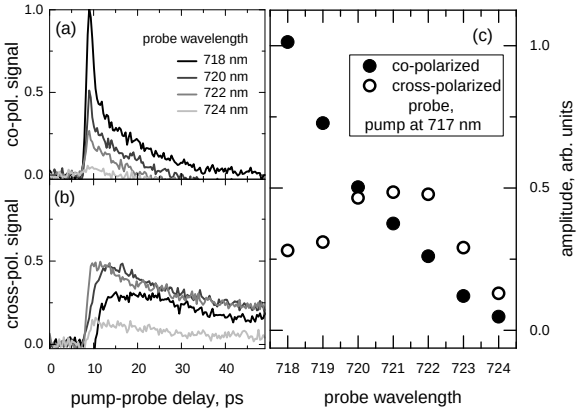

Figure 2: Pump-probe traces for 717 nm pump wavelength and co-circularly (a) and cross-circularly (b) polarized probe. (c) Amplitudes of signals from (a) and (b) versus probe wavelength. The peak of the cross-circularly polarized probe signal is red-shifted by about 6 meV.

Fundamental and applied optical properties of submonolayer quantum dots

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By depositing InAs in submonolayer sheets into a GaAs matrix, vertically aligned In-rich agglomerations are formed, which act as shallow localization centers for carriers (Fig. 1). These submonolayer quantum dots form with an areal density exceeding the densities reached in the traditional Stranski-Krastanov growth by one to two orders of magnitude. If pumped electrically, submonolayers show a remarkably stable emission, and thus promise to unite the favorable properties of quantum wells and quantum dots.

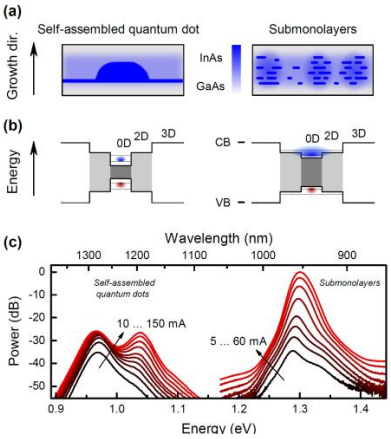
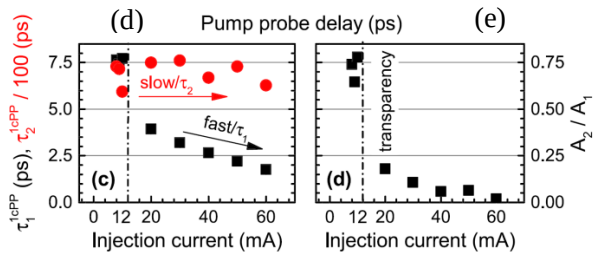
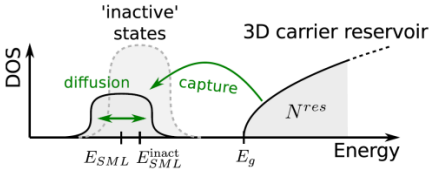


Figure 1: Self-assembled quantum dots vs. submonolayer quantum dots. (a) Schematic of the epitaxial structures. (b) Schematic of the electron (blue) and hole (red) wavefunctions. (c) Electroluminescence. (d) Slow and fast time constants of the gain recovery. (e) Amplitude ratio of slow to fast time constant.



We study the carrier dynamics in a semiconductor optical amplifier based on submonolayer quantum dots and compare it to observations made on self-assembled quantum dots and quantum wells. The submonolayer-based device shows a large gain of 80 cm^{-1}, and an ultrafast gain recovery after carrier depletion in optical pump-probe experiments [1]. The phase recovery, however, is largely desynchronized from the gain dynamics, and proceeds on a slower time scale. Rate equation simulations [2] reveal a lateral coupling between the submonolayer agglomerations, and the existence of a substantial reservoir of optically inactive carrier states (Fig. 2). These two effects provide an efficient recovery channel for depleted carriers, and on the other hand cause large refractive index variations following the intraband interaction with an optical pump pulse. The density of the optically active states providing the best fits to the data is a flat-top Gaussian, which unlike a two-dimensional distribution has a gap between the localized states and the GaAs bulk (Fig. 2). This feature explains the stability of the emission and the large gain of these structures. Submonolayer quantum dots are thus prone to induce a large chirp in transmitted optical pulses, but are potentially superior to self-assembled quantum dots for all applications requiring nonlinearities, such as cross-phase modulation.

Figure 2: Density of states of submonolayer quantum dots and carrier recovery channels.



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Time-resolved photoluminescence spectroscopy on blends of pentacene and perfluoropentacene

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Blends of organic semiconductors are receiving increasing attention due to their potential as active layer in novel optoelectronic devices [1]. Here, the question of intermolecular interactions between the two compounds becomes especially important and can strongly affect device performance as well as the photophysics of the material [1,2]. An understanding of the effects of charge transfer processes on the properties of these mixed systems is therefore important for applications but also interesting for fundamental research.
One of the prototypical organic semiconductors is pentacene (PEN, C22H14), which exhibits fast dynamics on a femtosecond timescale [3]. Blends of pentacene with its perfluorinated counterpart perfluoropentacene (PFP, C22F14) are one of the model systems to study intermolecular interactions and it has been demonstrated that a distinct charge transfer transition (CT) can be observed in absorption [4] as well as in photoluminescence [5] spectroscopy.
We discuss the results of time-resolved photoluminescence spectroscopy measurements performed at 10K on PFP:PEN blends with three different mixing ratios, focusing on the lifetime of the charge transfer state and its impact on excited states of PEN or PFP, respectively. We observe a lifetime of the CT state of up to several hundreds of picoseconds, which depends strongly on the mixing ratio. A possible explanation for the dependence of the lifetime on the mixing ratio will be discussed.

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[2] J.-L. Bredas et al., Chem. Rev. **104** (2004)
[3] M. W. B. Wilson et al., Acc. Chem. Res **46** (2013)
[4] K. Broch et al., Phys. Rev. B **83** (2011)
[5] F. Anger et al., J. Chem. Phys. **136** (2012).

Optical characterization of Au nanoparticles embedded TiO_2 thin films

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The effect of dielectric environment modifies the plasmon resonance effects of Au nanoparticles. And the absorption profiles of many semiconductors can be modulated to emit or absorb light in visible portion of the electromagnetic spectra [1]. Therefore, Au thin film have been embedded in TiO_2 and optical structure has been investigated through UV/Vis spectroscopy and spectroscopic ellipsometry. The effect of annealing has been monitored and it is observed that not only the UV/Vis absorption has been enhanced in visible part but parameters like complex refractive and dielectric function have also shown improved coherent oscillations resulting in increased activity of the structure in the UV part.

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[1] S. Linic, P. Christopher, and D. B. Ingram, "Plasmonic-metal nanostructures for efficient conversion of solar to chemical energy," *Nat Mater*, vol. 10, pp. 911-21, Dec 2011

Mass anisotropy in germanium revealed by terahertz spectroscopy

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Optical pump-THz probe spectroscopy can access the formation and decay of excitons in semiconductors by probing the intra-excitonic 1s-2p transition [1] which typically falls in the terahertz (THz) range. This characterization works for both direct- [2] and indirect-gap [3] semiconductors such as silicon and germanium. However, the indirect excitons in germanium have a strong mass anisotropy, which splits the 1s-2p transition into two distinct resonances [4]. Here, we experimentally observe this splitting for the first time.

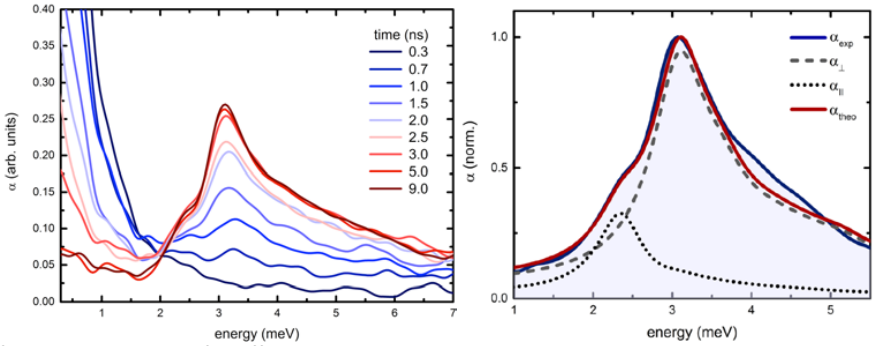

Figure 1: left part: THz absorption for different temporal delays between optical excitation and THz probe pulses. Right part: Comparison between the experimental and theoretical results. The measured spectrum (shaded area) was taken 7 ns after optical excitation. The theoretical spectrum (red) is the sum of absorption spectra for parallel (dotted) and perpendicular (dashed) polarization.

Our sample is a 500 µm thick piece of undoped n-type germanium. It is cooled down to 11 K. For the optical pump-THz probe experiments, we use the output of a 1 kHz Ti:sapphire amplifier system with 35 fs-pulses spectrally centered around 800 nm. The pulse train is split into three parts. After frequency conversion to 1550 nm, the first part optically excites the germanium crystal in the low energy tail of the absorption spectrum. The second part excites an LT-grown large aperture GaAs-antenna which emits THz pulses. The third part gates a ZnTe crystal. The left part in Figure 1 shows the absorption of germanium for different time delays between the optical excitation pulse and the probing THz pulse; the carrier density is estimated to be $5 \cdot 10^{14}$ cm^{-3}. After a few nanoseconds we observe the formation of excitons as indicated by the occurrence of a prominent intra-excitonic absorption peak at 3.1 meV. This peak shows a shoulder at 2.4 meV which can be explained by the anisotropic electron mass in the L-valley leading to a splitting of the 1s-2p resonance. Our data are in very good agreement with a microscopic theory based on the generalized Wannier equation extended to consider the mass anisotropy [4] (Fig. 1, right part).

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[4] P. Springer, S. W. Koch, and M. Kira, Journal of the Optical Society of America B **33**, 7 (2016).

Faraday rotation induced by the electron gas and nuclear spins in Si:GaAs in a GaAlAs/AlAs microcavity

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Controlled manipulation of the nuclear spin bath is an issue of fundamental importance in various systems, like quantum dots and impurity centers placed in a matrix of a host semiconductor, where the spatially localized electron can transfer its spin moment to the nuclear spin system. Modern studies of *n*-doped GaAs are based on the investigation of the Faraday rotation (FR) of the light passing through a semiconductor layer and probing the spin polarization of resident carriers in it. The sensitivity of a setup would be greatly enhanced by putting the subject of study in between the double Bragg reflectors (DBR) thus increasing the length of the optical path for the probe by Q times, being Q a quality factor of the microcavity (MC). On the other hand, the imperfectness of the DBR growth and the wedging of the structure would give an additional source of the light-polarization modification enhanced by the MC. The detailed investigation of the FR in $n_d \sim 10^{15}$ Si-doped GaAs placed within the $3\lambda/2$ active region of the $Q \simeq 30000$ GaAlAs/AlAs MC is addressed in this communication.

We use the optical-phase shifting polarimetry to investigate the time evolution of the nuclear spin bath relaxation in presence of the elliptically polarized probe light. The typical transmission spectrum of the cavity is shown in Fig. 1(a), where two orthogonal elliptically polarized cavity modes are present. Since the built-in splitting of the cavity mode results from a high tension of the MC, the probe light always have a circular component within the active region of the MC. Tuned in energy to slightly below D_0X transition, the probe beam initiates the optical orientation of the donor bounded electrons. Thus, the nuclear spin bath is getting polarized in the vicinity of the donor center, and the nuclear spin diffusion would allow for the nuclear polarization in an area around it. The time evolution of the FR initiated by, at first, deep cooling of the nuclear spin bath is shown in Fig. 1(b) where the slow evolution is turned by the nuclear spin demagnetization from the cooled nuclear spin state to the equilibrium defined in the Hanle depolarization curve represented in Fig. 1(c). In addition, there is a times faster process, possibly associated with the spin relaxation of nuclear spins in the vicinity of the donor center. The discussion of the nuclear spin relaxation in Si:GaAs MCs is provided.

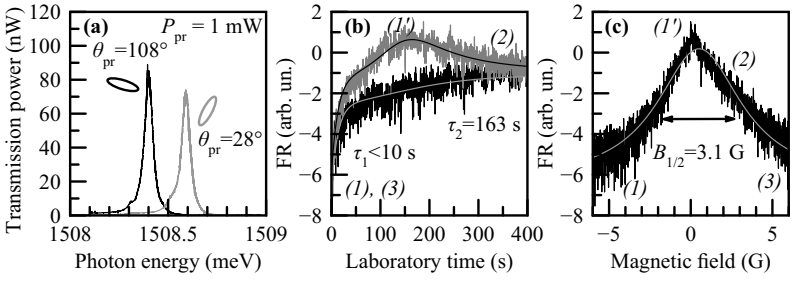

Figure 1: (a) Transmission spectrum of the cavity probed with the eliptically polarized light. (b) Dynamics of the FR amplitude; the trajectories $1 \rightarrow 1' \rightarrow 2$ (gray) and $4 \rightarrow 2$ (black) and their fitting (thin lines) is shown. (c) Hanle depolarization curve.

Impact of nuclear spin bath on carrier spin relaxation in InGaAs/GaAs self-assembled quantum dots

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The spin fluctuations of self-assembled InGaAs/GaAs quantum dots doped with single electron or hole spins, is measured optically in the limit of low laser intensity by spin noise spectroscopy. This allows to reveal fundamental properties of carrier spin dynamics which is governed through the interaction with surrounding nuclei at a level close to thermal equilibrium. We characterize the hyperfine interaction of electron and hole spins on time scales covering several orders of magnitude. Our results demonstrate (i) the intrinsic precession of the electron spin fluctuations around the effective Overhauser field caused by the host lattice nuclear spins, (ii) the comparably long time scales for electron and hole spin decoherence, as well as (iii) the dramatic enhancement of the spin lifetimes induced by a longitudinal magnetic field due to the decoupling of nuclear and charge carrier spins, see Fig. 1.

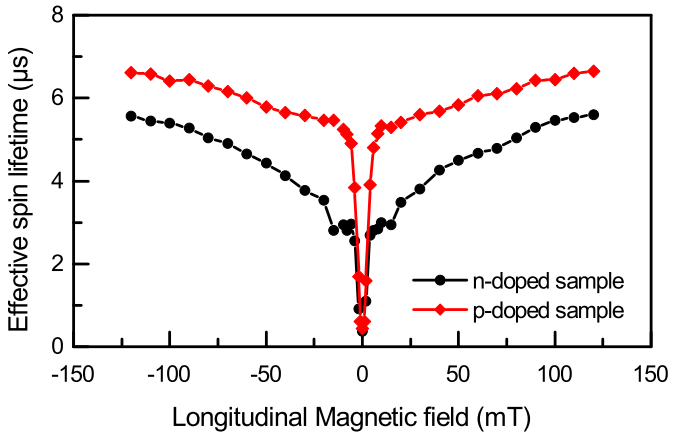

Figure 1: Dependence of the effective spin lifetime. Each sample shows characteristic signatures of a small fraction of opposite type of resident carriers.

Furthermore, we tested the applicability of two complementary theoretical approaches: the Chebyshev polynomial expansion technique (CET) and the semiclassical approximation. Comparison of the experimental data with the modeling shows that the CET approach is a powerful method to describe the spectral SNS shape in the intermediate- and high-frequency ranges[1,2].

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Bandstructure formation of exciton polaritons in lattice potential landscapes

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Exciton polaritons have emerged as a powerful system to study collective behavior of microscopic coherent quantum states in a solid state environment as they fulfill a range of important prerequisites. The technical possibility to engineer polariton trapping potentials with a tunable tunnel coupling between single traps by elaborated lithography and etching techniques has triggered the interest in using polaritonic systems to emulate the physics of graphene, high-temperature superconductors, or frustrated spin lattices. In this context polaritonic systems offer the benefit of a wide tunability of parameters as e.g. effective spin-orbit coupling [1], which e.g. is not accessible in graphene. We observe and study the formation of complex band structure formations in square [2], Lieb as well as honeycomb photonic crystal lattice arrays fabricated by the etch-trap-method [3] (Fig 1a) . Lieb lattices are particularly interesting as they allow for Flatband formation [4], compacton-like states as well as Dirac–type dispersions [5]. Here, we study the formation of flatband states as well as gap states in a Lieb lattice in a two-dimensional shallow potential landscape.

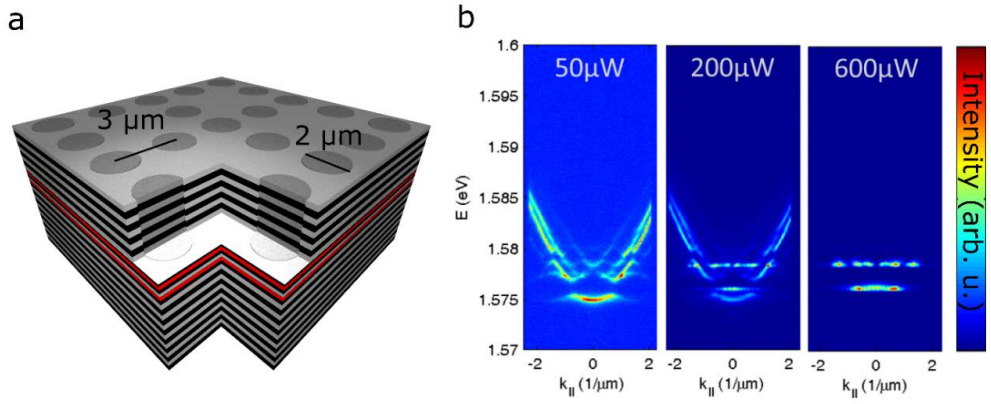

Fig. 1: (a) Schematic example of a Lieb lattice of 0D-polariton traps of 2 µm diameter, using a microcavity consisting of a AlAs-λ/2-cavity with GaAs quantum films embedded in AlGaAs/AlAs-DBR-mirrors. (b) Angle-resolved photoluminescence measurements of a Lieb lattice vs excitation power showing clear band formation and the appearance of a flatband-like gap state.

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[5] R. A. Vicencio et al., Phys. Rev. Lett. **114**, 245503 (2015).

Manipulation of dark solitons and vortices of exciton-polariton condensates in semiconductor microcavities

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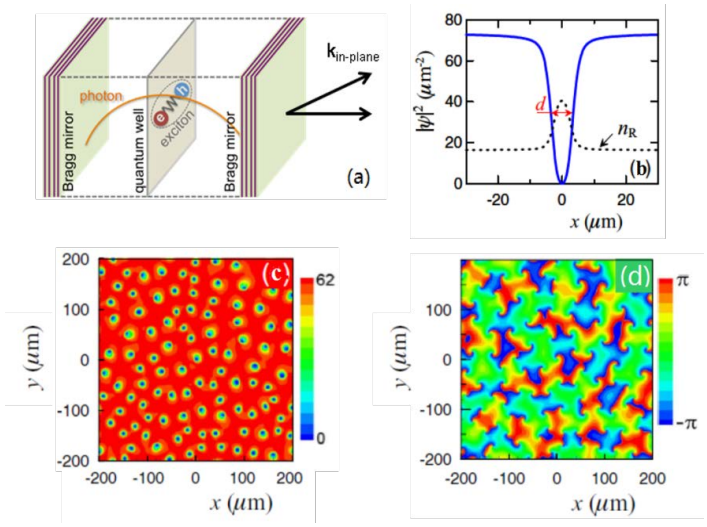

Fig. 1. (a) Sketch of a semiconductor microcavity with a quantum well (QW) sandwiched between two distributed Bragg reflectors (DBRs). (b) Profile of a dark soliton (solid line) and the reservoir density (dashed line). (c) Density distribution of collective vortices. (d) Phase distribution of (c). [1].

Exciton-polaritons are quasi-particles made of quantum well (QW) excitons coupled to cavity photons as illustrated in Fig. 1(a). They have very small effective mass ($10^{-4}m_e$, m_e is the free electron mass) and lifetimes on the tens of picoseconds scale. Due to their photonic properties, they can be excited by light and probed, respectively. Due to their excitonic properties, nonlinearity is introduced into this system at elevated densities. Polaritons, which are composite bosons, can undergo a condensation process (with similarities to Bose-Einstein condensation) under incoherent excitation. Many features in the dynamics of polariton condensates can be described by a modified Gross-Piteavskii equation (GPE). In our previous study based on the GPE, we investigate the phase defects under homogeneous excitations [1]. It was found that the dark solitons [Fig. 1(b)] are unstable in the 1D case. While, in the 2D case collective vortices with irregular movements are found as shown in Figs. 1(c) and 1(d). However, these vortices cannot be controlled optically. Recently, under periodic excitations we found stable dark solitons as well as fixed vortices. Importantly, a coherent optical pulse can be used to switch on or off a dark soliton, or to manipulate the motion of a vortex.

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Nanowire quantum dots tuned to atomic resonances

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Quantum dots (QDs) tuned to atomic resonances represent an emerging field of hybrid quantum systems where the advantages of quantum dots and natural atoms can be combined [1,2]. Embedding QDs in nanowires boosts this hybrid system with a set of powerful possibilities, such as precise positioning of the emitters, excellent photon extraction efficiency and direct electrical contacting of QDs.

Here we show, for the first time, nanowire QDs frequency-tuned to atomic transitions. We use GaAs QDs controllably grown inside AlGaAs nanowires [3]. We apply an external magnetic field to tune the emission of our QDs to the D_2 transition of ^{87}Rb. We then use the Rb transitions to precisely measure the actual spectral linewidth of QD photons (9.4 μeV), beyond the limit of a high-resolution spectrometer.

Our work therefore brings highly-desirable functionalities to quantum technologies, enabling, for instance, realization of an arbitrary number of nanowire single-photon sources, all operating at the same frequency of an atomic transition.

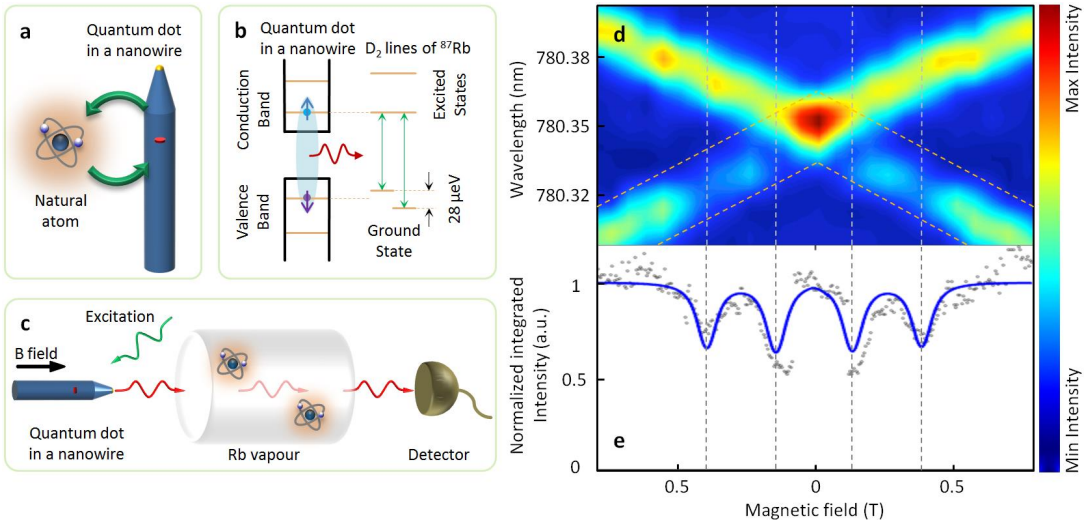

Figure 1: **Nanowire quantum dot tuned to atomic resonances. a)** Schematics of a hybrid system of a nanowire QD and natural atom, and **b)** their energy levels. **c)** Schematics of the experimental setup. **d)** Photoluminescence (PL) spectra of an exciton in a nanowire QD scanned through the atomic transitions. The data is interpolated for clarity. **e)** Transmission of the QD emission through the Rb, obtained by tracing the bottom line in d): experimental data (grey points) and fit of our model (blue line). The fit reveals very narrow emission linewidth of 9.4 μeV.

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[2] H. M. Meyer et al., Phys. Rev. Lett. **114**, 123001 (2015).
[3] C.P. Pedersen et al., In preparation

Systematic study of quantum dot laser emission controlled by coherent phonon wave packets

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Light emission from semiconductor nanostructures placed inside an optical resonator can be greatly modified by coherent phonons. Phonon wave packets shift the laser-active electronic transition with respect to the cavity mode. This can lead to a large enhancement of the emission intensity or to quenching, making phonons attractive for ultrafast control of the light-matter interaction. We here consider an ensemble of quantum dots (QDs) as active medium for which such a control of the light emission has recently been demonstrated experimentally [1]. This method has already been successfully extended to other nanostructures [2,3]. We here develop a theoretical model to study the phonon-controlled emission dynamics of the laser.

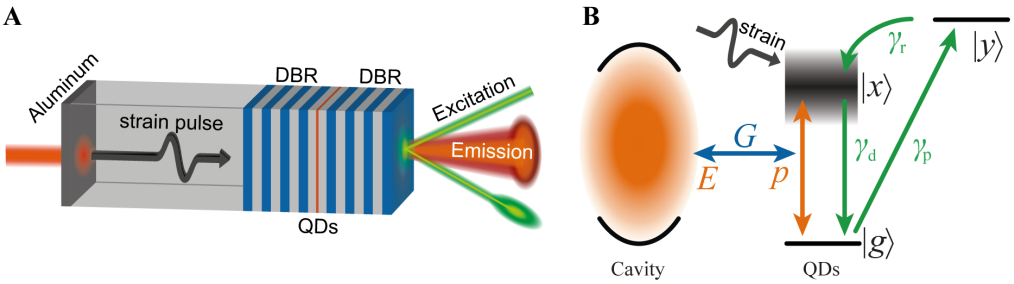

Figure 1: (A) Scheme of the experiment. (B) Sketch of the theoretical model.

In the experiment, which is schematically shown in Fig. 1 (A), the phonons are injected into the system by a strong laser pulse hitting an aluminum surface on the back side of the sample. Due to nonlinear propagation and multi-scattering processes when passing through the distributed Bragg reflector (DBR), the shape of the acoustic field hitting the QDs is quite involved. To fully explore the potential of this method, we develop a semiclassical model of the QD laser as depicted in Fig. 1 (B), which consists of three nonlinearly coupled subsystems: excitons, photons and phonons. Within this model we study how the laser emission is affected by simple and instructive phonon wave packets acting on the QDs. This gives insight into the fundamental interaction dynamics between phonons, excitons and light. In the next step we study the influence of the actual phonon field present in the experiment on the laser emission properties. By choosing different detunings and excitation powers close to the lasing threshold we extend the proof-of-principle experiment [1]. We find an excellent agreement between experiment and theory. Our combined approach helps us to understand the dynamics and interactions in detail which allows to propose new system designs to further optimize phonon controlled light-matter interaction.

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Carrier dynamics in transition metal dichalcogenides

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In the context of the current interest in devices based on transition-metal dichalcogenides, we study the optical generation and relaxation of excited carriers. In these two-dimensional atomically thin semiconductors, the Coulomb interaction is known to be much stronger than in quantum wells of conventional semiconductors like GaAs, as witnessed by the up to 50 times larger exciton binding energy. The question arises, whether this directly translates into equivalently faster carrier-carrier Coulomb scattering of excited carriers. We answer this question by combining ab-initio information about the band-structure and the single-particle wave functions with kinetic equations for the Coulomb-induced carrier scattering in the full Brillouin zone [1]. Our results yield carrier scattering only a factor of 3-4 faster than in GaAs QWs. The left panel of Fig. 1 shows results for the nonequilibrium dynamics of excited carriers due to carrier-carrier Coulomb scattering, indicating a sub-100fs carrier relaxation dynamics, which leads to ultrafast carrier population in different valleys of the band structure.

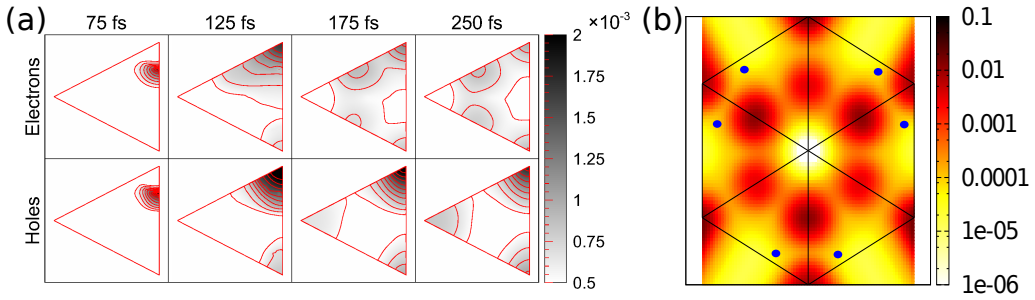

Figure 1: (a) Evolution of the excited-carrier population due to carrier-carrier Coulomb scattering following above band-gap optical excitation. Shown is the irreducible part of the first Brillouin zone for various times. (b) Electron distribution 100fs after above band-gap excitation due to carrier-phonon interaction. The blue dot markes the excitation (similar to the left panel at 75fs) in reciprocal space. The excited carrier density is lower than in the calculation shown in the left panel to focus on effects from the carrier-phonon interaction only. Shown is the full Brillouin zone.

The other main source of carrier relaxation is the interaction of the excited electrons and holes with phonons. To analyze carrier-phonon scattering, we solve kinetic equations, based on ab-initio carrier-phonon interaction matrix elements, both for carriers and phonons, thereby including heating effects due to the excitation of non-equilibrium phonons. In the right panel of Fig. 1 the carrier occupation is shown 100fs after above band-gap excitation and subsequent carrier-phonon relaxation. We find that within 100fs the electrons have relaxed from the excitation (marked by the blue dot) into the K, Σ, K' and Σ' valleys, demostrating fast carrier dynamics, which is accompanied by the generation of non-equilibrium phonons.. This process is followed by carrier cooling on a timescale of about 1ps, which is consistent with recent experimental findings [2,3].

[1] A. Steinhoff, M. Florian, M. Rösner, M. Lorke, T. Wehling, C. Gies and F. Jahnke, arXiv:1603.03633.
[2] Nie et al., ACS Nano **8**, 10931 (2014).
[3] A. Chernikov et al., Nature Photonics **9**, 466 (2015).

A triggered twin-photon source in the solid state

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The realization of an integrated light source capable of emitting an N-photon Fock-state $|N\rangle$ is a fascinating, yet equally challenging task at the heart of quantum optics [1]. Up to now, photon twins, e.g. photon pairs with identical energy and polarization, have mostly been generated using parametric downconversion sources [2] with Poissonian number distributions, or atomic clouds [3] - schemes which require complex and bulky experimental setups and suffer from a limited efficiency.

In this work, we propose and experimentally demonstrate the triggered generation of photon twins by exploiting the energy-degenerate biexciton-exciton (XX-X) radiative cascade of a semiconductor quantum dot (QD). For this purpose, we selected a QD whose exciton's finestructure splitting equals the biexciton binding energy $\Delta E_{FSS} = E_{bin}$ (cf. level scheme in Fig. 1(a)). Fig. 1(b) shows the corresponding energy- and polarization-resolved photoluminescence map of such a QD. In this unique case, one decay path of the XX-X radiative cascade reveals the emission of photon-twins. Deterministically integrated within a microlens, this system emits highly-correlated photon pairs, as demonstrated via measurements of the photon-autocorrelation $g^{(2)}_{auto}(\tau)$ presented in Fig. 1 (c) and (d). Furthermore, two-photon interference experiments reveal a significant degree of indistinguishability of the photon twins, indicating that our source indeed emulates a 2-photon Fock-state $|2\rangle$.

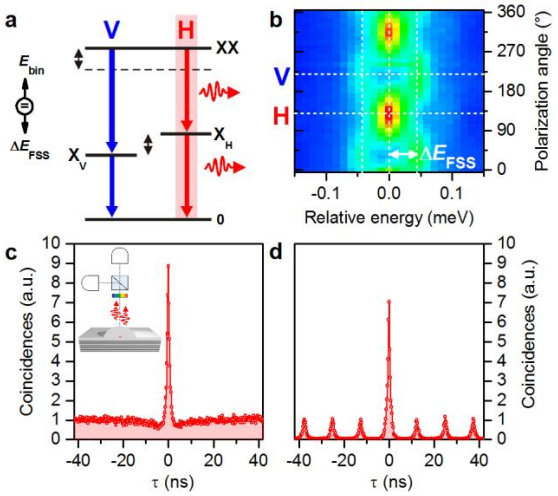

Figure 1: (**a**) Energy level scheme of a XX-X radiative cascade in the case of $\Delta E_{FSS} = E_{bin}$. The emitted photon pairs of one decay path (H-polarization) exhibit identical energy and polarization. (**b**) Polarization- and energy-resolved PL-map of such a twin-photon source. (**c**) and (**d**) Photon-autocorrelation measurements on the energy-degenerate decay channel (H-polarization) in continuous and pulsed excitation, respectively.

The twin-photon source presented in this work is an attractive type of quantum light source, which might be exploited in emerging research fields, such as quantum-optical spectroscopy [4] or quantum biology [5], where the photon statistics are a new degree of freedom.

[1] R. Loudon, The Quantum Theory of Light, Oxford Science Publications (1983).
[2] P. G. Kwiat et al., *Phys. Rev. Lett.* **75**, 4337 (1995).
[3] J. K. Thompson et al., *Science* **313**, 74 (2006).
[4] M. Kira and S. W. Koch, *Phys. Rev. A* **73**, 013813 (2006).
[5] N. Sim et al., *Phys. Rev. Lett.* **109**, 113601 (2012).

Correlation of Carrier Dynamics and Molecular Packing in Pentacene-Perfluropentacene Hybrids

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Aromatic molecules are among the most promising materials in the field of organic optoelectronic due to the favorable properties of delocalized π-electron systems present in those molecules. One of the most studied systems in this material class is the planar molecule pentacene. A promising application for pentacene is the incorporation into a donor-acceptor heterojunction in combination with perfluropentacene. The out-of-plane π-electrons of both materials can lead to significant coupling of both systems, enabling the formation of charge-transfer excitons across the heterointerface. Hence, studying this model system provides the optimal platform to investigate excitation transfer and charge separation in organic solar cells.

Here, we present a comprehensive study on the optical properties of pentacene - perfluropentacene hybrid systems. The samples are grown as thin films in different morphologies. [1] Time resolved luminescence and linear absorption spectroscopy are performed to obtain the carrier dynamics of the charge transfer states and response of the pure materials. The influence of different packing motifs on the optical properties is investigated.

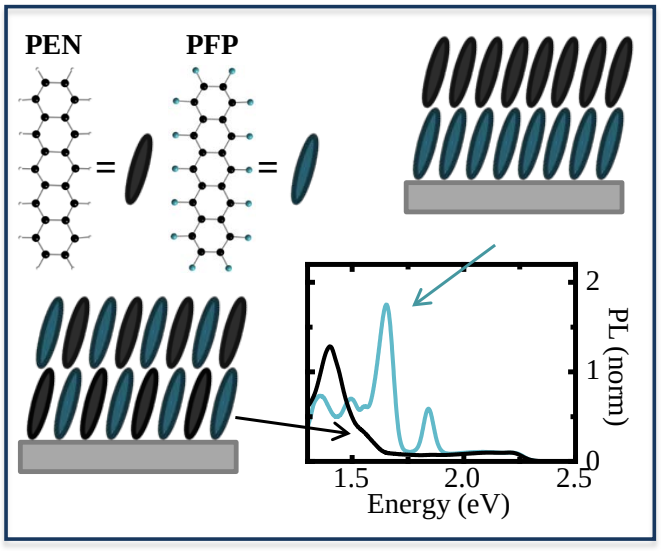

Figure 1: Pentacene and Perfluropentacene hybrid systems and their respective luminescence

[1] Tobias Breuer and Gregor Witte, ACS App Mat Intf, 7, 20485-20492 (2015)

Time-resolved photoluminescence studies of charge transfer states in weakly interacting organic mixtures

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The photophysics of charge transfer (CT) states at donor-acceptor interfaces in molecular heterostructures is a subject of ongoing research and of particular relevance to the field of organic photovoltaics (OPV). In many OPV systems, the CT oscillator strength is weak, but nevertheless, emission from these states can be significant, when they are populated indirectly via singlet excitons from either the donor or the acceptor component. Thus, temperature-dependent measurements of the CT intensity via photoluminescence (PL) spectroscopy can be applied to study these systems, for example to gain insight into the presence of thermally activated non-radiative decay channels. However, from steady-state PL measurements it is difficult to distinguish whether a non-radiative process (i) results from dissociation of the CT states or (ii) emerges from quenching at non-radiative recombination centers at the interface. The latter process requires that the CT states are mobile along the interface. In fact, CT mobility has recently been evidenced in a molecular donor-acceptor system.[1]

In this contribution, we investigate the CT emission in the molecular donor-acceptor system DIP:PDIR-CN2 by means of time-resolved PL over the temperature range between 10 and 290 K. A detailed analysis of the PL dynamics at different emission energies offers insight into the phenomenon of spectral relaxation. Decisively, the PL decay times are found to be similar over a wide range of emission energies. Thus, our results suggest that the CT states are immobile to a large extent. This is further supported by time-resolved measurements of the PL anisotropy, which remains constant over the whole investigated time window of 2 ns. In addition, we have made the important observation that the stability of the CT state increases with an increasing fraction of acceptor molecules, as evidenced by thermal quenching studies.

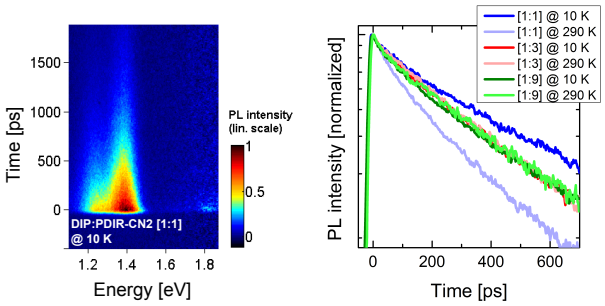

Figure 1: Representative 2D plot of the time-resolved CT PL (left) and PL transients for three different blends recorded at 10 K and at room temperature (right).

[1] P. B. Deotare, W. Chang, E. Hontz, D. N. Congreve, L. Shi, P. D. Reusswig, B. Modtland, M. E. Bahlke, C. K. Lee, A. P.Willard, V. Bulovi, T. Van Voorhis and M. A. Baldo, Nat. Mater. **14**, 1130 (2015).

Generation of indistinguishable single photons from incoherent solid-state emitters

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Important progresses have recently been achieved towards the on-demand generation of perfectly indistinguishable photons from solid-state devices, especially from quantum dots inserted in photonic microcavities [1]. Such experiments involve the bad-cavity regime of cavity-quantum electrodynamics (cavity-QED), in which indistinguishable photon generation requires minimizing the emitter decoherence processes with respect with the emission process into the cavity mode.

Here we propose totally different strategies that allows the generation of indistinguishable single photons in spite of rapid dephasing processes affecting the quantum emitter. The idea is to exploit good-cavity regimes of cavity QED, in which the broad line of a quantum emitter can be spectrally funneled into the narrow line of a high quality factor cavity. We study two different situations. First, in the case of a quantum emitter strongly broadened by pure dephasing processes, we show that arbitrarily high photon indistinguishabilities can be obtained using high-Q cavities, together with efficiencies much higher than using spectral filtering techniques [2]. Second, for emitters featuring optical-phonon sidebands, we show how it is possible to go beyond to combine perfect indistinguishabilities with on-demand efficiencies in spite of rapid dephasing processes. The idea is then to exploit irreversible phonon emission processes within a good-cavity regime of QED. Candidate systems for applying these two novel strategies are proposed, using self-assembled quantum dots or diamond color centers.

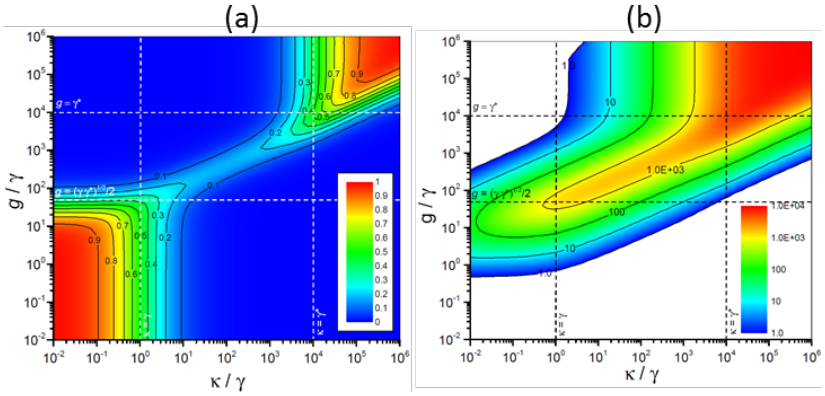

Figure 1: (a) Degree of indistinguishability as a function of the cavity linewidth κ and the coupling g between the quantum emitter and the cavity. The ratio of pure dephasing (γ^*) over decay rate (γ) is kept constant at $\gamma^*/\gamma = 10^4$. (b) Minimal efficiency enhancement with respect to spectral filtering effects for the same range of parameters.

[1] N. Somaschi et al., Nat. Photonics **10**, 340 (2016).

[2] T. Grange, G. Hornecker, D. Hunger, J.-P. Poizat, J.-M. Gerard, P. Senellart, A. Auffèves, Phys. Rev. Lett. **114**, 193601 (2015).

Experimental and theoretical investigations on the transition from spontaneous emission to lasing in high-β microcavity emitters

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The development of low-threshold micro- and nanolasers has become an important interdisciplinary research topic in recent years. Most of the related work focuses on the realization of high-β lasers, which efficiently couple the spontaneous emission of the mostly low-dimensional gain material into the lasing mode, with the ultimate goal of constructing a thresholdless laser. Along with the exciting progress achieved in this respect, a vivid debate about the correct definition of lasing and about the proof of lasing in the limiting regime of thresholdless operation has evolved (see e.g. [1]).

Here, we present a comprehensive study on the transition from spontaneous emission to stimulated emission of quantum dot microcavities in the regime of cavity quantum electrodynamics (cQED) involving measured and calculated results. The structures are based on high-Q, high-β semiconductor GaAs/AlAs micropillar cavities containing a single layer of optically pumped InGaAs quantum dots (QD) as active medium [2]. We focus on structures based on a low number (~10) of QDs in which the particular configuration of the emitters (number and coupling efficiency) decides if the microcavity operates as LED, in the regime of amplified spontaneous emission (ASE), or as high-β laser. Most importantly, we demonstrate that a structure operating in the regime of amplified spontaneous emission can easily been misinterpreted as very high-β laser when inspecting only the io-curve and the excitation power dependence of the emission linewidth. Instead, the autocorrelation function $g^{(2)}(\tau)$ turns out to be a sensitive and reliable indicator of lasing, even towards the limit of thresholdless lasing.

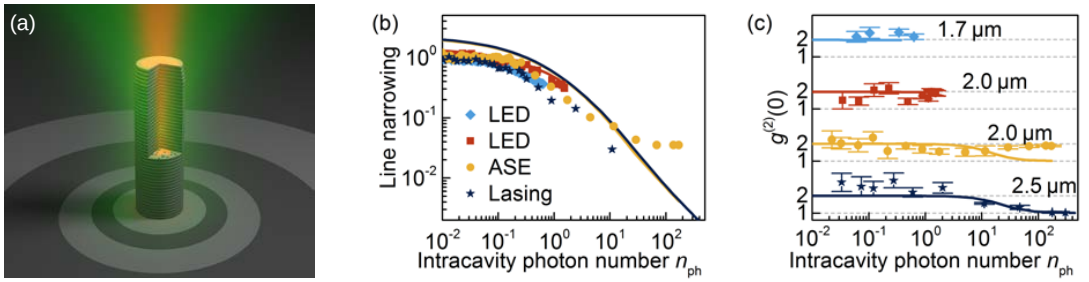

Figure 1: **(a)** Artist's impression of an optically pumped quantum dot GaAs/AlAs micropillar laser. **(b)** Above threshold at $n_{ph} = 1$, the spectral linewidth is inversely proportional to the intracavity photon number. **(c)** The equal-time second order autocorrelation $g^{(2)}(0)$ allows one to distinguish between LED operation (blue and red traces), amplified spontaneous emission (yellow trace), and laser operation (black trace), where $g^{(2)}(0)$ reaches unity above threshold.

[1] W. W. Chow et al., Light: Science & Applications **3**, e201 (2014).
[2] M. Lermer et al., Appl. Phys. Lett. **102**, 052114 (2013).

Excitonic linewidth and coherence lifetime in monolayer transition metal dichalcogenides

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[1] *Technische Universität Berlin, Germany;* [2] *Columbia University, New York, USA;* [3] *Stanford University, USA;* [4] *SLAC National Accelerator Laboratory, Menlo Park, USA;* [5] *Universität Regensburg, Germany;* [6] *Chalmers University of Technology, Gothenburg, Sweden*

Monolayers of transition metal dichalcogenides (TMDs) are direct gap semiconductors with a strong Coulomb interaction resulting in tightly bound excitons, which dominate the optical spectra. The complex electronic bandstructure gives rise to a variety of optically bright and dark excitonic states. Here, we present a joint theory-experiment study focusing on the elementary many particle processes, determining the homogeneous linewidth of excitonic resonances in optical spectra of TMDs. We show that phonon-assisted scattering into dark excitonic states strongly influences the homogeneous linewidth giving insights on the dark exciton configuration of the monolayers.

Our study is based on optical measurements combined with a tight-binding-based Heisenberg equation of motion formalism taking into account all relevant relaxation mechanisms at low excitation densities including radiative decay and exciton-phonon scattering. For our analysis, we focus on two representative TMDs ($MoSe_2$ and WS_2): While in WS_2 the dark excitonic states lie energetically below the bright states, the situation is inverse in $MoSe_2$, cf. Fig. 1 (a). As a direct consequence, the phonon-induced relaxation channels into dark states are very efficient in WS_2. Here, we predict strong scattering $\gamma^{K\Lambda}_{\text{non-rad}}$ even down to ultra-low temperatures inducing a significant phonon-induced homogeneous broadening [1], cf. Fig. 1 (b) . In addition, we find a temperature-independent homogeneous broadening of a few meV due to radiative recombination of the exciton [2]. At room temperature, we demonstrate both in theory and experiment a total homogeneous broadening of excitonic resonances of about 25 meV in WS_2 corresponding to a coherence lifetime of 30 fs, which is one order of magnitude faster than in conventional 2D materials.

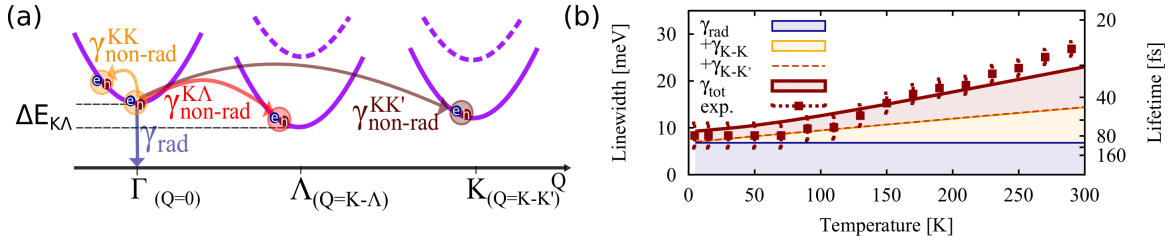

Figure 1: (a) Schematic view on the exciton dispersion in monolayer TMDs including bright ($Q = 0$) and dark ($Q \neq 0$) excitons. The solid lines show the dispersion of WS_2, where the dark states lie energetically below the bright exciton. The dotted lines indicate the different situation in $MoSe_2$. (b) Calculated and measured homogeneous linewidth of the bright exciton in WS_2 separating contributions from radiative coupling and different phonon-induced non-radiative channels.

[1] M. Selig et al., arXiv:1605.03359 (2016).

[2] G. Moody et al., Nature Commun. 6, 8315 (2015).

Optical properties of plasmonic nano-waveguides and their coupling to proximal atomically thin materials

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For practical nanoscale photonic applications, energy efficient light sources with small footprints are of central importance. In recent years, the field of atomically thin, two-dimensional semiconductors has attracted strong interest, both in the field of nano-optics and nano-electronics applications. Combining these novel materials with nano-plasmonic waveguides potentially opens the way to building integrable plasmonic light sources with subwavelength footprints with strong potential for nano-optics and sensing.

Here, we will present numerical simulations and first optical results obtained from monolayer $MoSe_2$ crystals that have been mechanically exfoliated onto plasmonic waveguides. Detailed numerical studies on hybrid plasmon polariton waveguides and slot waveguides are presented. Furthermore, their respective prospects building electrically pumped nanoscale integrated coherent light sources using atomically thin semiconductor layers as gain material are evaluated. These simulations indicate that plasmonic slot waveguides, consisting of two metal stripes separated by a ~80 nm wide dielectric slot, are a particularly promising geometry for such applications. For this geometry, numerical studies of the impact of geometrical scaling reveal easy tunability, stability against fabrication imperfections and threshold gain values for lasing of ~10^4/cm. Such plasmonic structures provide broadband waveguiding in the visible region of the spectrum and at the same time large electromagnetic intensity enhancements of up to 850x in the slot region. Lithographically defined gold slot waveguides were fabricated on silica for stripe width and slot size down to 130 nm and 80 nm, respectively. These structures enable strong transverse confinement of optical fields in the visible region of the spectrum down to $0.02/\lambda^2$ and at the same time exhibit propagation lengths up to 1 µm [1].

At direct contact of a $MoSe_2$ monolayer flake and such a waveguide, unexpectedly large confinement factors of up to 10 are feasible [2] due to the high optical field confinement in this coupled geometry. Optical studies of this coupled system reveal additional spectral features between 1.55 eV and 1.61 eV at the low-energy side of the pristine $MoSe_2$ emission induced by the near-by plasmonic waveguides. Polarization-resolved investigations show degrees of polarization in luminescence of up to 35% and allow us to distinguish different waveguide modes, facilitating the comparison of field enhancements to simulation data. In addition, spatially and spectrally resolved scans show plasmon propagation lengths on the order of ~380 nm, providing clear indication of waveguiding in this coupled geometry.

Last but not least, we will present first investigations of electrically contacted Ag-slot waveguides positioned on monolayer $MoSe_2$, facilitating electrical control and driving of the optical active medium and, thus, paving the way towards an electrically pumped nanoscale light source.

The results presented underpin the opportunity to realize nano-scale light sources based on the combination of nano-plasmonics concepts and atomically thin semiconductor materials for next-generation on-chip photonic circuitry.

[1] M. Blauth *et al.* in preparation (2016).
[2] S.-W. Chang *et al.* IEEE J. Quantum Electron. **45**, 1014 (2009).

Ultrafast electric phase control of a quantum dot exciton

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The excellent optical properties of single InGaAs QDs allow for the realization of new coherent optoelectronic functionalities. Coherent control of excitons in single QDs can be achieved by explioting the nonlinear response of such driven two level sytems. In the past we have already shown in a proof of principle experiment, that the coherent phase of a QD exciton can be manipulated electrically by phase-locked RF signals [1]. To put this concept closer to the application level, we introduce here a hybrid approach towards pulsed electric phase gates, see Fig. 1a. Universal coherent control of an exciton qubit can be achieved by combining occupancy control using optical pulses (red) with phase control using electrical pulses (green). To implement fast electric phase control, we have designed a SiGe:C hetero-bipolar electronic circuit for the generation of ultrafast electric signals, which act as phase gates for a single QD. The employed SiGe:C heterojuction bipolar technology is basically capable to provide rise times down to 3 ps. Our current circuit design generates rise times below 30 ps and it is fully operational at liquid Helium temperatures, see Fig. 1b and 1c. Electric connections between the SiGe chip and the QD photodiode are currently established by short distance wire bonding, see Fig. 1d. This hybrid approach enables us to combine ps double pulse laser excitation with additional fast electric control as an extension to previous Ramsey experiments [2]. We demonstrate a coherent electric phase manipulation over upto 12π, see Fig. 1f, and corresponding nonlinear control of QD occupancy on time scales below the dephasing time of the ground state QD exciton.

[1] S. de Vasconcellos et al., Nature Photonics **4**, 545 (2010).
[2] S. Stufler at al., Phys. Rev. Lett. **96**, 037402 (2006).

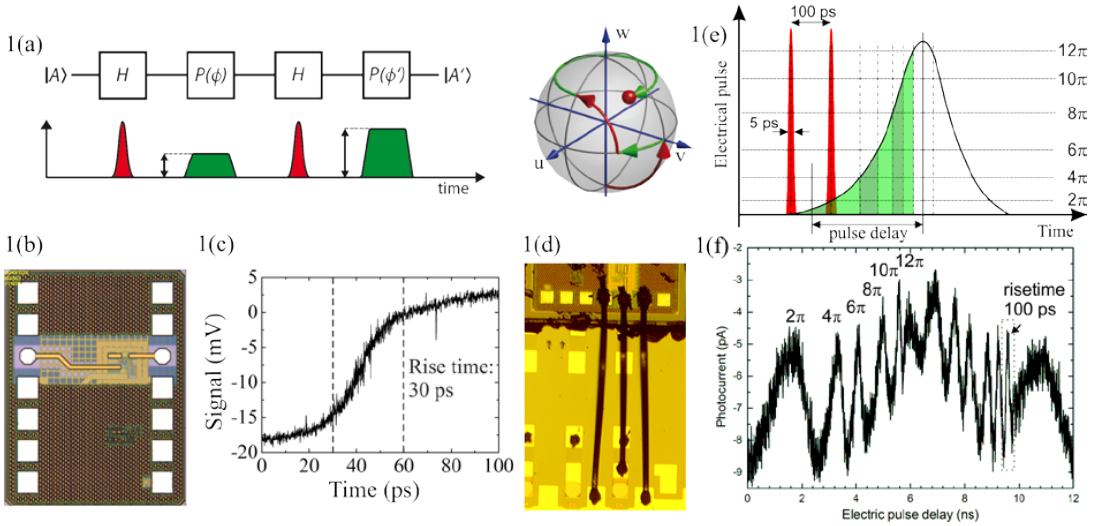

Figure 1: (a) Universal coherent control using optical pulse (red) for occupancy control and electric pulse (green) for phase control. (b) Photograph of SiGe chip. (c) Output signal from the chip (d) QD photodiode wire bonded with chip output, (e) Schematic representation of the electric pulse in the Ramsey experiment, (f) QD-photocurrent representing occupancy as a function of the electric pulse delay.

Bright Solid State Source of Photon Triplets

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[b] *Waterloo Institute for Nanotechnology, University of Waterloo, Ontario, Canada*
[c] *Institut für Experimentalphysik, Universität Innsbruck, Technikerstr. 25, 6020 Innsbruck, Austria*
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Producing advanced quantum states of light is a priority in quantum information technologies. While remarkable progress has been made on single photons and photon pairs, multipartite correlated photon states are usually produced in purely optical systems by postselection or cascading, with extremely low efficiency and exponentially poor scaling. Multipartite states enable improved tests of the foundations of quantum mechanics as well as implementations of complex quantum optical networks and protocols. It would be favorable to directly generate these states using solid state systems, for better scaling, simpler handling, and the promise of reversible transfer of quantum information between stationary and flying qubits. Here we use the ground states of two optically active coupled quantum dots to directly produce photon triplets.

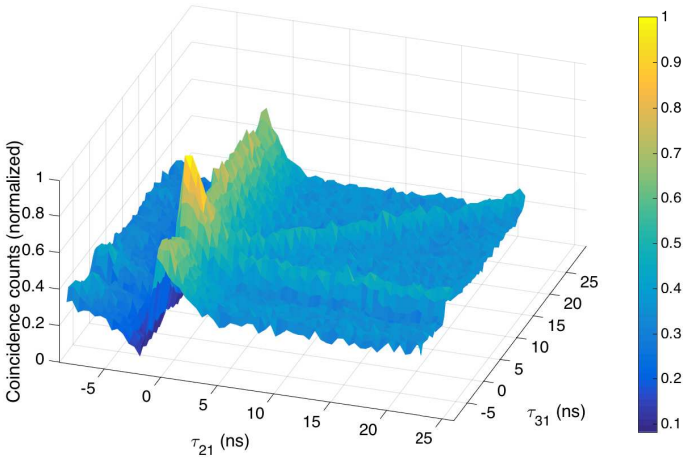

Figure 1: The triple coincidence histogram (total recording time 3 h) was measured at PD = 460 mW/mm2 and is plotted versus τ_{21} and τ_{31}, linearly interpolated with a color-mapped surface. The threefold coincidence peak near the origin signifies the strong temporal correlations of the emitted photons.

The wavefunctions of photogenerated excitons localized in these ground states are correlated via molecular hybridization and Coulomb interactions. The formation of a triexciton leads to a triple cascade recombination and sequential emission of three photons with strong correlations. We record 65.62 photon triplets per minute, surpassing rates of all earlier reported sources, in spite of the moderate efficiency of our detectors. Our structure and data represent a breakthrough towards implementing multipartite photon entanglement and multi-qubit readout schemes in solid state devices, suitable for integrated quantum information processing.

Coherence of excitation and degree of time-bin entanglement from quantum dots

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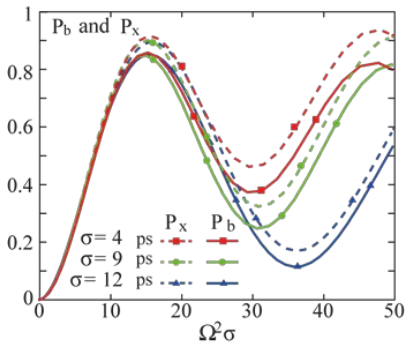
[a]*Institut für Experimentalphysik, Universität Innsbruck, Innsbruck, Austria*
[b]*Institut für Theoretische Physik, Universität Innsbruck, Innsbruck, Austria*
[c]*Joint Quantum Institute, National Institute of Standards and Technology and University of Maryland, Gaithersburg, Maryland 20849, USA*
[d]*Institute for Quantum Optics, University of Ulm, Ulm, Germany*

An on-demand generation of photon pairs in quantum dot systems requires deterministic population of the biexciton state, which in principle can be done by coherent two-photon excitation [1]. We performed a theoretical and experimental investigation of the excitation requirements for generation of deterministic photon pairs. These also happen to be the prerequisite for generating coherent superposition of the ground and the biexciton state, which is an essential requirement for the generation of time-bin entanglement [2].



Pulse length (ps)	Concurrence	Fidelity	Coherence
4	0.56(7)	0.78(3)	−0.28(3)
9	0.71(6)	0.83(3)	−0.36(3)
12	0.78(6)	0.88(3)	−0.39(3)
15	0.78(5)	0.88(3)	−0.40(3)
20	0.61(5)	0.80(3)	−0.32(3)

Figure 1. (left) Rabi oscillations (theory) for constant dephasing as a function of $\Omega^2\sigma$, where Ω is the Rabi frequency and σ the pulse length. The emission probabilities for the biexciton, Pb (solid), and the exciton, Px (dashed), levels are shown. The Rabi oscillation damping is strongly dependent on the length of the excitation pulse. (right) Values for the fidelity of the time-bin entangled with the maximally entangled Bell state, concurrence, and coherence (maximal off-diagonal element of the density matrix) for five different excitation pulse lengths.

Our results indicate very strong dependence of the coherence of the process on the length of the applied excitation pulse (shown in Figure 1). Particularly, an efficient and coherent excitation of the biexciton requires elimination of the single exciton probability amplitude in the excitation pulse and reaching the lowest possible degree of dephasing caused by the laser excitation. These two conditions impose contradictory demands regarding the excitation pulse-length and its intensity. We demonstrate that there is an optimized operation regime for the system under consideration. Furthermore, using optimized pulse length we reach record fidelities for time-bin entanglement obtained in quantum dot systems. We show that an optimal excitation process requires a trade-off between the biexciton binding energy and the excitation laser pulse length. It favors the use of quantum dots with large biexciton binding energy that in return allow for use of short excitation pulses.

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Ultra-low power all-optical switch using a single quantum dot embedded in a photonic wire

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We present experimental results on two-mode optical giant non-linearity of a single InAs quantum dot (QD) embedded in a GaAs tapered photonic wire (fig. 1a). This system, in which the QD is efficiently coupled to a single guided mode, has been exploited to realize ultrabright single-photon sources [1,2]. We exploit here its broad operation bandwidth (>100 nm around 950 nm) to efficiently address two different transitions of the QD with two different laser beams (fig. 1b) to implement a two-color giant non-linearity: a weak probe laser coupled to the upper transition has its reflectivity controlled by a few photons of the control laser.

By performing a reflectivity experiment, we show that a control laser of 10 nW (50 photons per emitter lifetime) can modify the transmission of the probe laser, realizing an ultra-low power all-optical switch (fig. 1c).

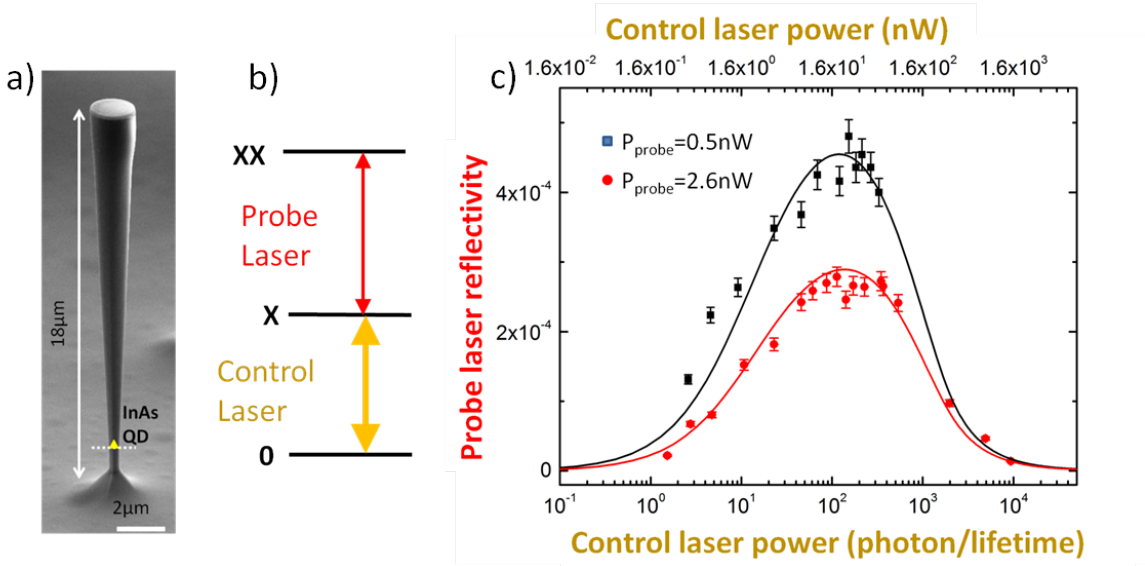

Figure 1. *(a) Scanning electron microscope image of a trumpet like photonic wire. (b) Energy scheme for a quantum dot three-level system with the control and probe laser respectively on resonance with the excitonic (0-X) and biexcitonic (X-XX) transitions. (c) The reflectivity of the probe laser depends on the control laser power. The probe reflectivity can be turned on by an ultra-low control laser power (10 photons/lifetime~2nW).*

[1] J. Claudon et al, *"A highly efficient single-photon source based on a quantum dot in a photonic nanowire "*, Nat. Phot. **4**, 174 (2010)

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Spatio-temporal evolution of electronic wavepackets in one-dimensional nanosystems

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Exploiting flying electronic wavepackets to encode information offers an electronic alternative to photon-based quantum information processing. For this purpose it is crucial to have spatially localized electron distributions [1]: Here we compare their propagation in one-dimensional nanosystems with different electronic spectra, i.e. parabolic vs. linear. In parabolic materials, such as quantum wires or semiconducting single-walled carbon nanotubes (SWNTs), even without scattering a traveling wavepacket experiences a spatial broadening, which could limit the operation timescale. In contrast, in systems such as the metallic SWNTs the linear spectrum guarantees unaltered travels along the SWNT (see the thin lines in Fig. 1), at least in the absence of scattering mechanisms.

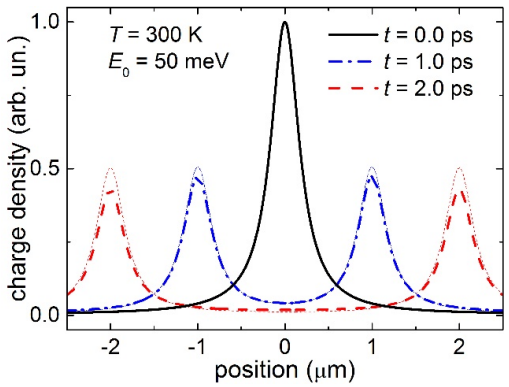

Figure 1: Room-temperature propagation of an electronic wavepacket along a metallic SWNT: the thick (thin) curves show the evolution with (without) electron-phonon coupling.

Implementation in realistic devices requires to determine the impact on the propagation of electron-phonon mechanisms, which are indicated by experiments as the main source of scattering at intermediate and room temperature in SWNTs [2]. In order to properly describe the nontrivial interplay between coherence and scattering-induced dissipation/decoherence, we adopt the non-linear Lindblad-based density-matrix approach recently proposed in [3].

Considering a spatially localized nonequilibrium electronic distribution centered around an excess energy E_0 in a metallic SWNT, we present a detailed analysis of its evolution in the presence of electron-phonon coupling [4]. Similarly to the case of an equilibrium carrier distribution [5], for reasonable E_0 also in this nonequilibrium case the shape of electronic wavepackets remains essentially unaltered up to micron distances at room temperature (see Fig. 1), in spite of the significant energy-dissipation and decoherence dynamics induced by the electron-phonon coupling on the nonequilibrium excitation [4]. This dispersionless propagation happens due to a cancelation between various intraband scattering contributions. Such a cancellation is a key feature of the linear spectrum and is not in general present in parabolic systems, where its absence further speeds-up the scattering-free spatial broadening [6]. We thus conclude that metallic SWNTs are a promising platform for the non-dispersive transmission of electronic wavepackets.

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[4] R. Rosati, F. Dolcini, and F. Rossi, Phys. Rev. B 92, 235423 (2015).
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Excitation-energy dependent carrier dynamics in silicon

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Silicon is a prime candidate material for spin-based electronics and quantum information technology. Recent theories predict that spin polarization can be realized using selection rules for phonon-assisted transitions near the indirect band gap of silicon [1], while experimental investigations of optical spin orientation across an indirect band gap are scarce [2]. In this presentation, we will report on a new type of carrier generation via a phonon-assisted transition in high-purity silicon revealed by time-resolved cyclotron resonance (TRCR).

We have developed the TRCR method as a unique tool to investigate carrier relaxation dynamics as well as effective mass anisotropy and carrier drift mobility [3,4]. Further, the CR signals measured as a function of excitation photon energy provide an excitation spectrum which helps clarifying the energy structure of exciton levels [5]. For optical carrier injection near the indirect absorption edge of silicon (hν=1.1－1.2 eV), we used nanosecond laser pulses from an optical parametric oscillator. The sample was placed in a dielectric cavity under a magnetic field resonant to the light hole (B=0.0488 T), and transient absorption of the X-band microwave was measured by an oscilloscope.

The inset of Fig. 1 shows a contour plot of the transient CR signals obtained at 10 K for various excitation photon energies. The transients were strongly dependent on the excitation photon energy. By extracting the signal amplitude at a fixed time delay *t*, we obtained CR excitation spectra as shown in Fig. 1. The solid line clearly indicates the transverse-acoustic phonon assisted transition to the indirect band gap, implying generation of free carriers at t < 20 ns, which is usually masked by absorption to the exciton state observed at later times (the dotted line). As the difference of the two edges, exciton binding energy of 14.7 meV was obtained. The two distinct features (a, b) in the decay dynamics, as shown in Fig. 2, were ascribed to free carriers and excitons, respectively.

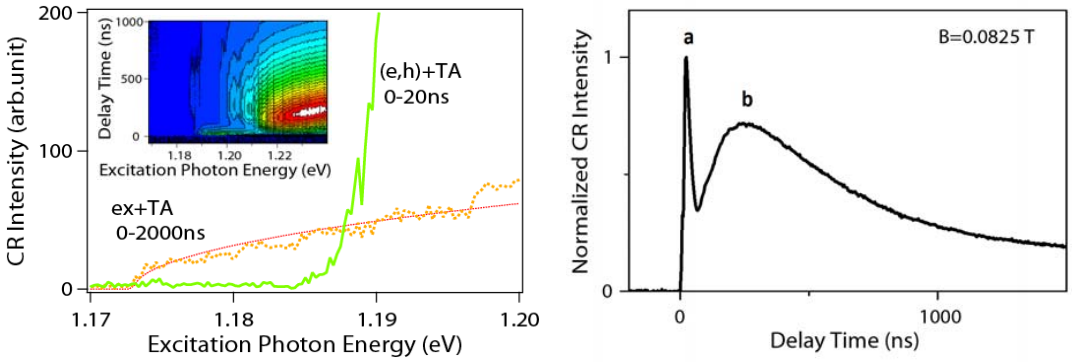

Figure 1 (left): CR excitation spectra at 10 K for delay times 0-20 ns (solid line) and 0-2000 ns (dotted line). Inset shows contour plot of CR signal intensity as a function of delay time and excitation photon energy.
Figure 2 (right): Example of CR transient at the electron resonance under photo-excitation at 1.20 eV.

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Nonlocal coupling of light and weakly confined excitons in Cu_2O thin films

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Recent observation of light-coupling modes of confined excitons in high-quality thin-film semiconductor [1] has been attracting attention as a novel optical response due to nonlocal coupling of excitons with light. This coupling occurs beyond the long wavelength approximation and modifies radiative recombination rates, when excitons having long-range coherence are confined within a dimension comparable with the wavelength of light. In this study, we find out a systematic thickness dependence of the radiative recombination rate of 2p excitons in Cu_2O, known for giant Rydberg exciton states [2].

A high-quality Cu_2O thin film with monotonically varying thickness (16-2500 nm) [3] was mounted on a piezo stage incorporating an aspherical lens of N.A. = 0.60 in a helium bath cryostat. The thickness resolution was 4 nm. Figure 1(a) shows photoluminescence (PL) spectra of the yellow exciton series under continuous-wave excitation at 2.33 eV. The PL intensity and the PL spectral width (FWHM) of 2p excitons periodically varied depending on the film thickness. As shown by squares and circles in Fig. 1(b), the peaks of the FWHM appeared at thicknesses different from those for the intensity peaks. The oscillating PL intensity is explained by multiple reflections of the incident light and PL (the solid line in Fig. 1b). The varying FWHM is reproduced by the radiative width calculated using the Green's function approach [4] to the nonlocal response caused by the interaction between weakly confined excitons (the dotted lines). The good agreement between the experimental results and calculations, including the difference between the peaks in the PL intensity and the FWHM, clearly demonstrates that the radiative recombination rate of 2p excitons is enhanced due to the nonlocal response depending on the film thickness.

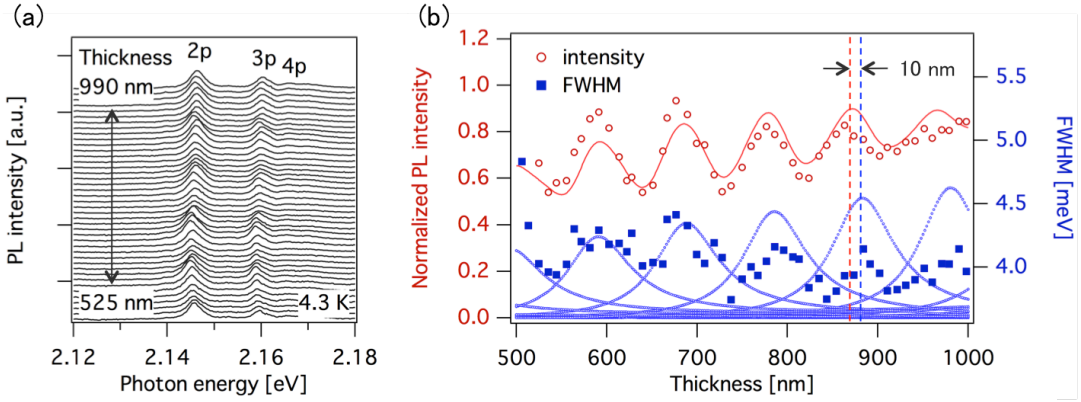

Figure 1: (a) PL spectra of a Cu_2O thin film at 4.3 K, measured in steps of about 10 nm thickness. (b) Thickness dependence of intensity (red circles) and FWHM (blue squares) of 2p exciton PL in comparison with calculations assuming multiple reflections (solid line) and nonlocal response (dotted line).

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Charge carrier dynamics at the Pentacene - C_{60} interface

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Organic molecular solids feature various properties considered advantageous for next-generation photovoltaic devices such as mechanical flexibility and ease of fabrication by, e.g., large-scale and large volume printing. Additionally, Singlet-Exciton Fission may allow surpassing the Shockley-Queisser limit. Here, one photoexcited singlet-type exciton decays into two triplet-type excitons, effectively doubling the number of excited charge carriers. Hence, above-unity quantum efficiencies may be achieved in photovoltaics and have been reported in for example, pentacene (PEN) –C_{60} heterojunctions[1].
Here, we study the carrier dynamics at well-defined PEN-C_{60} interface model systems by time-resolved photoluminescence spectroscopy experiments for different excitation photon energies. Thereby, we disentangle charge transfer and excitation dynamics, i.e., injection, transport, dissociation, and extraction.
The photoluminescence spectra reveal two distinct transition energies associated with charge-transfer states expected from photoelectron spectroscopy experiments [2]. These long-lived transitions show a clear dependence on excitation energy, corroborating the proposed CT transitions and revealing the fact that carriers need to be created in both individual constituents for CT transitions to be observable.
Additionally, the C_{60} photoluminescence efficiency strongly quenches for increasing PEN coverage while the lifetime is drastically enhanced (Fig. 1) yielding strong evidence for an electron transfer between the PEN ground state and C_{60} when only the latter is photoexcited.

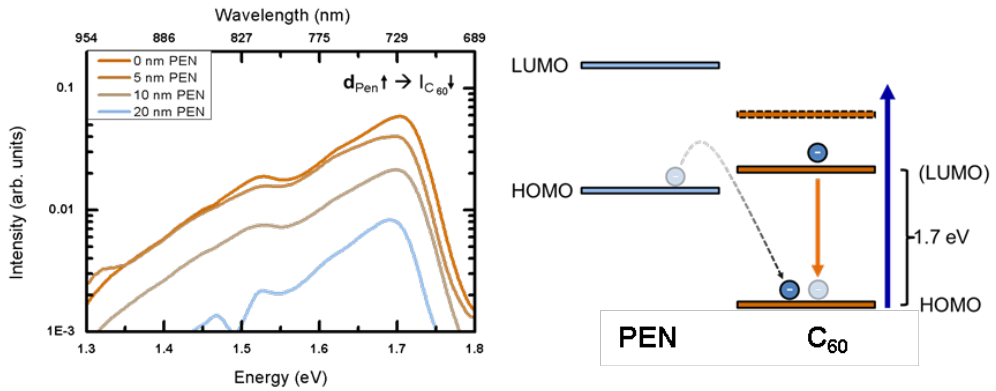

Figure 1: Photoluminescence efficiencies for different PEN coverages of bulk crystalline C_{60} (l.h.s.) and proposed electron-transfer mechanism at the PEN-C_{60} interface.

[1] D. N. Congreve et al., Science 340, 334–337 (2013).
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The study of thermal dissociation of acceptor-bound positively charged excitons in GaAs/Ga1-xAlxAs quantum wells

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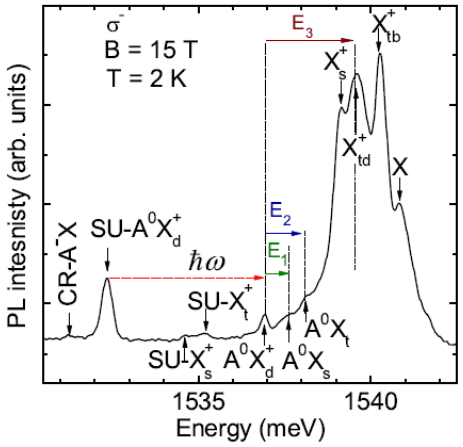

Fig. 1. Comparison of activation energies of dissociation processes with PL spectra.

The three-particle system of fermions, bound by Coulomb interaction are fundamental problem in nuclear, atomic and solid-state physics. Negative and positive trions (X^- =2e+h or X^+=2h+e), analogs of the negative hydrogen ion (H^-) and the positive hydrogen molecule (H^+_2), have been successfully detected in the two dimensional (2D) structures. All investigations of 2D trions were performed at low temperatures, mainly due to their small binding energy. However, temperature dependent emission investigations of trions, free or bound on impurities, may provide valuable information on trion physical properties. Here, we study the thermal dissociation of free and acceptor-bound positive trions by measurements of temperature dependence of the integrated emission in high magnetic fields up to 17 T in superior quality GaAs quantum wells with 2D hole gas. Three dissociation processes are observed for the well-resolved hole cyclotron replicas ("shake-up") of positive trions bound to neutral acceptors in the hole spin-doublet state (SU-$A^0X^+_d$). To proof that the hole involved in the shake-up process is not bound by the Coulomb interaction to the charged A^0X^+ complex, we have performed numerical calculations of the valence band Landau levels in the Luttinger model beyond the axial approximation. The calculated value of the hole cyclotron energy agrees well with the experimental value of the energy separation of the AX^+ and SU-AX^+ lines determined from the PL spectra. At low temperatures, below 6 K, the dominant dissociation results in a free hole and the exciton bound to the neutral acceptor in the hole spin-singlet or -triplet state ($A^0X^+_d \rightarrow A^0X_s$+h or A^0X_t+h). At higher temperatures, above 9 K, the dissociation into the free positive trion and the neutral acceptor ($A^0X^+_d \rightarrow A^0+X^+$) predominates. From the temperature evolution of the integrated emission of free trion lines (X^+) we evaluated transition energy between two triplet trion states: dark (X^+_{td}) and bright (X^+_{tb}). The ionization energies of all detected dissociation processes are compared with the spectral positions of relevant radiative recombination lines and an excellent quantitative agreement was achieved.

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Two-color two-photon biexciton generation in single quantum dots

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Quantum dots are among the best controlled solid state emitters at the single photon level. One particular area of interest is the generation of single photons at emission wavelength different from the excitation wavelength using nonlinear two-photon transitions between the ground state and the biexciton state of quantum dots. A promising approach to gain even more control over the emission wavelength and polarization is to generate single photons by a stimulated downconversion process from the biexciton state. [1] As preliminary work, we performed degenerate (one-color) and nondegenerate (two-color) resonant two-photon biexciton generation in InGaAs-quantum dots embedded in a n-i-Schottky-photodiode. This allows for detection of the resulting excitations in the photocurrent with good accuracy. We demonstrate two-color two-photon excitation of the biexciton state and compare it to the degenerate process, see Fig.1. We use cw-excitation as it allows higher spectral resolution in comparison to pulsed excitation. Furthermore, we measure the biexciton peak amplitude as function of the energy separation between the two excitation lasers in a regime up to 4.32 meV.

[1] D. Heinze et al., Nature Communications **6**, 8473 (2015).

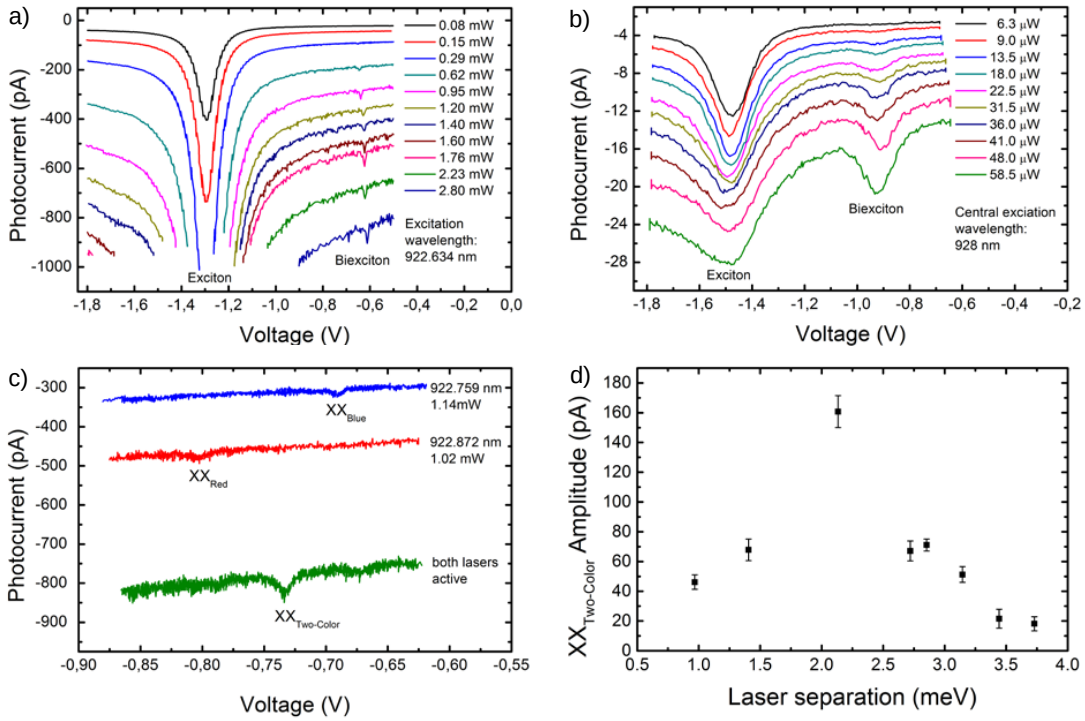

Figure 1: Photocurrent measurement with a) cw-excitation b) pulsed excitation c) Two-color two-photon excitation of biexciton d) Dependence of two-color two-photon excitation of biexciton on laser separation

Polygon patterns in a polariton parametric oscillator

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Nonequilibrium pattern formation in open systems occurs ubiquitously in nature, from the self-organization of cells in biology and self-assembly of molecules in chemistry, to liquid crystal ordering in physics. The theoretical foundation, first elucidated by Alan Turing[1], also applies to optical systems, where the interplay between diffraction of light, rather than diffusion of chemical species, and nonlinearity leads to spontaneous symmetry-breaking and the formation of stationary structures. With a combination of diffractive spatial propagation and giant $\chi^{(3)}$ nonlinearity[2], exciton-polaritons offer a unique platform for studying pattern formation.

Here we study a coherent polariton fluid in a GaAs microcavity with three $In_{0.04}GaAs$ quantum wells, pumped at normal incidence by circularly polarized 100 ps pulses, blue-detuned from the bottom of the lower polariton branch (LPB). Above some critical pumping power, the system becomes unstable against the growth of small perturbations generated by incoherent scattering processes. As confirmed by a linear stability analysis, signal and idler modes with nonzero orbital angular momentum experience positive growth rates as the system enters a regime of energy-degenerate optical parametric oscillation (OPO), breaking the azimuthal symmetry of the density distribution and generating transverse polygon patterns. Simultaneously, a renormalization of the polariton dispersion occurs as the fluid density increases, causing a second threshold at higher pumping powers as the LPB ground state blueshifts into resonance with the pump. At this threshold, bistable behavior is evidenced by second order correlation function measurements where a sharp jump in the value of $g^{(2)}(0)$ from 1 to 2 is observed, indicating a stochastic fluctuation of the internal polariton field between the lower and upper bistable branches. This behavior can be reproduced by a simple three-mode OPO model.

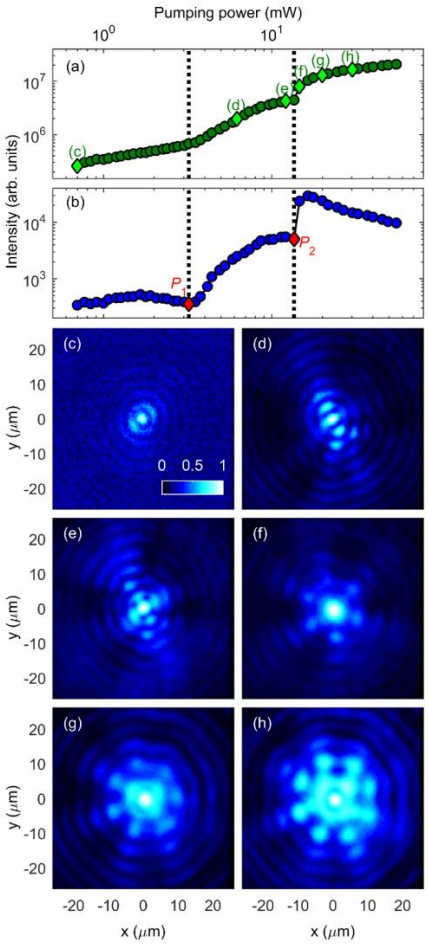

FIG. 1. Integrated (a) and peak (b) emission intensity against pumping power. At low pumping powers the real space density distribution has azimuthal symmetry (c). Above the parametric scattering threshold (P_1) patterns with two (d) and four (e) bright lobes are generated. Above the bistable threshold (P_2) patterns with six (f), seven (g) and eight (h) bright lobes are observed.

The polariton picosecond response time combined with demonstration of controllable switching between different stable pattern states makes this system a suitable candidate for ultrafast optical switching applications.

[1] Turing, A. Phil. Trans. R. Soc. Lond. B 237, 37-72 (1952).
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Giant Nonlinear Spatio-Temporal Modulation in Polaritonic Waveguides

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Strong coupling of photons to quantum well (QW) excitons leads to the formation of hybrid light-matter quasiparticles, so-called exciton-polaritons. These experience interparticle nonlinear interactions at least three orders of magnitude larger than photons in any other nonlinear medium [2]. Exciton polaritons have been studied intensively in Bragg microcavities where condensates, quantized vortices and separate temporal and spatial solitons were observed. Compared to those works our waveguide system [1] exhibits an order of magnitude larger velocity and propagation distance, comparable to typical waveguides in the nonlinear optics field [3,4]. In this work we discuss novel spatio-temporal polariton solitons [2], self-phase modulation (SPM) and quasi-continuum generation in polaritonic waveguides. We observe strong nonlinear modulation at pico-Joule pulse energies on 100-600 μm length scales.

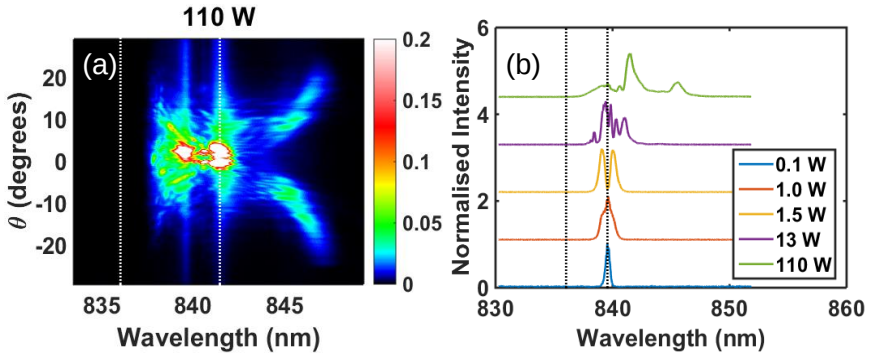

FIG. 1. (a) Inter-dependent spatio-temporal spectra at high pulse power. (b) Spectra at $\theta = 0$ vs. peak power. SPM is followed by more complex evolution and quasi-continuum at 110 W.

Pulses between 0.3 ps and 2ps with 20 μm spatial envelope were injected into a GaAs waveguide containing three $In_{0.04}GaAs$ QWs and cooled to 10 K. When the nonlinear (L_{NL}), dispersion (L_D) and diffraction (L_{DF}) lengths are all on the order of 40 microns we observe bright temporal solitons and temporally-bright spatially-dark spatio-temporal solitons [2]. When L_{NL} is much shorter than L_D and L_{DF} we observe a novel spatio-temporal cross-modulation where the spectrum and angle-spectrum become inter-dependent. For pulses with peak power of 1.5 W the spectrum evolves to the characteristic SPM spectrum for a 1.5π phase shift after 600 μm propagation [3]. For 110 W pulses the spectrum broadens by a factor of 20 forming a quasi-continuum with width 15 meV comparable to the Rabi splitting.

The strong spatio-temporal effects on short length scales are made possible because the nonlinearity is so large that no transverse mode confinement is required to enhance the optical field. We also observe that in the CW regime the polariton induced nonlinearity is another order of magnitude larger again compared to the ps pulsed regime. These results highlight the novel nature of the polaritonic nonlinearity and the utility of this system for the study of spatio-temporal nonlinear phenomena [4] and development of potential optoelectronic devices.

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The influence of Coulomb attraction on the carrier diffusion in semiconductors of mixed dimensionality

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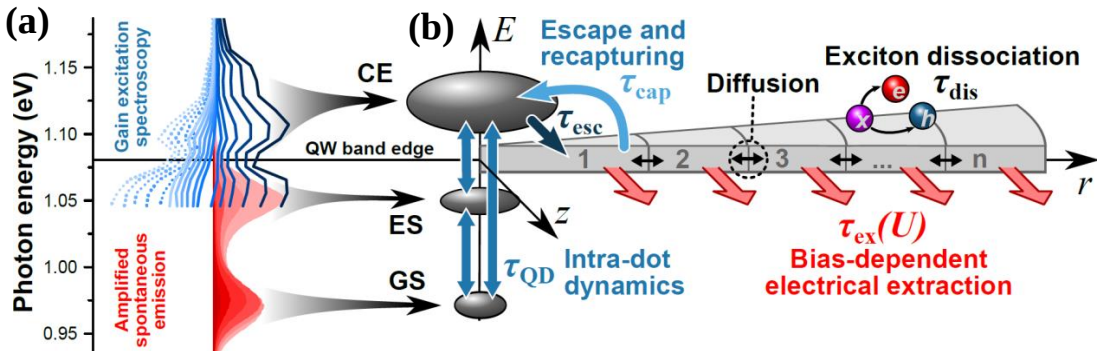

Figure 1: (a) While QD ground and excited state (GS and ES) are obvious in amplified spontaneous emission (filled red), gain excitation spectroscopy (bold blue) reveals crossed excitons (CEs) [3], i.e. Coulomb-bound states even above the QW band edge. From low to high injection currents (dark to light color), a persistent structure is observed, indicating an immediate response of the QD GS at specific excitation energies. (b) A rate equation model implementing these states and diffusive coupling via the QW resembles a broad set of pump-probe curves. An external extraction potential is used to proof the validity of the model under different conditions. [2]

Spatial mobility of carriers in nanostructured semiconductors is a critical parameter in nano-photonics, both for light emitting and collecting devices. Coulomb correlation between confined and continuum states modifies the energy structure [1] by formation of crossed excitons (CEs) and can influence the diffusion dynamics by keeping continuum carriers localized. As a prototypical nanostructured system we use Stranski-Krastanov grown InAs quantum dots (QDs) in an In(Ga)As quantum well (QW). The dot-in-a-well system is embedded in the *pin*-structure of a semiconductor optical amplifier (SOA). An efficient two-color heterodyne pump-probe (PP) setup including simultaneous multi-power measurements [2] enables us to acquire and analyze a large amount of data to extract hidden dependencies.

The presence of CEs located around the QD is confirmed by gain excitation spectroscopy (Fig. 1a): From 168 PP curves (pumping around QW band edge, probing the QD GS) reduced to their immediate response (<1 ps) we extract the spectral distribution of CEs [3]. The impact of the CEs on the carrier dynamics is demonstrated for the “solar cell case” (external potential set to carrier extraction). We fit a rate equation model (Fig. 1b) to 178 PP curves under varying excitation and extraction conditions. The model implements CEs as an intermediate state between QD and QW. Diffusive inter-dot coupling mediated by the QW is integrated by a random walk. Three carrier types (electrons, holes, and excitons) and three spectral sub-ensembles are considered. The model shows excellent agreement when diffusion is dominated by excitons rather than by single carriers [2]. Beyond this, ongoing investigations of the complex energy structure using the Frequency-Resolved Optical Short-pulse Characterization by Heterodyning (FROSCH) technique [4] will be presented.

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Nonlinear modulation response of PbS/CdS quantum dots to excitation with high repetition rate

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Due to their adaptiveness and scalable production, colloidal quantum dots are attractive as active media in nanophotonics. We investigate the response of PbS/CdS core-shell nanocrystals to an optical excitation at high repetition rate, mimicking the application in fast all-optical data processing and wavelength conversion. The PbS/CdS material system is attractive for nanophotonics, as the emission wavelength can be tuned through the telecommunications spectral windows. As for all colloidal quantum dots, however, the long lifetime of the ground state exciton enforces using a nonlinear interaction for all fast switching and modulation purposes.

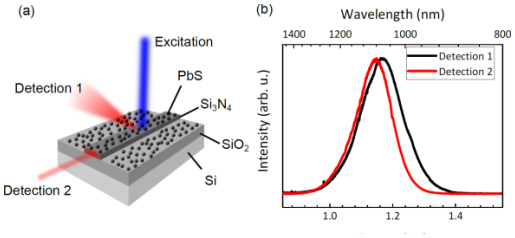

Figure 1: (a) Device geometry. (b) Quantum dot luminescence

We investigate the response of a hybrid photonic device composed of a silicon nitride waveguide coated with a layer of quantum dots to an optical perturbation with high repetition rate. Silicon nitride does not display large intrinsic nonlinearities, and thus allows to isolate the quantum dot response from the waveguide response.

To resolve the small signal in amplitude and phase, we implement sideband pump-probe spectroscopy. The basis is the traditional heterodyne pump-probe setup with balanced detection, but we add an additional fast modulation of the pump and detect the ratio of the resulting beat to the heterodyne signal. The method is largely insensitive to laboratory drifts, and allows to resolve differential transmission changes of the order of 10^{-5}, and phase changes of the order of arcseconds.

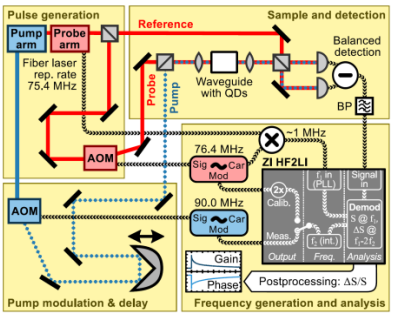

Figure 2: Sideband pump-probe spectroscopy

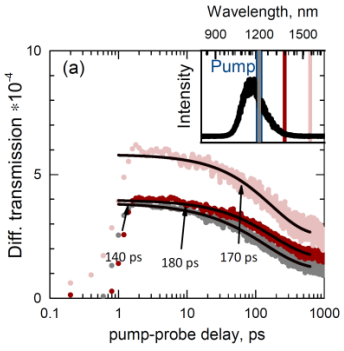

Figure 3: Differential transmission of hybrid QD/SiN waveguides

The differential amplitude changes induced by the interaction of the PbS/CdS quantum dots to an excitation with a repetition rate of 75.4 MHz is shown in Fig. 3. The traces can be fitted with stretched exponential decays with time constants typical for the decay of the biexciton in these structures. A closer analysis of the phase response reveals the presence of a second nonlinear process taking place preferentially at long wavelengths close to or in the band gap. This is interpreted as an interband contribution to the signal.

Nuclear spin dynamics in bulk n-GaAs

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Controlling and manipulation of nuclear spins in semiconductor is an important issue of both techonological and fundamental science. First experimental evidence of electron and nuclear spin orientation in semiconductors has been provided 50 years ago [1]. Early studies on bulk semiconductors demonstrated that combining optical pumping with certain external magnetic field makes it possible to achieve a very small temperatures of the Nuclear Spin System (NSS), below lattice temperature [2]. Such a precise control over NSS would give a new possibilities for semiconductor spintronics, where the long lifetime of the spin states can be used to create a qubit.

In this work, we investigate the short and long lifetimes of the NSS dynamics in bulk n - type GaAs in different external magnetic fields (between 10 and 500 mT) and modulation of excitation polarization. It allows us to investigate mechanisms of the nuclear spin relaxation of the nuclear spin bath in the vicinity of the donors.

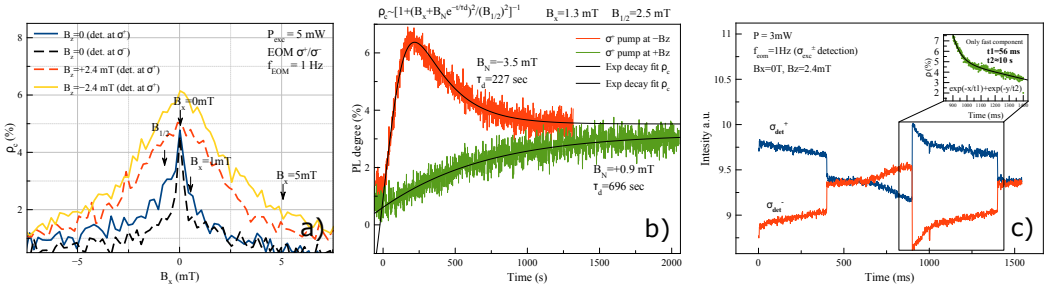

Figure 1. **(a) Hanle depolarization curve, (b) slow time evolution of the electron spin polarization, (c) NSS relaxation curve with circular polarization evolution (inset).**

In order to investigate the spin relaxation times, we make use of the time-resolved polarized photoluminescence (PL) detection. The PL is excited with Ti:Sapphire laser tuned to an absorbtion band of GaAs at 800 nm. The degree of circular polarization, ρ_c, is analyzed with a standard modulation technique at frequency of modulation, $f = 50$ kHz, determined by the resonant photo-elastic device. The PL is dispersed by 0.5 m monochromator, and detected with a single-photon counter at photon energy of D_0X transition. The main results are summarized in Fig. 1. Figure 1(a) shows the Hanle depolarization curve of the electron spin in transverse magnetic field measured at modluated helicity of optical excitation. Figure 1(b) demonstrate the slow time evolution of the electron spin polarization in a small transverse magnetic field initiated after a long-term cooling of the NSS in a longitudinal magnetic field. Fitting of the electron spin depolarization with an analytical function representing the Hanle contour allows us to extract the times of the NSS relaxation determined by the spin diffusion. The processes of the nuclear spin relaxation of the NSS within the vicinity of the donors are investigated under sub-second modulation of the optical excitation. The results of such an experiment are represented in Fig. 1(c). Fitting of the data resolves a bi-exponential decay with the fast component relaxation ranged between 100 ms to 10 s. A discussion of the possible mechanisms of such a fast NSS relaxation is provided.

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Free induction decay cutoff in Brewster angle reflection spectroscopy

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Ultrafast coherent control of excitons in A3B5 quantum wells (QWs) could be used for optical computing. Free induction decay (FID) indicates the ability of a system to conserve optical phase coherence. Induction of the 2D layer of two level systems (TLS), a good physical model of which could be excitons in QWs [1], after the excitation decays exponentially with characteristic rate Γ. Time-integrated (TI) reflection spectrum, being a Fourier transform (FT) of the decay, is a Lorentzian with HWHM Γ. Analysis of the coherent response of the QW is complicated by a non-resonant reflection of the sample surface. Here we employ beam of p-polarized light at the Brewster angle of incidence to eliminate the later reflection. This allows us to study model behavior of the QW reflection, including FT calculation.

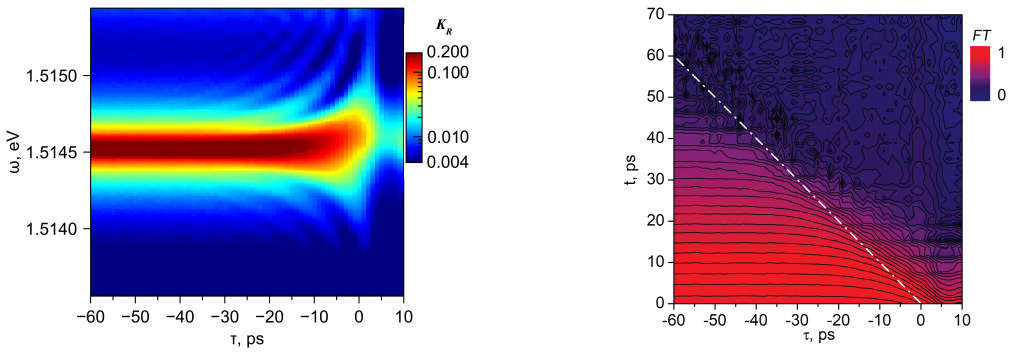

Figure 1: Reflection spectra as a function of τ (a) and FT of these spectra (b) (log intensity scales). Pump arrival time is indicated by the dashed line.

TI reflection spectra of 2 nm InGaAs/GaAs QW at 3.5K near the heavy hole exciton resonance (HH-exc) are shown in Fig.1(a) as a function of the delay τ between the probe pulse (20 μW) and pump pulse (32 mW) resonant to the HH-exc. Pump pulse virtually instantly increases exciton density so that they do not longer behave like TLS (their radiative rate abruptly drops [2]) and FID becomes cut at the moment of pump arrival. Mathematically it is described as a product of the exponent and temporal boxcar π-function with duration equal to τ. FT of this product is a convolution of Lorentzian and sinc function. In Fig.1 (b) an inverse FT of the observed spectrum is presented demonstrating the abruptly cut of the exponential FID.

The technique of FT of the observed TI reflection spectra could also be employed to study beats between several optical resonances and even more complicated time-domain coherent processes [3]. The reported study was partially supported by RFBR project 16-29-03115 ofi_m and carried out in the SPbU Resource Center "Nanophotonics".

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Plasmon induced enhancement of four-particle radiative reconmbination in SiGe/Si quantum well

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As far as we are aware, experimental observation of the plasmonic amplification for a collective recombination process, in which the emitted photon gains an energy released after the annihilation of several electron-hole pairs, has not been reported previously. The well-known example of such a process is so-called 2Eg photoluminescence (PL) of silicon (Si) and Si-based quantum wells (QW's) observed in the yellow-green spectral range [1,2]. 2Eg PL corresponds to the process for which after simultaneous recombination of two holes and two electrons from the opposite valleys the energy is transferred to a single photon. In the present work we demonstrate an increase of 2Eg PL quantum yield for biexcitons (BE's) and quasi-two-dimensional electron-hole droplets (EHD) localized in SiGe/Si QW as a result of their interaction with the plasmon subsystem of gold nanoparticles (NP).

To form a system that enables an interaction of BE's and EHD with plasmons of gold NP's we used thin (5 nm) $Si_{0.95}Ge_{0.05}$/Si quantum well (QW) with Si cap layer of 30 nm, grown by molecular beam epitaxy. BE's and EHD are the dominant many-particle states emitting 2Eg quanta in such a structure at 5K [2]. NP's with the diameter of 11±1 nm producing a wide plasmon resonance (PR) at 2.2-2.4 eV (see upper curve in fig.1A) were deposited on the structure surface from the water solution of cyclodextrin. As one can see from fig. 1A, PR falls far from the spectral range of ordinary infrared PL of QW (see curve "IR" in fig. 1A) as well as from excitation quanta (labeled by the arrow). But it almost perfectly fits the position of 2Eg PL (see curve "2Eg" in fig. 1A).

Fig. 1B illustrates the enhancement of 2Eg PL as a function of NP surface density at 5K. It should be noted that (1) rapid growth of 2Eg PL does not accompanied by the growth of IR PL; (2) quantum yield of 2Eg PL returns to its ordinary value near the boundary of the area covered with NP's and (3) the increase of 2Eg PL reveals a sharp dependence on the photon energy thus reflecting different enhancement value for different many-particles states, see fig.1C. The later results from the fundamental dependence of plasmonic enhancement on the matrix element of the dipole moment. It is naturally to assume that matrix element of the dipole moment should be different for the transitions related with EHD and BE's thus explaining the sharp spectral dependence of 2Eg PL enhancement. The unexpected effect – non-monotonic spectral dependence of plasmon enhancement for EHD emission line (see fig. 1C), requires further investigations.

The work was supported by Russian Science Foundation (Grant No. 14-22-00273).

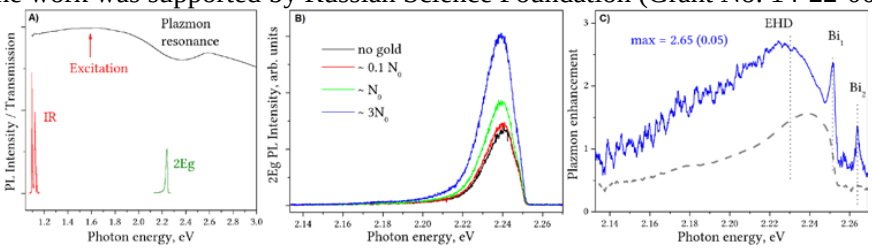

Figure 1A: Energy scheme of the processes involved. 1B: Growth of 2Eg PL quantum yield as a function of NP surface density, $N_0 = 3 \cdot 10^{11} cm^{-2}$. 1C: Spectral dependence of plasmonic enhancement (blue line) and 2Eg PL spectra in logarithmic scale (gray dashed line).

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Isolated (quantum) emitters related with extended defects in ZnSe/ZnMgSe quantum well

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Extended defect in a semiconductor heterostructure is a rather complex system for which the interfaces between the different layers and/or local disorder may lead to drastic changes of the electronic spectrum on the nanometer scale. To perform a systematic study of such complex systems one needs to employ local methods for the separation of a single object from the inhomogeneous macroscopic ensemble. In the present work similar approach is realized using microphotoluminescence (MPL) measurements to study the properties of point and extended defects in thick (20 nm) ZnSe/$Zn_{0.84}Mg_{0.16}S_{0.12}Se_{0.88}$ quantum well (QW) grown by MBE on GaAs substrate.

Measurements of MPL spectra under cw excitation (λ = 405 nm) were carried out at a temperature of 5K using backscattering geometry. Twenty times enlarged MPL image was focused on the entrance slit of the grating spectrograph with a linear dispersion of 1.6 nm/mm equipped with CCD matrix detector. The image obtained on the CCD corresponds to "spectral-spatial" map of the MPL signal. The spectral resolution of the system was better than 0.035 nm and the spatial resolution was about 1 μm in the central part of CCD.

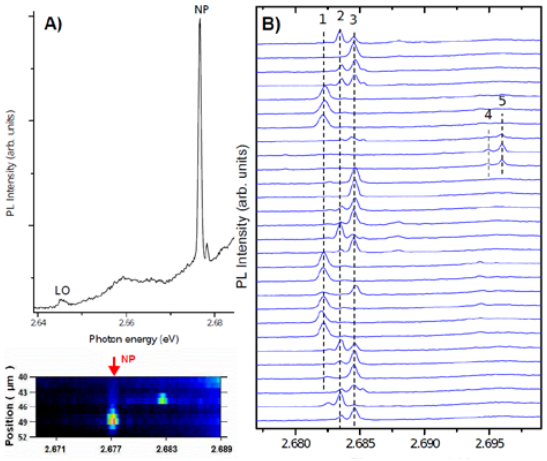

Figure 1A: An example of MPL spectra for dislocation-related single emitter. The inset in the bottom shows emitter on the map of SPL signal. 1B: Blinking of no-phonon line for the emitter in fig. 1A. The spectra were recorded sequentially with a constant time delay of 5 min. Temperature 5K.

Using the method described above the isolated (quantum) emitters characterized by an abrupt change in energy of the emitted photons at several meV during the time of ~1-10 minutes have been revealed. The corresponding beating of no-phonon (NP) MPL line exhibits the unusual fine structure, with the components unticorrelating with each other, see fig. 1. The relationship of the detected emitters with ZnSe layer has been proved due to a presence of phonon replica, 31.5-32.0 meV shifted from the zero-phonon line for each emitter. This shift corresponds to the energy of longitudinal optical (LO) phonons in ZnSe. Unusual properties of the detected emitters can be explained if one considers the emitter as a system with a significant dipole moment in its ground state. The interaction of the dipole with the nearest (randomly) charged defects results in the discrete changes of ground state energy thus producing unique fine structure of the emission line for each (quantum) emitter. The simplest emitter of this kind corresponds to a single donor-acceptor pair or its analog formed with the participation of the extended defect.

The work was supported by Russian Science Foundation (Grant No. 14-22-00273).

Gate Tuning of Förster Resonance Energy Transfer in Graphene - Quantum Dot Photo-Detection

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In this work, monolayer graphene functionalized by colloidal quantum dots (cQDs) has been employed in a field-effect transistor (FET) device for effective photo detection in the visible range of light. It is known that a charge or energy transfer from the more efficiently absorbing cQDs to graphene has to take place in order to obtain a change in the source-drain current of the FET as a consequence of illumination [1]---yet, the transfer from the cQDs to graphene is not sufficiently understood. In our study, CdSe/ZnS core shell cQDs covering the conductive channel of a self-made graphene field-effect transistor is characterized with respect to the energy transfer dynamics in this system. Therefore, we have measured time-resolved cQD photo-luminescence in dependency of the applied back-gate voltage. Here, gate tuning of the photo-luminescence lifetime clearly indicates a change of the decay channels. To support our observation, we provide data for a model based on non-radiative Förster resonance energy transfer [2] as a function of the gating-voltage. By applying an external back-gate voltage, both model (see [3]) and experiment reveal that, via the absorption of graphene tuned with respect to the photo-luminescence of the cQDs, the transfer rate in such photo-detectors can be strongly altered [4,5].

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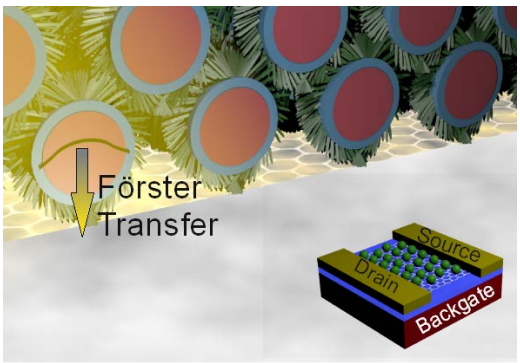

Fig. 1: Schematic representation of a cQD-graphene photo-detector. Colloidal quantum dots drop-casted onto a graphene field-effect transistor allow for the absorption of optical power by the cQDs with long ligands prior to a non-radiative transfer to graphene leading to a change of the obtained source-drain current. The applied backgate-voltage is shown to alter the Förster transfer rate via a shift of the relative Fermi energy in graphene [5]. The inset shows a schematic view of such a photo-detecting structure including its contacts.

Ultrafast Control of Few-Fermion Spin and Inversion Dynamics in Single CdSe/ZnSe Quantum Dots

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Beyond deterministic single-photon emission and the manipulation of single qubits, concepts based on semiconductor quantum dots (QDs) are in the future poised for synthesis of photonic states with a well-defined number of quanta. Large Coulomb correlation energies and high confinement potentials render II-VI variants particularly attractive for such nonlinear quantum optics tasks. In this work we address donor-charged single CdSe/ZnSe QDs [1], which are endowed with a bright three-particle ground state (trion, X^-) and have been successfully exploited to achieve single-photon gain on a timescale of tens of picoseconds [2]. The inversion dynamics, triggered by ultrafast initialization by the resonant excitation pulse, intimately depends on the resulting spin configuration of the few-fermion state [2,3]. In this work we analyze evolution of gain for various spin configurations and under the influence of an external magnetic field B. We first work without field and initialize with a linearly polarized pump resonant on the p-p transition. Differential transmission as monitored at the fundamental trion X^- position reveals two timescales of 5 ps and 60 ps, respectively (Fig. 1, gray dashed line). They represent the relaxation times of the hot electron into the s-shell, governed by the selection rules of the two possible electronic spin configurations. Fast relaxation is associated with antiparallel spin projections of the injected (p-shell) electron and the resident fermion (s-shell). Inversion dynamics for the case of parallel spins is instead delayed by the Pauli blockade, which can only relax via a spin flip process. The two scenarios become distinguishable in an external magnetic field of B = 5 T. Now pump pulses of opposite helicity deterministically initialize the spin configurations. Maximal gain is accomplished on a time scale of 5 ps for antiparallel spins. Instead for parallel spins, a rapid rise to half of the maximum transmission change is seen initially, revealing Coulomb renormalization. The subsequent gain reaches the same maximal value as obtained by antiparallel spin initialization after 60 ps. An average of the two signals matches the observations for B = 0 T. Recent results on femtosecond hole dynamics will also be discussed which is accessible by pumping on the d-s transition, thus exciting the electron directly into its lowest state where it cannot contribute to the dynamics. These combined findings motivate new strategies toward single-photon amplifiers operating on sub-picosecond timescales and in a fully deterministic regime.

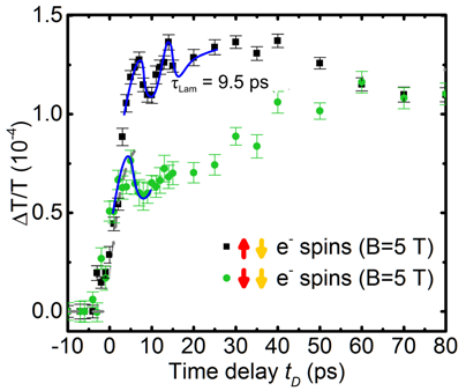

Figure 1: Ultrafast increase of differential transmission in a single CdSe/ZnSe QD at a temperature of 2 K. For B = 5 T, the buildup of gain is controlled by the spin configuration of the initialized states, containing either parallel (green circles) or antiparallel (black squares) electron spins. Fits including the Larmor spin precession of the trion are shown in blue.

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Localization Dynamics of Excitons in Disordered Semiconductor Quantum Wells

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The transport of optically created excitations in semiconductor nanostructures is critical for optoelectronics applications and is affected by unavoidable structural defects. For example, carriers excited in a semiconductor quantum well (QW) can be localized due to its interface roughness. Thus, it is important to understand the carrier localization dynamics in heterogeneous solid-state systems. Isolating these dynamics from other physical phenomena such as Coulombic interactions is often difficult. Exciton diffusion can shed light on the effect of structural disorder on charge transport because the charge-less nature of excitons significantly reduces the Coulomb interactions.[1]

In this work, we have studied heavy-hole exciton diffusion in disordered GaAs QWs using two-dimensional coherent spectroscopy (2DCS). 2D photon-echo spectra are measured for different wait times, T. The exciton resonance is inhomogeneously broadened due to spatial variations in the width of the QWs. Consequently, spatial motion of excitons results in a change in their resonance energies, which is directly measured through 2DCS. Figures 1(a) and 1(b) show the measured 2D spectra for wait times $T = 0.2$ and $T = 30$ ps, respectively. The change in peak shape with increase in the wait time clearly shows preferential relaxation of high-energy excitons to low-energy localized states over tens of picoseconds. Simulations based on microscopic calculations for randomly disordered QWs reproduce the experimental findings qualitatively, as shown in Figs. 1(c) and 1(d).

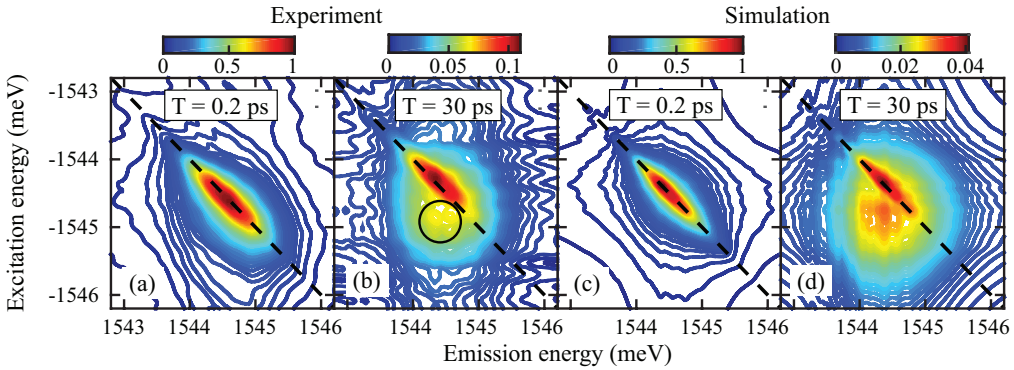

Figure 1: 2D spectra for sample temperature of 5K. Experimental results for (a) $T = 0.2$ ps and (b) $T = 30$ ps. The simulated spectra corresponding to (a) and (b) are shown in (c) and (d), respectively. Equal magnitude of the excitation and emission energies are indicated by dashed lines. Note the relative increase in the signal within the circled region in (c).

The 2DCS experiments were repeated for higher temperatures, which also show excitation of localized excitons to delocalized states due to increase in the phonon population.

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Phase and Amplitude Demodulation in Quantum Dot Spectral Hole Burning Spectroscopy

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Spectral hole burning spectroscopy is a powerful tool for obtaining the homogeneous properties of inhomogeneously broadened materials. Typically, a strong pump beam induces a narrow-bandwidth change in the absorption and refractive index. This change is monitored by measuring a weak probe beam after it traverses the pump-modulated region of the sample under investigation. For sensitive measurements, the pump is modulated with an AOM or mechanical chopper and the response of the probe at this frequency is measured. If one simply measures the power of the transmitted probe (*i.e.* with a standard photodiode), the change of the absorption coefficient is measured and interpretation is fairly straight forward (saturation and coherent population oscillations). A more powerful technique adds a phase-sensitive heterodyne detection scheme for amplitude and phase measurements at the shot noise limit. In this case, careful attention to the detection method is required because amplitude and phase modulation can be difficult to separate completely.

In this presentation we will discuss our results on full phase and amplitude demodulation of the spectral hole burning response of positively charged excitons in InAs self-assembled QDs. We show ultra-narrow spectral holes in the absorption profile and a corresponding dispersive lineshape in the index response. Simultaneously, we measure spin dynamics on the timescale of the modulation frequency, as this manifests as a millisecond timescale delay of the amplitude modulation. We believe that unambiguous determination of these different processes has not been previously reported on QDs.

A summary of our results is displayed in Fig. 1. In the top panels we show the phase response as a function of detuning and incident pump photons, demonstrating an approximate 0.04π shift near one pump photon per lifetime. The bottom panel depicts the amplitude modulation dynamics and the corresponding phase shift ϑ_M with respect to the modulated pump waveform (dashed curve). Because spin lifetimes are sensitive to a magnetic field, we observe that the amount of shift depends on the magnitude of the external field. This information enables sensitive measurements of the spin lifetime.

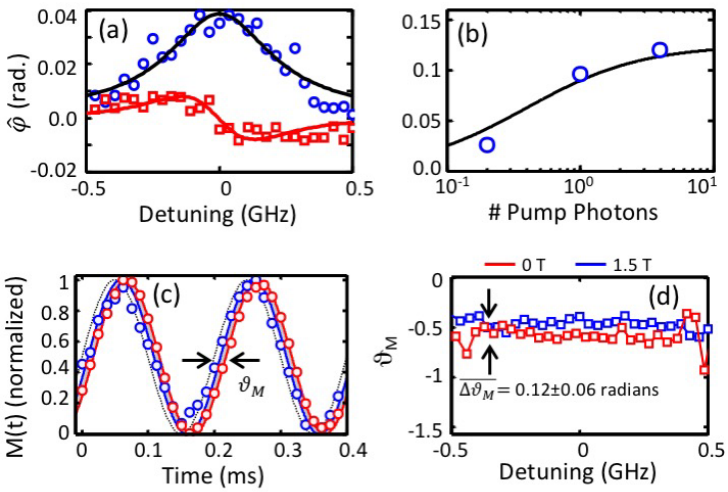

Figure 1: (a) Phase (red squares) and amplitude (blue circles, normalized) response of the QDs. (b) Magnitude of phase response as a function of incident photons, which exhibits a saturation behavior (solid line). (c) Demodulated amplitude response in time domain with (blue) and without (red) an applied magnetic field. (d) Lag in amplitude response versus pump-probe detuning and magnetic field strength.

Spin relaxation due to electron-phonon coupling revisited

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We have recently reexamined spin relaxation due to electron-phonon interaction [1], which is usually described in terms of the Elliott-Yafet (EY) spin relaxation mechanism. The EY spin relaxation time was originally derived for Kramers degenerate bands by Yafet [2], who combined the modulation of the electronic spin-orbit interaction due to phonons ("Overhauser mechanism") with spin-diagonal scattering between spin-mixed states ("Elliott mechanism"). We showed that, for Kramers degenerate bands, purely *spin-diagonal* electron-phonon interactions (such as the interaction with polar optical phonons in GaAs) *do not result in spin relaxation*, and that spin relaxation due to electron-phonon scattering for Kramers degenerate bands only occurs if explicitly spin-dependent coupling mechanisms are taken into account. We also derived the spin-relaxation time for this case, which corrects the shortcomings of Yafet's treatment. Our results shed some new light on the microscopic basis of spin relaxation due to different scattering mechanisms in general.

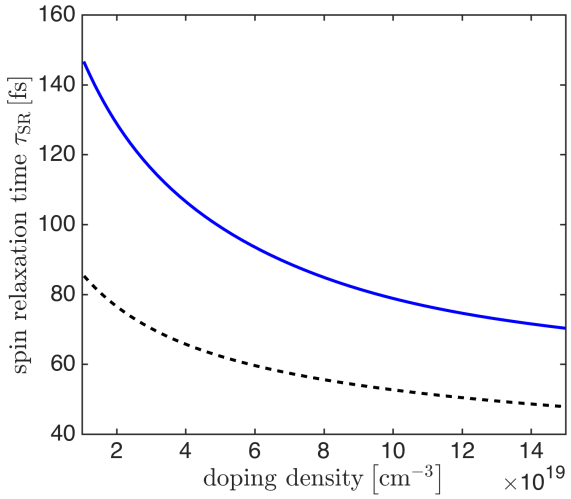

Figure 1: Intraband spin relaxation time for heavy holes in p-doped GaAs due to electron-phonon scattering at T=300 K (solid line) compared to conventional EY spin-relaxation time (dashed line).

The purpose of this contribution is to present our derivation for the correct spin relaxation time [1], evaluate it numerically, and compare with the widely used conventional EY spin-relaxation time [2]. We consider here the case of scattering of holes in p-doped bulk GaAs with phonons. Due to the complexities of the different scattering contributions [3], we concentrate on the intraband scattering of heavy-holes. Figure 1 shows the hole-density dependence of the spin-relaxation time. We compare our result (solid line) with the conventional EY spin-relaxation time [2] including all electron-phonon coupling mechanisms (dashed line). It is seen that the conventional EY result underestimates the spin-relaxation time by about 40%, mainly because the EY spin relaxation time contains an incorrect contribution of the spin-diagonal polar optical phonon scattering.

If time permits, recent extensions of this work to magnetization dynamics in a ferromagnetic Rashba model will be presented. Even though in such a spin-split system spin *dephasing* occurs, depending on the electron-phonon coupling strength the magnetic splitting can lead to an effective EY-like magnetization quenching and relaxation.

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Exciting a quantum dot resonantly with thermal light

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The interaction of a two level system (TLS) with a resonant optical field, despite its conceptual simplicity, allows to study a wide range of phenomena stretching from the Mollow triplet emission spectrum to the generation quadrature squeezed photons [1]. Interestingly, its fermionic character renders the TLS also especially sensitive to the photon statistics of the exciting field [2]. Here, we address a so far unexplored regime of resonance fluorescence in which a semiconductor quantum dot (QD), a solid-state TLS, is excited not with a laser but with a Martienssen lamp, a narrowband, chaotic light source.

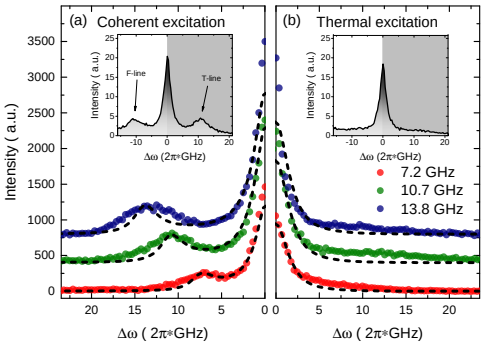

Figure 1: Emission spectrum of the strongly driven QD. (a) Results obtained for coherent excitation. The T-line of the Mollow triplett is clearly visible. For chaotic excitation, shown in (b), no side peaks are discernible.

In our experiments, we compare and contrast the influence of coherent and thermal photon statistics on the response of InGaAs QDs which are embedded in a planar low-Q cavity. In the steady-state, we observe a reduced absorption cross-section under chaotic excitation. In the transient regime, the Rabi oscillations, visible when the quantum dot is excited coherently, disappear when the excitation is chaotic. Likewise, in the emission spectrum the well-known Mollow triplet is observed exclusively under coherent excitation and vanishes under chaotic driving (cf. Fig. 1). Furthermore, measurements of the intensity autocorrelation function reveal that the photon statistics of the emission remains non-classical irrespective of the photon statistics of the excitation. Our observations confirm theoretical predictions and are fully consistent with calculations based on a quantum mechanical description of the experimental conditions [3].

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Dynamical calculation of third harmonic generation in 2-dimensional semiconductors

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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) with a semiconductor quantum well (QW) 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 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 (THG) in a InGaAs QW that is illuminated with intense femtosecond pulses [3].

When the excitation is well below the bandgap of the QW, i.e., no carriers are created in the semiconductor, we found that the THG intensity has a cubic dependence on the intensity of the exciting pulse. This is in agreement with a description based on an expansion in powers of the field with constant non-linear susceptibilities as coefficients. For an intense pulse resonant with the exciton energy, a substantial carrier density is created from absorption at the excitonic resonance. This acts to weaken the excitonic absorption and red-shifts the band-gap of the QW due to band-gap renormalization effects. The creation of charge carriers also affects the way in which the THG intensity depends on the intensity of the exciting pulse. We observe that the dependence stays a power law, where the characteristic exponent, δ, depends on the detuning between the pulse frequency and the excitonic resonance. In particular δ appears to decrease smoothly from the off-resonant value of 3 to a resonant value of about 2.6.

The simultaneous spatio-temporal description of the light field and carrier dynamics provided by our model is also readily expandable to other 2-dimensional semiconductor systems like graphene or the newly found transition metal dichalcogenides. Furthermore, the model allows for the description of semiconductor systems as parts of complex optical environments, like combined plasmonic-semiconductor structures.

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Collective emission from quantum dot ensembles: numerical simulation of second order correlations

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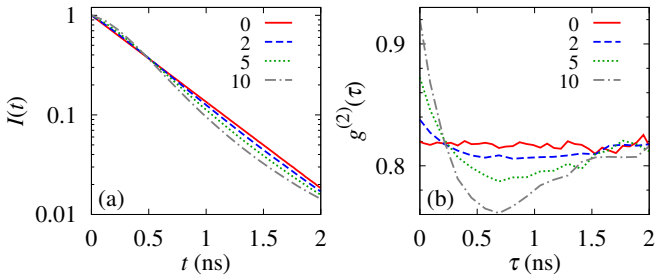
In this contribution I will present a theoretical analysis of the intensity correlation functions for the spontaneous emission from a planar ensemble of self-assembled quantum dots [1]. I will show that the second-order correlation function of the emitted field contains qualitative features that provide a more sensitive fingerprint of cooperative effects as compared with the enhanced decay rate of ensemble luminescence observed in the experiments performed so far [2].

The evolution of the system is simulated numerically using the quantum jump approach. From the simulation results, the photon-photon delay time statistics is constructed, approximating the second-order correlation function of the field in a way that mimics the recently developed experimental technique [3]. The form of this correlation function in the case of collective emission from a highly homogeneous QD ensemble qualitatively differs from that characterizing an ensemble of independent emitters (inhomogeneous ensemble of uncoupled dots). The signatures of collective emission are observed also in the case of an inhomogeneous but sufficiently strongly coupled ensemble and have the form of a pronounced non-monotonic dependence on the delay time (right panel in the Figure). These qualitative signatures are present even in the cases when the luminescence decay is nearly indistinguishable from simple exponential (cf. the left panel in the Figure). Different forms of the correlation functions are observed in the intensity autocorrelations and in cross correlations between various spectral ranges, revealing the quantum state projection associated with the detection event and the subsequent interaction-induced redistribution of occupations. The predicted effect of collective dynamics on the correlation functions appears under various excitation conditions.



Comparison of the decay of the luminescence intensity $I(t)$ (a) and the normalized correlation function $g^{(2)}(\tau)$ (b) for an ensemble of 6 QDs with the transition energy dispersion of 10 meV and various strengths of the inter-dot coupling V_0 as shown (in meV). The results have been averaged over 10^6 repetitions of the numerical experiment.

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Subwavelength solitons in graphene-coated nanowire lattices

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Compared with noble metals, graphene plasmonics opens novel opportunities for nanoscale optical operations in a wide frequency range from THz to infrared, with striking optical and electronic properties [1]. The material can be tailored, wrapped, or assembled with other dielectric structure, and its ultra-large nonlinear coefficient can lead to enhanced nonlinear effects such as soliton formation with small power consumption [2].

We propose a new type of periodic plasmonic nanostructure constituted by closely packed graphene-coated nanowires, in both 1D and 2D arrangements. With such configurations, we investigate the waveguides coupling, discrete diffraction, as well as nonlinear modes by strictly solving the Maxwell's equations. Our results demonstrate the existence of discrete solitons, whose characteristics, including the mode localization, the soliton power and the propagation length, exhibit feasible tunability through controlling the Fermi energy or the input beam intensity. In the 1D configuration, the power required for the deep-subwavelength confinement is found to be extremely low, see Ref. [3]. The propagation length is highly controllable with the Fermi energy and can achieve ~20λ_{SP}.

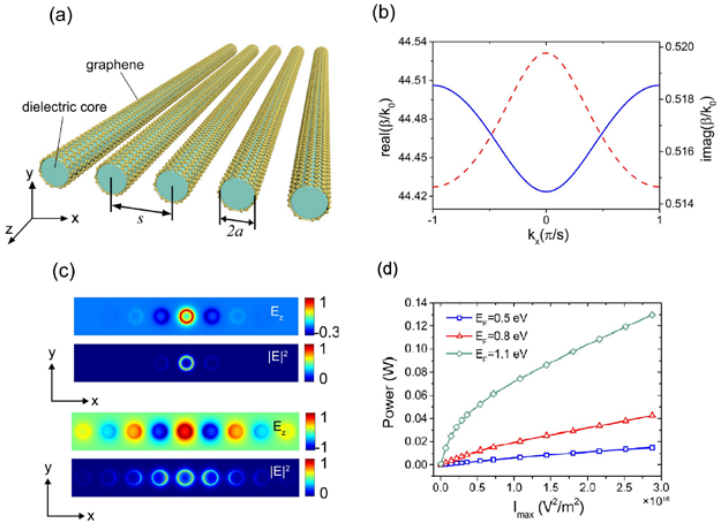

Figure 1: (a) Schematics of an array of dielectric nanowires coated by graphene monolayer. (b) Diffraction relation of the fundamental transmission band for a=100 nm, s=4a. (c) Profiles of the normalized tangential electric field E_z and light intensity $|E|^2$ for 1D graphene-based solitons at E_F=0.5 eV and 1.1 eV. (d) Soliton power vs. beam intensity.

We also demonstrate the existence of subwavelength solitons in a 2D lattice, including fundamental modes and quadrupole modes, with Fermi energy controllable characteristics, showing different field pattern but similar confinement and loss. The strong tunability of discrete diffraction and mode properties may render the graphene-based solitons intriguing applications in nanoscale optical switching, signal processing and active nanophotonic devices.

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Probing the coherent and incoherent responses of a quantum dot cavity-QED device with polarization tomography

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Future quantum networks require an efficient interface between stationary and flying qubits. In this respect, a single semiconductor quantum dot (QD) in a micropillar cavity can act both as a bright emitter [1] and an excellent receiver for single photons. In the latter case, the QD transition modifies the photon characteristics [2], and, reciprocally, the QD state can be manipulated with few incoming photons [3]. However, unveiling the coherent and incoherent contributions of the quantum optical fields arising from a resonantly-driven QD-cavity system remains an open challenge. Here we show that polarization tomography provides a global approach towards this goal, via the analysis of all the optical fields reflected and emitted by the device.

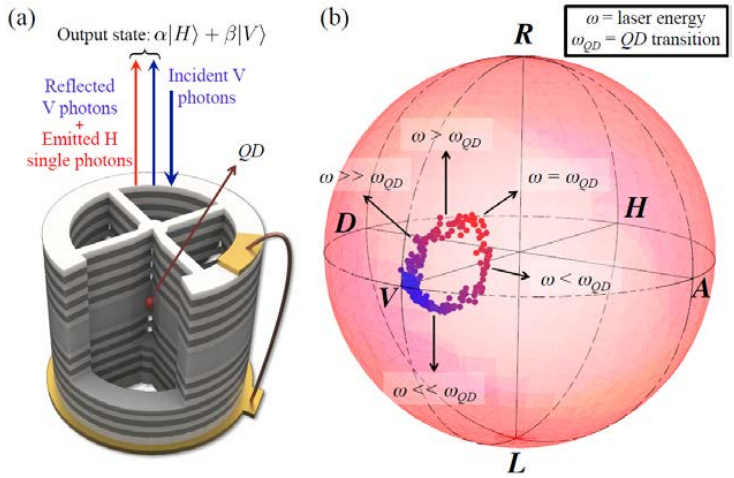

Figure 1: (a) Scheme of the electrically-controlled QD-cavity device and the input-output fields. (b) Representation of the polarization state in the Poincaré sphere for varying excitation laser energy ω. Each point is colored according to its polarization purity from 99 % (blue) to 84 % (red).

In our experiments we investigate determistically-coupled, electrically-controlled QD-micropillar devices (Fig. 1(a)). We observe that a single QD excitonic transition induces a macroscopic rotation of more than 10° on the polarization of the reflected photons, with a polarization purity remaining above 84%. The evolution of the output state can be illustrated in the Poincaré sphere while varying the excitation laser energy ω around the QD transition ω_{QD} (Fig. 1(b)). We show that the coherent part of the QD resonance fluorescence contributes to polarization rotation, whereas its incoherent part contributes to degrading the polarization purity [4]. Polarization tomography thus provides a powerful probe of the physical processes at play in cavity-QED systems, which is both of fundamental interest and technologically relevant for the implementation of coherent light-matter operations.

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Room-temperature polariton superfluidity in a cavity with embedded MoS_2 monolayer: theory and applications in nanophotonics

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In the past decade, the physics of polaritons, a quantum superposition of excitons and cavity photons, has attracted significant attention due to fundamental interest in the macroscopic collective quantum phenomena in this system [1], as well as their potential applications in photonics and optoelectronics, including polariton Bose-Einstein condensates in optical computing and nonlinear interferometry, novel light sources, and atomtronics (see Ref. [2] and references therein).

Transition-metal dichalcogenide monolayer crystals provide an unprecedented opportunity to transfer these achievements from helium to the room-temperature scale. In contrast to another near-perfect two-dimensional material, graphene, single-layer molybdenum and tungsten-based transition metal dichalcogenides are direct-zone semiconductors with the sizable bandgap E_g~1−2 eV, large light–matter interaction strength (the Rabi splitting ~50 meV), and large exciton binding energy ~0.3–0.9 eV.

In this work, we determine a range of experimentally relevant parameters, for which the superfluidity of a polariton gas can be achieved at room temperature in an optical microcavity with an embedded MoS_2 monolayer. Specifically, by considering the quasi-classical diffusive dynamics of a trapped polariton gas, we determined the values of the strength of a parabolic trapping potential, laser pump power, and polariton life time and diffusivity, for which the room temperature polariton superfluidity can be observed. The results of our studies are summarized in a phase map in Fig. 1. We also developed an analytical model, which is consistent with the results of our numerical studies. Finally, we discuss a few design strategies for room-temperature photonic integrated circuits suitable for the use in optical information processing systems with low energy consumption.

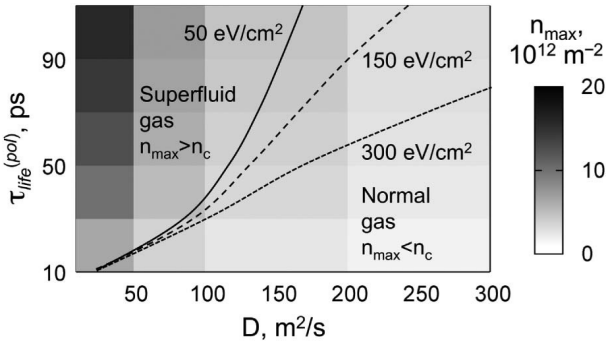

Figure 1: Phase diagram showing the domains in the parameter space where a trapped polariton gas in a cavity with an embedded MoS_2 monolayer is in the superfluid and normal states at the room temperature T=300 K. The curves show the boundary between the two states for three different trapping potential strengths. Here, $n_c = 4.2\times10^{12}$ m^{-2} is the Kosterlitz-Thouless transition density for cavity polaritons at the room temperature, $n_{\max}$ is the maximum density in the trapped polariton cloud, D and $\tau_{life}^{(pol)}$ are the respective polariton diffusivity and life time. From Ref. [3].

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Mid-Infrared Quantum-Dot Quantum Cascade Laser: A Theoretical Analysis

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Although quantum cascade lasers (QCL) based on quantum wells (QW) have been very successful, using low-dimensional systems such as quantum dots (QDs) instead of QWs as active QCL regions promises advantages, such as a reduction of current requirements for comparable gain. Steps in this direction have been the design of midinfrared photodetectors using QDs, and the observation of midinfrared electroluminescence at room temperature.

We have proposed a QW-QD-QW structure design for an QCL active region [1] similar to an experimental structure already realized for midinfrared electroluminescence, and discussed theoretical requirements for an optimal line-up of QW and QD states. We found that to achieve steady-state gain, it is important to have an efficient extraction of carriers by an additional collector structure, which prevents an accumulation of carriers in continuum states. Based on our proposed band line-up for the active region in combination with such an efficient extraction process, we predicted [2] reduced current requirement for a gain-length product comparable to that of QW-based devices.

In this contribution [3], we focus on two important quantum-dot material parameters, namely inhomogeneous broadening and quantum-dot sheet density, and investigate their influence on the performance of our proposed quantum cascade laser design. Because the different scattering pathways through the QD active region also have an important influence on the performance, we analyze the different contributions to the current in some detail, which might be helpful for understanding how a QD-based design for a QCL active region works in general.

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Electric Field Effects on Excitons and Quantum Coherence of Rydberg-Excitons in Cu_2O

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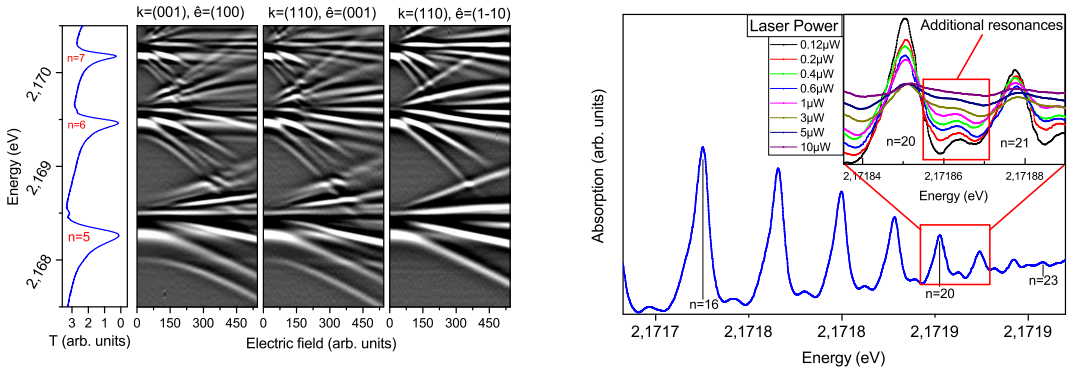
In this work we present both the measurements of the electric field effect on excitons in Cu_2O and the observation of quantum coherence for excitonic states with high principal quantum numbers, so called Rydberg-Excitons [1].



(a) (b)

Figure 1: (a) Polarization dependent Stark-Shift of the excitonic states with principle quantum number $n = 5$ to $n = 7$ with increasing electric field for $\vec{k}$ as the direction of light and $\hat{e}$ as the polarization. (b) Power dependence of the additional resonances appearing halfway between two excitonic absorption lines.

Through symmetry reduction in an external electric field we get optical access to dark states and thus are able to resolve the fine structure splitting of excitonic states with different angular momentum. The data are interpreted by means of an effective quantum defect model in analogy to many-electron atoms [2][3]. This non-degeneracy further leads to the observation of anti-crossings between states of different principal quantum numbers n in the spectra with increasing electric field. For these states we also show a polarization dependence (Fig. 1(a)) and compare the spectra with theoretical calculations.

Furthermore, recently observed excitonic states of high principal quantum numbers up to $n = 25$ [1] show additional resonances between the excitonic absorption lines. These resonances only appear in coherent excitation with a narrow-bandwidth laser, but are not observed in a broadband white-light excitation. We demonstrate a power dependence of these resonances (Fig. 1(b)), which can be explained theoretically by a V-type three level system and coherences between the states [4].

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Quantum Chaos of Rydberg Excitons in Cu_2O

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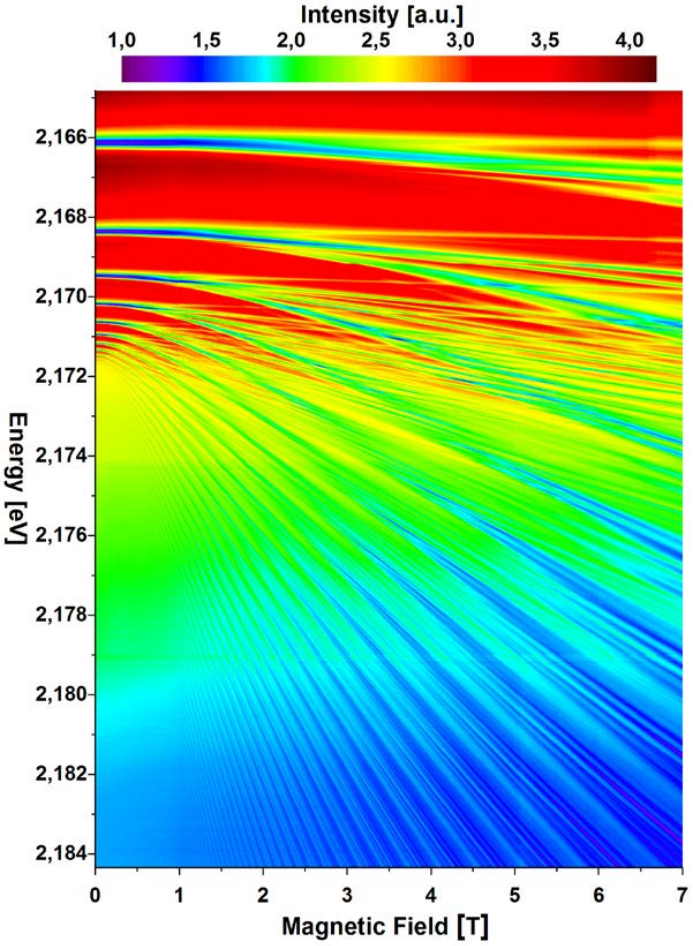

Figure 1: Transmission spectrum of the yellow exciton series in Cu_2O at different magnetic fields up to 7T. The first absorption line at 2.166eV represents the exciton state with principal quantum number n=4.

In classical mechanics, an important signature of chaos is the exponential divergence of a system's trajectory when varying its initial conditions. In quantum mechanics, the concept of a trajectory is not well defined anymore. Therefore, other measures have been developed in the past to identify chaotic behavior in quantum mechanical systems. One example is the nearest neighbor spacing distribution (NNS) of a system's energy levels. Classical chaos and quantum chaos are linked by the Bohigas-Giannoni-Schmit conjecture, which states that a quantum system with a chaotic classical analog, e.g. a quantum billiard, exhibits specific NNS-distributions that are well described by random matrix ensembles [1]. Depending on the random matrix ensemble that is matched by the system's level statistics, you can also gain knowledge about its underlying symmetries.

However, in a system without a classical analog, like Rydberg excitons in Cu_2O, we can also apply the mentioned statistical analysis if there are enough energy levels accessible. Because these excitons can be observed to high principal quantum numbers [2], we were able to detect chaotic signatures by analyzing transmission spectra of Cu_2O for different magnetic fields (figure 1). The analysis indicates that not only the system shows a transition towards quantum chaos but also all anti-unitary symmetries are broken [3].

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[2] T. Kazimierczuk, D. Fröhlich, S. Scheel, H. Stolz, and M. Bayer, *Nature* **514**, 343-347 (2014).
[3] M. Aßmann, J. Thewes, D. Fröhlich, and M. Bayer, *Nature Materials* **15**, 741-745 (2016).

Advanced pump-probe Faraday rotation spectroscopy of electron spin dynamics in n-type GaAs

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The standard pump-probe Faraday rotation spectroscopy allows one to study electron spin dynamics by varying the delay between the pump and probe laser pulses. Time resolution of the technique is determined by the laser pulse width (typically 1 ps), while possible time range is determined by the length of mechanical delay line and is typically few nanoseconds. We extend the standard technique to reach much larger time range and get tailored pump pulses protocol, while keeping 1 ps time resolution, by using combination of electro- and acousto-optical modulators. To demonstrate the capabilities of the new technique we investigate long electron spin dynamics in n-doped bulk GaAs. We directly observe submicrosecond decay of the electron spin prececcion in magnetic field applied in Voigt geometry [Fig. 1(a), line] and determine spin coherence time T_2^*, so far extracted from the width of resonant spin amplification (or Hanle) curve [1] or spin noise spectrum [2]. In magnetic field applied in Faraday geometry we observe monotonous spin polarization decay [Fig. 1(a), symbols] and determine longitudinal spin relaxation time T_1. In the limit of low temperatures and low magnetic fields $T_2^* \approx T_1 \approx$ 200 ns. With measured magnetic field and temperature dependencies of T_2^* and T_1 we discuss mechanisms of the electron spin relaxation.

As another demonstration of the new technique we show the buildup of the resonant spin amplification with increasing number of the pump laser pulses [Fig. 1(b)].

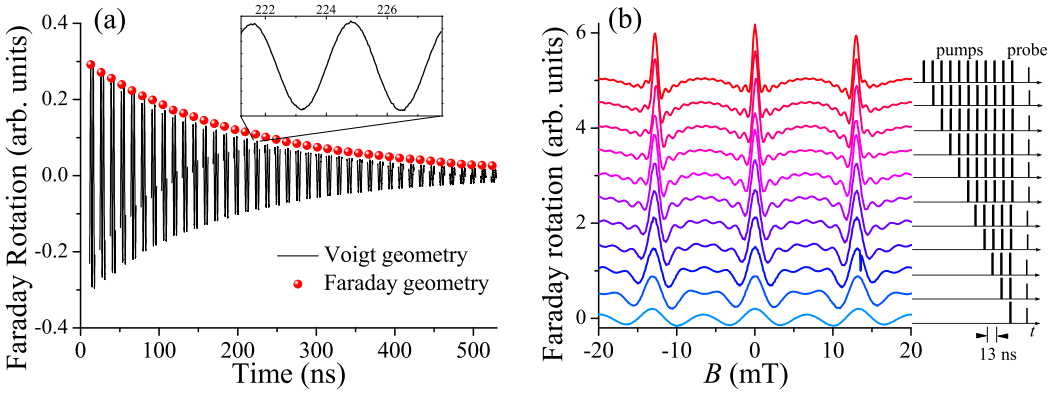

Figure 1: (a) Dynamics of the Faraday rotation signal for the magnetic field $B = 50$ mT applied in Voigt (black line) and Faraday (red symbols) geometry. Inset shows closeup of the spin precession. (b) Resonant spin amplification curves for different numbers of the pump pulses (from 1 to 9) as shown in the right panel.(a),(b) $T = 6$ K.

[1] J. M. Kikkawa and D. D. Awschalom, Phys. Rev. Lett. **80**, 4313 (1998).
[2] S. A. Crooker, L. Cheng, and D. L. Smith, Phys. Rev. B **79**, 035208 (2009).

Tuning valley polarization in a WSe_2 monolayer with a tiny magnetic field

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In monolayers of semiconducting transition metal dichalcogenides (S-TMDs), the light helicity ($\sigma^{\pm}$) is coupled to the valley degree of freedom ($\pm K$), leading to the possibility of optical initialization of distinct valley populations [1]. Unfortunately, an extremely rapid valley pseudospin relaxation (at the time scale of picoseconds) occurring for optically bright (electric-dipole active) excitons [2] imposes severe limitations on the development of opto-valleytronics. The character of the ground exciton states in S-TMDs monolayers can be, however, very different, depending on the actual order of spin-orbit split bands in the conduction band. Whereas the ground state of the exciton appears to be optically active in monolayers of molybdenum dichalcogenides, in tungsten dichalcogenides (such as WSe_2) it is, to the first approximation, electric-dipole forbidden (optically dark).

Here we show that the inter-valley scattering is suppressed by two orders of magnitude for the dark excitons in a WSe_2 monolayer as compared to previously studied bright excitons. Moreover, we demonstrate that this inter-valley scattering can be completely switched off by a tiny magnetic field < 100 mT [3]. These findings are evidenced by our optical orientation experiments. The photoluminescence (PL) spectra measured under circularly polarized excitation (Fig. 1) clearly demonstrate the effect of the enhancement of the PL polarization upon application of the magnetic field in the Faraday geometry, which appears in the low energy range corresponding to the localized excitons (LEs). Crucially, the critical field $B_0 \approx 20$ mT needed to enhance the polarization is found to be the same for all LEs evidencing their common origin. Based on the long valley pseudospin depolarization time deduced from the small value of B_0 we conclude that the effect occurs at the intermediate state being the dark ground state of the neutral exciton, which is rather weakly affected by depolarization effects arising due to the electron-hole exchange interaction [2]. Our interpretation is finally confirmed by the time-resolved experiments, which reveal the pseudospin dynamics to be a two-step relaxation process. An initial decay of the pseudospin occurs at the level of dark excitons on a time scale of 100 ps, which is tunable with the magnetic field. This decay is followed by even longer decay (> 1 ns), once the dark excitons form the LEs allowing for their radiative recombination. Our findings of slow valley pseudospin relaxation easily manipulated by the magnetic field open new prospects for engineering the dynamics of the valley pseudospin in S-TMDs.

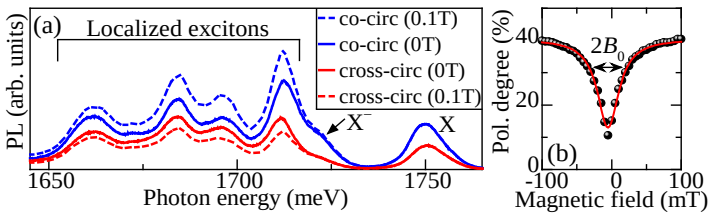

Fig 1. (a) PL spectra of the WSe_2 monolayer detected in opposite circular polarizations under σ^- polarized excitation (at two values of the magnetic field, as indicated). (b) The circular polarization degree of the LEs emission as a function of the magnetic field.

[1] T. Cao *et al*, Nature Commun. **3**, 887 (2012).
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[3] T. Smoleński *et al.*, Phys. Rev. X 6, 021024 (2016).

Photon echo from InGaAs quantum dots embedded in Tamm-plasmon microcavity

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We report on coherent optical response from ensemble of InGaAs semiconductor quantum dots (QDs) embedded in planar Tamm-plasmon (TP) microcavity. We observe enhancement of light-matter interaction under selective coherent interaction of the QDs in resonance with the cavity mode. This is manifested in observation of Rabi oscillations of the photon echo (PE) amplitude which scale linearly with quality factor.

The essential feature of our TP structure, namely covering only one part of the sample with gold, allows us to compare the strength of light-matter interaction within one structure where the size distribution and density of QDs are identical. The investigated sample and experimental approach are summarized in Fig. 1 (a). A single InGaAs QD layer is located about 125nm above GaAs/AlAs DBR mirror and 40nm below the surface, which corresponds to one of the maxima of the cavity electric field. Half of the sample is covered with a 40nm thick gold layer, which leads to formation of TP photonic mode. Coherent optical response is determined by PE measured using transient four-wave-mixing (TFWM) technique with a sequence of two spectrally narrow ps-pulses in non-collinear reflection geometry.

Fig. 1 (b) shows Rabi oscillation in the PE amplitude as a function of the second pulse area (proportional to the square root of the power). A π-pulse in TP structure is achieved for a laser power of approximately 5mW while 650mW would be necessary to realize it on uncovered sample part. The ratio corresponds to the quality factor 130 which can be extracted from the TP structure's reflectivity spectrum.

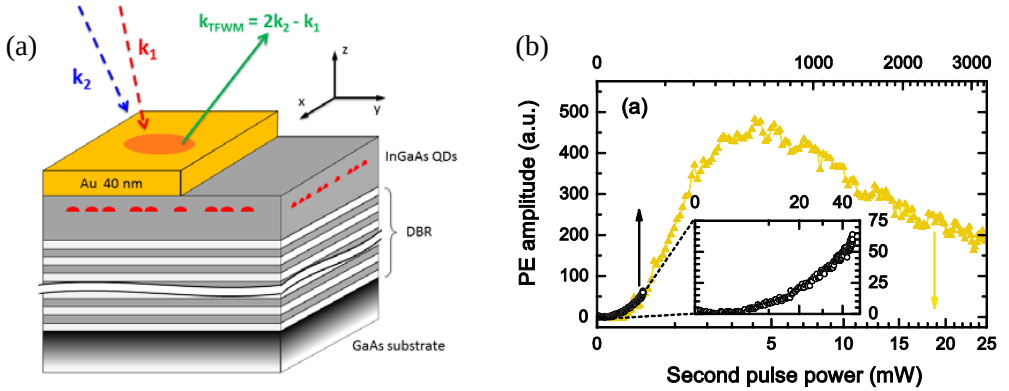

Figure 1: (a) Schematic representation of the investigated TP structure and TFWM. (b) Rabi oscillation measured from PE amplitude as function of the second pulse power. Yellow triangles correspond to TP structure and refer to bottom x-axis, black circles depict bare QDs and refer to the top x-axis. The scaling of the x-axis is chosen to be linear with the square root of the power.

Interlayer excitons in van der Waals heterostructures

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Recent success in producing vertical stacks of different two-dimensional (2D) materials has enabled development of novel devices based on van der Waals heterostructures (HSs) [1]. Properties of such HSs can be suitably tuned by incorporating monolayers of semiconducting transition metal dichalcogenides (TMDCs) having direct bandgaps [2] and large binding energy of excitons [3-5]. The presence of long-lived interlayer excitons (IXs) in HSs with type-II band-alignment (Fig. 1(a)) has been recently demonstrated [6].

In our work, we investigate IXs in $MoSe_2$-WSe_2 HSs using photoluminescence (PL) and photoluminescence excitation spectroscopy. We demonstrate that their binding energy and PL intensity can be highly tuned by electrostatic gating (Fig. 1(c)). The IX PL signal exhibits a blueshift with increasing laser excitation power (Fig. 1(d)), occurring due to repulsive interaction between IXs [7]. This opens the way to explore many-body physics in TMDCs, which otherwise are only accessible at very high exciton densities due to small exciton radii in these materials.

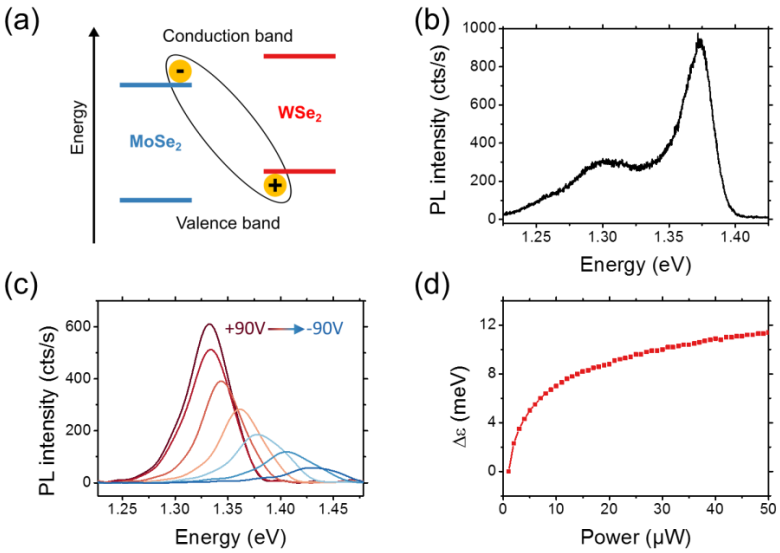

Fig. 1. (a) Schematics of band alignment in $MoSe_2$-WSe_2 HS. (b) IX PL signal from HS for laser excitation power 20 μW and temperature 8 K. (c) IX PL spectrum as a function of applied gate voltage. (d) IX peak blueshift Δ as a function of excitation power.

[1] A. K. Geim, I. V. Grigorieva, Nature, 499, 419–425, (2013)
[2] K. F. Mak, et al, Physical Review Letters, 105 (13), 136805
[3] K. He, et al, Physical Review Letters, 113, 026803, (2014)
[4] M. M. Ugeda, et al, Nature Materials, 13, 1091-1095, (2014
[5] A. R. Klots, et al, Scientific Reports, 4, 6608, (2014)
[6] P. Rivera, et al, Nature Communications. 6, 6242, (2015)
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Band-edge exciton fine structure and circular polarization in CdSe colloidal nanoplatelets

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Semiconductor nanoplatelets (NPLs) is a new class of nanostructures which holds a great promise to become the most efficient colloidal luminophores. Due to a uniform thickness that is controllable up to the atomic scale, the width of photoluminescence (PL) line of NPLs is much narrower than in ensembles of other colloidal nanocrystals and the radiative decay times are much shorter [1]. Although NPLs emission is obviously connected with two-dimensional excitons, the mechanisms responsible for their radiative decay and the PL linewidth have not been understood yet. We study exciton fine structure and magneto-optical properties of CdSe NPLs with 3, 4 and 5 monolayer (ML) thickness using combined time- and spectrally-resolved spectroscopy in high magnetic fields (up to 15 T) at cryogenic temperatures (down to 2.2 K). We observe a bi-exponential PL decay, which is a sign of an interplay between a bright (upper) and a dark (lower) exciton states (Figure 1a). The energy splitting ΔE_{AF} between the two states is of the order of several meV with a scaling law proportional to inverse thickness. We find a strikingly high circular polarization degree ρ, up to 60% at a magnetic field of 3 T. By contrast with colloidal quantum dots (QDs), the circular polarization degree displays a non-monotonous magnetic field dependence: after reaching a maximum of 60% at 3 T, it drops to less than 30% at 15 T (Fig. 1b). We show that the two predominant orientations of NPLs, namely, laying on the plane and standing on the edge due to stacking, could play a crucial role in the non-monotonous behaviour of the circular polarization degree.

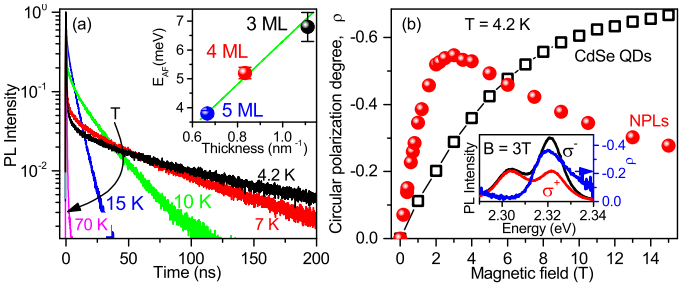

Figure 1: (a) PL decay curves of the 4 ML sample at various temperatures. Inset: energy splitting between bright and dark exciton states, ΔE_{AF}. (b) Circular polarization degree, ρ in CdSe QDs and NPLs. Inset: PL spectrum and time-integrated ρ.

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High optical orientation degree of the indirect excitons in indirect band-gap (In,Al)As/AlAs quantum dots

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(In,Al,As)/AlAs quantum dots (QDs) with an indirect band gap and type-I band alignment may be considered as promising semiconductor structures for realizing spin memory applications due to the long exciton lifetimes and longitudinal spin relaxation times of several hundreds of microseconds [1,2]. The indirect-in-momentum space exciton in these QD ensembles can optically be addressed via the mixing of the conduction band levels at the Γ- and X-valley of the Brillouin zone, thus making them good candidates for optical spin manipulation [3]. In that context, a highly essential and open question is the behavior of the spin polarization of indirect excitons at weak magnetic fields in the mT-range and the underlying depolarization mechanisms.

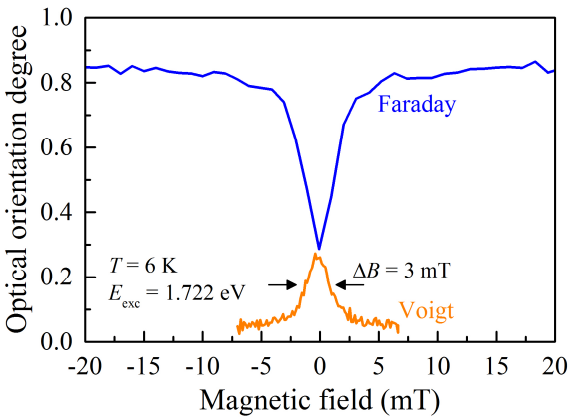

Figure 1: Optical orientation degree of the PL of the indirect exciton in Faraday and Voigt geometry at weak external magnetic fields strengths.

We investigate the polarization features of the time-integrated photo-luminescence (PL) of (In,Al)As/AlAs QDs by tuning the excitation energy through the inhomogenously broadened dot ensemble. At low temperatures, we observe that the optical orientation degree of the indirect-in-momentum space exciton increases up to 85% for small magnetic fields (mT-range) applied along the QD growth axis (Faraday geometry), see blue curve in Fig. 1. The recovery of the optical orientation degree hints at a suppression of nuclear spin fluctuations acting predominantly on the X-valley electron of the exciton. The high optical orientation degree itself can be related to the high QD symmetry, where light-heavy-hole mixing and spin-orbit interaction are negligible, as well as to a strongly extended spin relaxation time being even longer than the exciton recombination time. In transverse magnetic field, the width of the Hanle curve corresponds however to a spin lifetime of only a few nanoseconds. The angle and temperature dependences of the optical orientation degree as well as the impact of the laser power are discussed. Furthermore, it is shown that optical orientation degrees are only present for specific excitonic transitions whose origins are evaluated from photoluminescence excitation spectroscopy data.

[1] T. S. Shamirzaev, J. Debus, D. S. Abramkin, D. Dunker, D. R. Yakovlev, D. V. Dmitriev, A. K. Gutakovskii, L. S. Braginsky, K. S. Zhuravlev, and M. Bayer, Phys. Rev. B **84**, 155318 (2011).
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Single photons from dissipation in coupled cavities

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An ideal single photon source would operate under low excitation power at room temperature and require the smallest fabrication footprint possible on an integrable and scalable architecture. Unfortunately, none of the existing technological platforms - whether based on blockade mechanisms or heralding protocols - is fulfilling simultaneously these requirements.

In this framework, we propose a quantum mechanism, compatible with passive Silicon-based photonic technology, producing a strongly antibunched output from cavity modes subject to an arbitrarily small nonlinearity and ultra-low input power [1]. Contrarily to the unconventional photon blockade mechanism (UPB) [2,3], the present new proposal takes advantage of one-directional transmission (i.e. dissipative coupling) between two optical resonators. This scheme solves a critical longstanding issue preventing weakly nonlinear sources to operate under pulsed excitation and offers a high level of indistinguishability.

The proposed configuration relies on a simple pair of Kerr-nonlinear optical cavities subject to a dissipative coupling associated with a one-directional transmission (see figure). The cavities are driven by a mutually coherent fields of equal frequency, whose relative phase can be tuned to reach a regime of strong antibunching for arbitrary system parameters. Crucially, as opposed to the UPB mechanism [2,3], the delayed two-photon correlations behave similarly to conventional single photon sources and demonstrates long anticorrelation time (see figure). We therefore explicitly demonstrate the compatibility with pulsed excitation and study a realistic implementation of the one-directional transmission. We briefly discuss a 3 cavity scheme producing pair correlated photons under weak nonlinearity allowing for heralded single photons. Our results could pave the way to a significant improvement of the single photon generation technology.

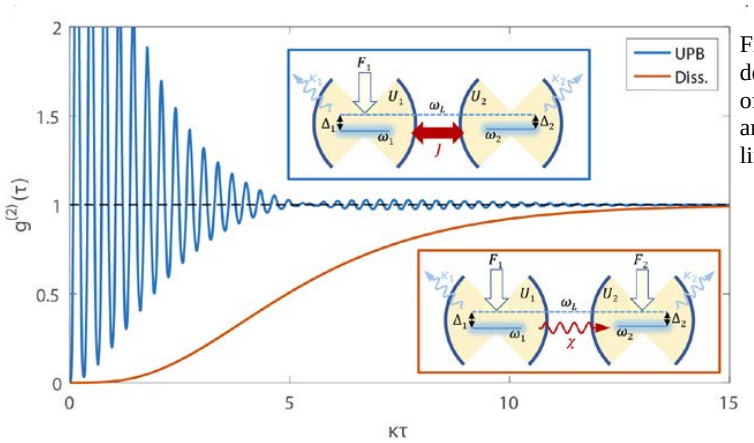

Figure: Comparison between the delayed two-photon correlations of the UPB (blue line and frame) and the dissipative scheme (red line and frame).

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The broadening and narrowing of high-gain parametric down conversion spectrum

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Bright Squeezed Vacuum (BSV) is a macroscopic non-classical state of light, which can be created through high-gain parametric down conversion or four-wave mixing. BSV is very promising for different applications in quantum optics and quantum information, due to its non-classical features such as macroscopic correlations, huge photon number per mode, noise reduction below the shot-noise limit etc. Its detailed theoretical description is therefore of high importance.

Earlier works by different groups used the approximate numerical solution of integro-differential equations [1-3] or analytical solution in terms of the Schmidt modes [4,5] but with some restrictions. The analytical Schmidt modes approach allows one to explain many features of BSV, including different correlation characteristics, intensity profile and narrowing of the spectrum with increasing the parametric gain in schemes with two non-linear crystals and air gap between them (spatial domain) or two non-linear crystals and a dispersive medium between them (frequency domain). But due to some restrictions the broadening of the single crystal spectrum with the increasing of the pump power, a well-known experimental effect, never did not described by such approach. In contrast, the approximate solution of integro-differential equations grasps the effect of the spectrum broadening but cannot explain the narrowing effect.

In this work we present a method based on the exact numerical solution of the systems of integro-differential equations for the plane-monochromatic-wave operators. This method is general, does not contain any assumptions and allows one to explain simultaneously the broadening of the single-crystal spectrum and the narrowing of the spectrum in the two-crystal configuration case with a medium between them (Fig. 1). All obtained results are in good agreement with the experimental data.

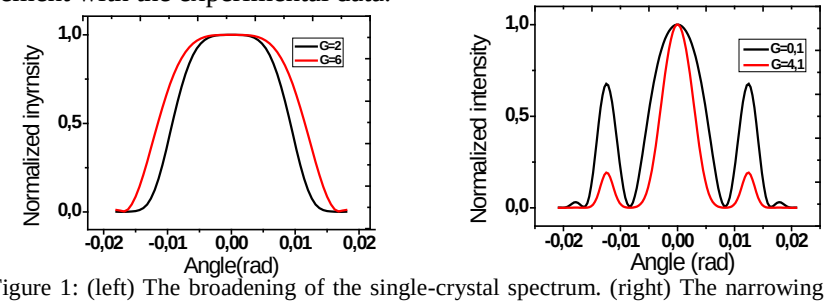

Figure 1: (left) The broadening of the single-crystal spectrum. (right) The narrowing of the spectrum in the two-crystal configuration case with an air gap between them.

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Higher Order Spin Correlation in Semi-Conductor Quantum Dots

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We study higher order auto-correlation functions of electron spin decay in an isolated semi-conductor quantum dot described by the central spin model. The electronic central spin is coupled to a bath of nuclear spins via hyperfine interaction, which dominates the short time regime. In a mean field approach the nuclear spin field is assumed to be frozen, since the precession frequency of the electron in the nuclear hyperfine field is much greater than the precession frequency of the nuclei in the hyperfine field of the electron.

Via quantum measurement theory we show that the experiment by Bechtold et al. (arXiv:1511.03684) can be described as a fourth order auto-correlation function. We compare our results to the experimental results. In order to observe similar long time dynamics in the forth order autocorrelation we incorporate the nuclear Zeeman splitting and the strain induced quadrupolar moment of the nuclei.

Non-equilibrium nuclear spin distribution function in quantum dots subject to periodic pulses

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In pump-probe experiments electron spin polarization in a semiconductor quantum dot is generated by periodic optical excitations. The decoherence of this polarization is dominated by the hyperfine interaction with a bath of nuclear spins in the short time regime. We aim for a theory that combines the effect of the periodic laser pump pulses and the nuclear spin bath on the electron spin polarization. Since the laser pulses occur on the shortest time scale of the system, and the electronic decay times are small compared to those of the nuclear spin bath, we treat the laser pumping quantum-mechanically using a Lindblad approach and keep the nuclear spins as frozen during that time. Then a classical simulation of the Overhauser field bridges the time until the next laser pulse. On one hand we analyze the time dependence of the electron spin dynamics and on the other hand present data for the non-equilibrium steady state spectral distributions of the Overhauser field in all spatial directions for the long time limit. For the electron spin dynamics a revival effect right before the next pulse is observed. The Overhauser field shows mode locking effects in the component parallel to the external magnetic field and build-up of nuclear spin polarization perpendicular to it.

2DEG and exciton dynamics in highly doped CdTe and CdMnTe quantum wells

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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 (PL) in the stationary and time-resolved regime. It also shows a very long lifetime of several hundreds of microseconds for a CdTe/CdMgTe modulation-doped QW at different magnetic fields. In a CdMnTe/CdMgTe modulation-doped QW the exciton magneto-photoluminescence surprisingly demonstrates variations in the energy for different quantum Hall regimes at elevated temperatures above 1.5 K. In particular, we observe a strong enhancement of the PL energy at 4.63 T, where the Hall resistance is strongly decreased. This may be due to the fractional quantum Hall effect with $\nu = 11/3$. Moreover, the 2DEG- and exciton-photoluminescence lines may anticross at different points in time with increasing magnetic field, see fig. 1 for $B = 4.7\,\mathrm{T}$, thus hinting at an interaction between the exciton coupled to the 3d Mn electrons and the electrons occupying Landau levels. The exciton and 2DEG PL is spectrally selectable in the time domain, in particular, due to the giant Zeeman shift of the exciton PL.

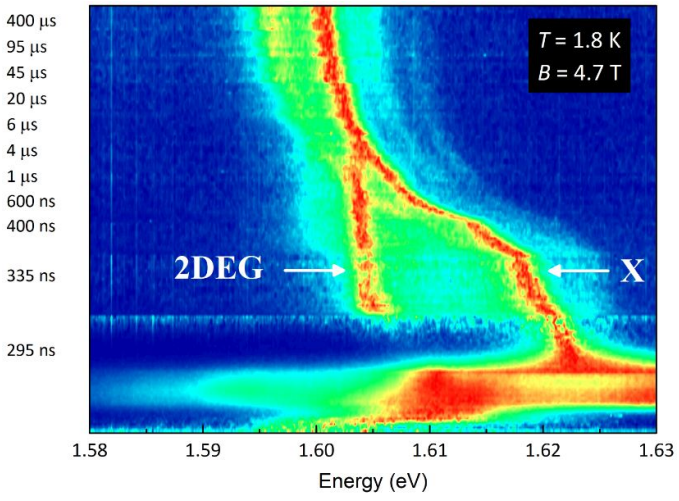

Figure 1: Time-resolved photoluminescence of the 2DEG and the exciton, marked by arrows, highlighting the anticrossing and following the modified Brillouin function.

Wednesday, 12.10.2016

Session We1: 09:00 - 11:00 (Quantum Dots 2)

Session We2: 11:30 - 13:30 (TMDC 2)

Ultrafast cavity switching : a novel resource for solid-state CQED

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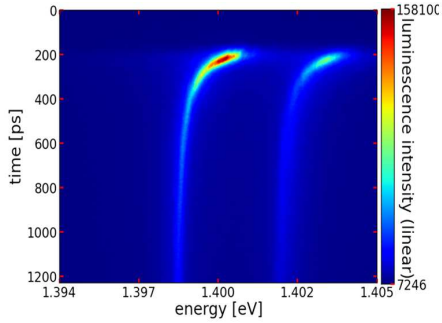

Fig : Multimode switching events in a QD-micropillar, as observed by a streak-camera.

It has been known since the 80's that the optical modes and optical response of semiconductor microcavities can be changed in a transient and reversible way through a modification of the refractive index of the semiconductor matrix. Initially developed in view of all-optical data processing and computing, "cavity switching" induced by the electrical injection of free carriers is nowadays widely used for the reconfiguration of photonic circuits.

In the context of CQED, cavity switching appears as a very powerful tool enabling to tailor the spontaneous emission properties of embedded emitters, through a dynamic control of the emitter-cavity mode detuning [1].

As a first example, we present recent switching experiments performed on micropillars containing collections of QDs. We observe large switching amplitudes (by as much as 20 linewidth), as well as differential switching of the pillar modes [2], using ultrafast optical carrier injection. By filtering the micropillar emission within a narrow spectral window, we observe ultrashort spontaneous emission pulses (down to 4ps!), which are generated by the QDs during their transient coupling with the cavity mode. Cavity switching here as a way to switch on and off the QD spontaneous emission into the cavity channel. In clear contrast to Fourier-transform laser pulses of similar duration, such pulses display a much shorter coherence time, as highlighted e.g. by transmission experiments through scattering media.

Recent theoretical advances also highlight the huge interest of cavity switching for CQED. For instance, single photons with a tailored time-envelope can be generated by a single quantum dot (QD) in a state-of-the-art microcavity, with a high efficiency and fidelity, by adjusting in real-time the magnitude of the Purcell effect [1,3]. This is noticeably the case for Gaussian time-envelopes and time reversed-exponential envelopes, both important resources for photonic quantum information processing. Finally, we have also reported Kerr-switching on the sub-ps time scale [4], which could be used to control Rabi oscillations in strongly-coupled semiconductor systems.

[1] H. Thyrrestrup et al, Opt. Exp. **21**, 23130 (2013).
[2] H. Thyrrestrup et al, Appl. Phys. Lett. **105**, 111115 (2014).
[3] G. Hornecker et al, SPIE Optics and Optoelectronics 2015, Prag, doi:10.1117/12.2178991; E. Peinke et al, submitted
[4] G. Ctistis et al, Appl. Phys. Lett. **98**, 161114 (2011); E. Yüce et al, Opt. Lett. 38, 374 (2013)

Polarisation Independent In-plane Spin Initialisation of a Quantum Dot in a Nanobeam Waveguide

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We have shown previously that the position and the spin state of an emitter within a nanobeam waveguide determines the propagation direction of an emitted photon due to the intrinsic chirality of the electrc fields at the nanoscale[1]. This allows for effective spin readout of the quantum dot (QD) spin state. Here we demonstrate that the spin state of an exciton in a QD, positioned at a chiral point of the nanobeam waveguide, can be effectively initialised using in-plane quasi-resonant excitation (experiment scheme Fig. 1a). We show that the initialisation of the spin state in a QD is independent of the input polarisation. The initialised spin state is determined only by the direction of the excitation laser in the waveguide. Spin initialisation of the QD is verified by the spin-dependent directional emission initially in non-zero magnetic field where two spin Zeeman components are split and allow for clear detection (Fig. 1b (top)). The spin initialisation and readout are also demonstrated to work in the absence of a magnetic field (Fig. 1b (bottom)). We also perform control measurements for a QD at a non-chiral point of a waveguide where directional spin readout and initialisation are not possible.

The chirality in nanophotonic waveguides with embedded quantum dots (QDs) allows for effective spin initialisation and readout in-plane. Architectures based on such waveguides will offer a potential route for future optical quantum information processing on-chip.

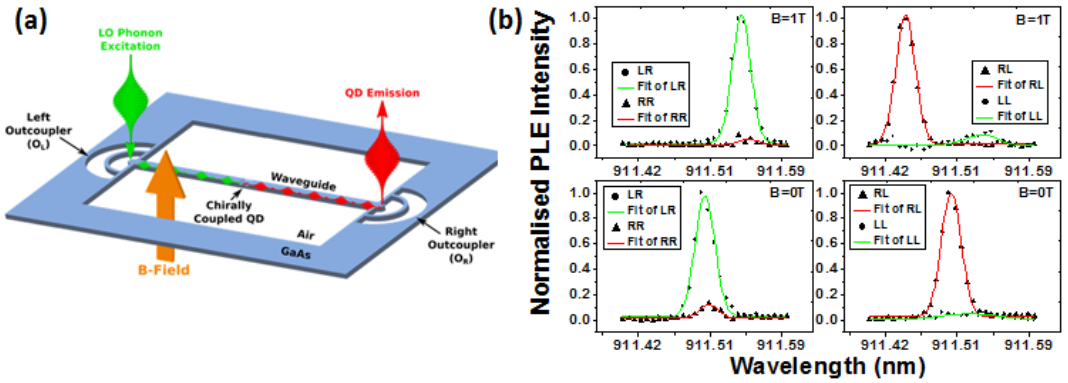

Figure 1: a) Schematic of nanobeam waveguide and experimental arrangement. QD emission was collected from the left (right) out-coupler. The position of quasi-resonant laser and collection can be moved between the out-couplers. b) PL spectra of a chiral QD showing initialisation and readout of mainly one spin component taken at B=0T (top) and B=1T (bottom).

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GaAs Quantum Dots in AlGaAs Nanowires

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Quantum dots in nanowires are one of the most promising systems for numerous applications in quantum nanophotonics. Recently, several groups have successfully demonstrated nanowire quantum dots in various material systems [1,2]. However controlled growth of high quality GaAs quantum dots in nanowires remains a challenge [3,4].

Here we show controllably grown GaAs quantum dots in AlGaAs nanowires with excellent optical properties. We use molecular beam epitaxy technique to grow our samples on a Si substrate. Our growth method results in quantum dots with very narrow spectral linewidth (< 10ueV) [5], single-photon and cascaded-photons emission. Moreover, we precisely control the dimensions of quantum dots and their position inside nanowires, and demonstrate that the emission wavelength can be engineered within the range of at least 30 nm around 765 nm.

Our work allows for integration of several key advantages of nanowires with GaAs quantum dots, enabling, for instance, direct vertical stacking of multiple quantum dots, efficient waveguiding of photons emitted from quantum dots and precise positioning of quantum dots on a chip.

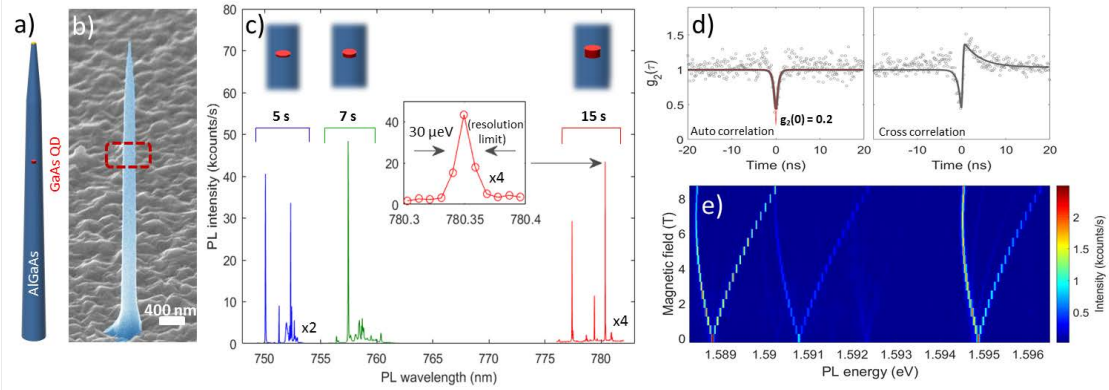

Figure 1: GaAs quantum dots in AlGaAs nanowires. a) Schematics of the sample. **b)** Scanning electron microscopy image of the sample. **c)** Photoluminescence (PL) spectra of three samples with different growth times of a quantum dot (5, 7 and 15 seconds). Inset shows a spectral zoom of one of the emission lines. **d)** Auto-correlation (left) and cross-correlation (right) measurements demonstrating single-photon and cascaded-photons emission respectively. **e)** Photoluminescence spectra under external magnetic field.

[1] D. Dalacu et al, *Nano Lett.*, **12**, 5919 (2012)
[2] M. Heiss et al, *Nature Materials* **12**, 439 (2013)
[3] V. N. Kats et al, *Semicond. Sci. Technol.*, **27**, 015009 (2012)
[4] J. Heinrich et al, *Appl. Phys. Lett.*, **96**, 211117 (2010)
[5] L. Leandro et al., In preparation

Quantum Nanophotonics

Kai Mueller, Kevin Fischer, Linda Zhang, Constantin Dory, Konstantinos Lagoudakis, Tomas Sarmiento, Armand Rundquist, and Jelena Vuckovic

Ginzton Laboratory, Stanford University, Stanford, CA, 94305-4088, USA

By embedding a single quantum emitter inside a nanoresonator that strongly localizes optical field, it is possible to achieve a very strong light –matter interaction. The strength of this interaction is characterized by the coherent emitter-field coupling strength (g), which increases with reduction in the optical mode volume and which also sets the limit on the operational speed of such a system. With InAs quantum dots inside GaAs photonic crystal cavities, coupling strengths of 40 GHz can be reached (much greater than the record values in atom-cavity QED systems). Such a quantum dot-nanocavity platform is of interest for various quantum technologies, as well as in optical switching/computing [1-3].

Finally, alternative material systems such as impurities in silicon carbide or diamond [4] that could potentially bring the described experiments to the room temperature regime are investigated, as well as the applications beyond quantum technologies, including optical switches and biosensors.

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[2] Kevin A. Fischer, Kai Müller, Armand Rundquist, Tomas Sarmiento, Alexander Y. Piggott, Yousif Kelaita, Constantin Dory, Konstantinos G. Lagoudakis, Jelena Vuckovic, "Self-homodyne measurement of a pulsed Mollow triplet in the solid state," *Nature Photonics*,vol. 10, pp. 163-166 (2016)

[3] Kai Mueller, Armand Rundquist, Kevin Fischer, Tomas Sarmiento, Konstantinos G Lagoudakis, Yousif Kelaita, Carlos Sanchez Munoz, Elena del Valle, Fabrice P. Laussy, and Jelena Vuckovic, "Coherent generation of nonclassical light on chip via detuned photon blockade" *Physical Review Letters*, vol. 114, 233601 (2015)

[4] Jingyuan Linda Zhang, Hitoshi Ishiwata, Thomas M. Babinec, Marina Radulaski, Kai Müller, Konstantinos G. Lagoudakis, Constantin Dory, Jeremy Dahl, Robert Edgington, Veronique Soulièr, Gabriel Ferro, Andrey A. Fokin, Peter R. Schreiner, Zhi-Xun Shen, Nicholas A. Melosh, Jelena Vučković, "Hybrid group IV nanophotonic structures incorporating diamond Silicon-Vacancy Color Centers," *Nano Letters, vol.* 16 (1), pp. 212-217 (2016)

Phonons as a major source of decoherence in quantum-dot-based single-photon sources

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Semiconductor quantum dots (QDs) have proven to be an excellent interface between stationary and flying qubits [1–3]. However, achieving a fully coherent electron-photon conversion remains a challenge. So far, photon coherences with indistinguishabilities of 85–99% at temperatures of 4 K have been reported [2]. This suggests that the source(s) of decoherence vary over more than an order of magnitude, i.e., the dephasing may be sensitive to the QD microscopic parameters. The origin of this dephasing mechanism is an open question.

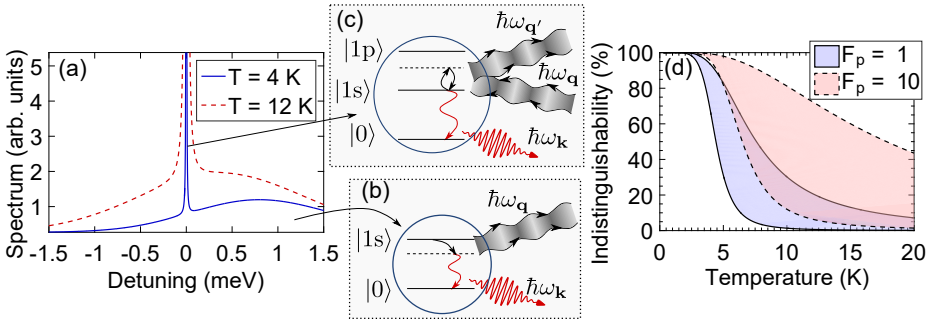

Figure 1: Phonon dephasing of QDs. (a) The QD emission spectrum consists of a narrow ZPL and broad sidebands. The latter stems from the linear exciton-phonon coupling as shown in (b), where both a phonon and a photon are emitted. (c) The ZPL is broadened by the quadratic exciton-phonon coupling consisting of virtual transitions mediated by the exciton excited state. (d) Calculated indistinguishability for pulsed resonant excitation of a QD with Purcell enhancements $F_p = \{1, 10\}$. The colored area is obtained by sweeping the spherical QD diameter from 3.5 to 6 nm, and the energy between the 1s and 2s excitons from 20 to 40 meV.

Here we show that phonons play a major role in dephasing the QD zero-phonon line (ZPL). The widely studied linear exciton-phonon coupling leads to broad sidebands in the spectrum, cf. Fig. 1(a,b), which can be eliminated by spectral filtering [2]. The quadratic exciton-phonon coupling [4] acts as a source of pure dephasing and broadens the ZPL, cf. Fig. 1(a,c).

We build on the formalism presented in [4], in which an infinite diagram of scattering events is considered. We find that a single scattering event is an excellent approximation for In(Ga)As QDs [5]. We are able to derive a simple analytic expression for the QD dephasing rate [5], which is found to scale dramatically with temperature as $\Gamma_{\rm ph} \propto T^{11}$. The calculated indistinguishability for pulsed resonant excitation is plotted in Fig. 1(d) and shows that, unlike charge and spin noise, phonon decoherence plays a major role on picosecond-to-nanosecond time scales at temperatures of 4–10 K but can be eliminated at temperatures $\lesssim 2$ K. We also find a pronounced variation in the dephasing rate with the QD size resulting in the colored area in Fig. 1(d).

[1] A. V. Kuhlmann, ..., R. J. Warburton, Nat. Commun. **6**, 8204 (2015).
[2] N. Somaschi, ..., P. Senellart, Nat. Photon. **10**, 340 (2016); S. Unsleber, ..., S. Höfling, arxiv/1512.07453.
[3] P. Lodahl, S. Mahmoodian, and S. Stobbe, Rev. Mod. Phys. **87**, 347 (2015).
[4] E. A. Muljarov and R. Zimmermann, Phys. Rev. Lett. **93**, 237401 (2004).
[5] P. Tighineanu, P. Lodahl, and A. S. Sørensen, in preparation.

Determining the photon number distribution of a bimodal quantum dot microlaser via a transition edge sensor

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Microlasers operating in the regime of cavity quantum electrodynamics (cQED) exhibit enhanced coupling of spontaneous emission into the cavity mode (high β-factor) which greatly reduce their threshold powers if compared to standard semiconductor lasers. High β-factors lead to a smooth transition from thermal to coherent emission and a smeared-out threshold characteristics which disappears completely in the case of a thresholdless laser with $\beta = 1$. In this respect it is crucial to determine the second order autocorrelation function $g^{(2)}(\tau)$ as a unambiguous proof of laser action. For these microlasers a power dependent study of $g^{(2)}(\tau)$ shows a transition from value of 2 at zero time delay ($g^{(2)}(0)$) for thermal light towards a value of 1 in the coherent regime[1]. In addition, it is interesting to have also access to the excitation power dependent photon number distribution, in particular in case of bimodal micropillar lasers[2].

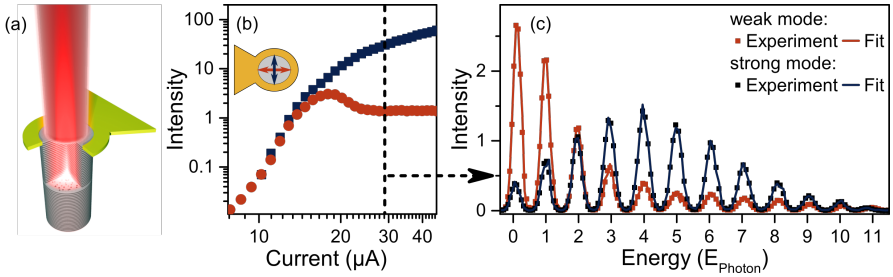

Figure 1: (a) Schematic view of an electrically contacted micropillar laser. (b) Double-logarithmic input-output characteristic of a bimodal micropillar laser. The schematic inset shows the micropillar seen from top. Arrows indicate the polarization of the two modes. (c) TES measurements exhibit thermal photon number distribution for the weak non-lasing mode and poissonian distribution for the lasing strong mode.

Here we report on a comprehensive study of a bimodal, high-β quantum dot microlaser, which includes for the first time a detailed analysis of the photon number distribution in the transition region between spontaneous emission to stimulated emission. The micropillar laser under study possesses two orthogonal modes which share the same gain medium. To determine the excitation power dependent photon number distribution we apply a state-of-the-art photon number resolving transition edge sensor (TES)[3]. Using the detector we obtain important and direct insight into the relative contribution of spontaneous emission and stimulated emission in the two modes of the microlaser which is not directly accessible by photon autocorrelation measurements. Thus, our work goes beyond the usual analysis of the photon statistics via a Hanbury-Brown and Twiss confguration. As such, TESs prove to be powerful and valuable tools to characterize and deeply understand microlasers in the few photon regime. We gratefully acknowledge NIST for providing the TES.

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[2] H. A. M. Leymann et al., Phys. Rev. A **87**, 053819 (2013)
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Exciton and Valley Dynamics in MoS_2, $MoSe_2$ and WSe_2 monolayers

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We have investigated the exciton and valley properties in transition metal dichalcogenide monolayers MoS_2, $MoSe_2$ and WSe_2 with cw and time-resolved polarized photoluminescence spectroscopy.

We present linear and non-linear optical spectroscopy experiments which evidence the giant exciton binding energy (~500 meV) and its consequences on ultrafast intrinsic radiative lifetime at low temperature [1,2].

The key role played by exciton exchange interaction will be discussed. It has a dramatic impact on both the luminescence yield through the interplay between bright and dark excitons [3,4] and on the spin/valley depolarization mechanism [5].

We also demonstrate the control of the exciton 'valley coherence' by tuning the applied magnetic field perpendicular to the monolayer plane [6,7].

[1] G. Wang *et al*, PRL **114**, 97403 (2015)

[2] D. Lagarde *et al*, PRL **112**, 047401 (2014) ; C. Robert *et al*, PRB **93**, 205423 (2016)

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[5] M. Glazov *et al*, PRB **89**, 201302(R) (2014)

[6] G. Wang *et al*, PRL **115**, 117401 (2015)

[7] G. Wang *et al*, ArXiv 1606.205 (2016)

Room temperature Tamm-Plasmon Exciton-Polaritons with a WSe_2 monolayer

Nils Lundt[‡], Sebastian Klembt[‡], Evgeniia Cherotchenko[§], Oliver Iff[‡], Anton V. Nalitov[§], Martin Klaas[‡], Simon Betzold[‡], Christof P. Dietrich[‡], Alexey V. Kavokin[§,#], Sven Höfling[‡,*] and Christian Schneider[‡]

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Transition metal dichalcogenides represent a novel emerging class of materials which seems almost ideal to study light-matter coupling in solid state. In this talk, we address the case of a single monolayer of WSe_2 embedded in a metal-based photonic structure, and discuss the observation of Tamm-Plasmon Exciton-Polaritons at room temperature. The high thermal stability and large oscillator strength of excitons in monolayers of transition metal dichalcogenides make them ideal candidates for room temperature polaritonics. Recently, photoluminescence emission in the strong coupling regime was reported for a $MoSe_2$ monolayer at 4 K [1]. Compared to $MoSe_2$, WSe_2 monolayers exhibit a strongly enhanced photoluminescence (PL) yield at room temperature and a significantly narrower PL emission linewidth compared to MoS_2 [2].

We confirm strong coupling conditions at ambient conditions, and mapped out the characteristic exciton-polariton dispersion relation by in-plane momentum-resolved PL spectroscopy. Figure 1a shows the PL spectra for various in-plane momenta. Fitting the peak energies allows to map the full dispersion relation presented in figure 1b (symbols). The acquired dispersion relations can be well fitted with a coupled-oscillator model (solid lines in figure 1b) featuring a Rabi splitting of 23.5 meV and a distinct potential minimum at zero momentum [3]

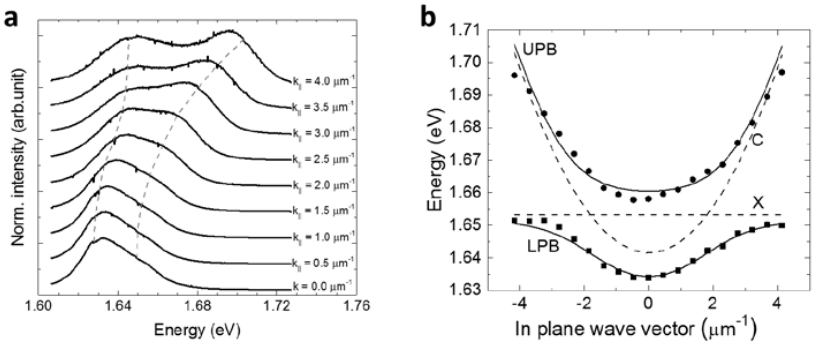

Fig. 1. a, PL spectra at various in-plane momenta. b Polariton dispersion relations at 300 K.

[1] Dufferwiel, S. *et al.,* Nat. Commun. **6,** 8579 (2015)
[2] Wang, G. *et al.,* Nat. Commun. **6,** 1–9 (2015)
[2] Lundt, N. *et al., arXiv:1604.03916* (2016) (2016)

Electric field controlled linear and non-linear light emission from few-layer MoS_2 and plasmonic antennas

M. Kaniber[a], J. Klein[a], J. Wierzbwoski[a], K. Müller[a], and J. J. Finley[a]

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Atomically thin two-dimensional semiconductors are highly attractive for new-generations of (opto-)electronic, photonic and quantum devices. Transition metal dichalcogenides (TMDCs) are of particular interest due to their direct electronic band gap in the monolayer limit, and lack of inversion symmetry that provides direct access to fascinating spin-valley photo-physics. The ability to control the optical and electronic properties of few-layer TMDC crystals is essential for both fundamental physics studies and device applications.

Here, we will present recent studies in which we employ strong (±5MV/cm) DC-electric fields to control the linear and non-linear optical response of mono- and few-layer 2H stacked MoS_2 crystals. Few layer crystals are prepared by mechanical exfoliation and embedded within the dielectric region of a Si-SiO_2-TMDC-Al_2O_3-metal photo-capacitor. Such devices provide optical access to the mono and few-layer regions of the TMDC flake while electric fields are applied perpendicular to the basal plane. We observe strong tunability of the A-exciton in emission, with DC Stark shifts up to ~16 meV from which we obtain a very low exciton polarizability $\beta = (0.58 \pm 0.25) \times 10^{-8}$Dm V^{-1} consistent with the large binding energy [1]. Interestingly, β is shown to be independent of the thickness of the 2D crystal, indicative of strong localization of both electron and hole wave-functions within each individual layer. Unlike monolayers, bilayer Bernal stacked MoS_2 are inversion symmetric in the absence of applied electric field.

Electric fields are shown to result also in tuning of the the local symmetry of the electronic structure, reflected by the strength of second-harmonic generation (SHG) [2]. Hereby, we excite bilayer regions of the MoS_2 crystal at an energy below the A-exciton using ~70 fs duration pulses (E_L=1.24 – 1.47 eV) and detect the signal at $2E_L$. The strength of the SHG is found to be strongly dependent on E_L and a pronounced resonance is observed close to the C-peak at $2E_L$=2.75eV. Moreover, the SHG signal is shown to be electrically switchable, increasing by almost two orders of magnitude upon breaking the inversion symmetry with the applied electric field.

The pronounced electrical controllability of TMDC emission and strong second order non-linearities render atomically thin materials natural candiates for integration into true nanoscale plasmonic devices. First results in coupling TMDCs to individual bowtie nanoantenns [3, 4] will be presented as well.

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[4] A. Regler *et al.* in preparation (2016).

Intervalley coupling in transition metal dichalcogenides

Gunnar Berghäuser[1,2],Malte Selig[1], Robert Schmidt[3],Robert Schneider[3],Philipp Tonndorf[3], S. Michaelis de Vasconcellos[3], Rudolf Bratschitsch[3], Andreas Knorr[1], and Ermin Malic[2]

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Monolayers of transition metal dichalcogenides (TMDs) are direct-gap semiconductors with strong light-matter and Coulomb interaction. These materials allow valley selective optical excitation via circularly polarized light suggesting the valley quantum number as a new degree of freedom. However, recent experiments characterizing the lifetime of the optically generated valley polarization indicate a strong coupling between the valleys. This is a major obstacle on the way to promising valleytronic devices, where a controllable and stable degree of valley polarization is required. Therefore, a profound microscopic understanding of the underlying elementary processes is of high interest for both fundamental research and technological applications. Here we present a joint theory-experiment study on excitonic intervalley coupling mechanisms determining the lifetime of the valley polarization in different TMD materials [1]. Our approach combines microscopic modelling based on excitonic correlation within a semiconductor Bloch equation approach with ultrafast polarization-resolved pump-probe experiments. We study the importance of different Coulomb-induced intra- and intervalley processes including electron-hole exchange coupling and direct Coulomb interaction, cf. Fig.1 (a). Finally, we discuss the influence of experimentally accessible quantities, such as excitation energy, pump fluence cf. Fig. 1(b), temperature as well as degree of sample impurity on the lifetime of the valley polarization.

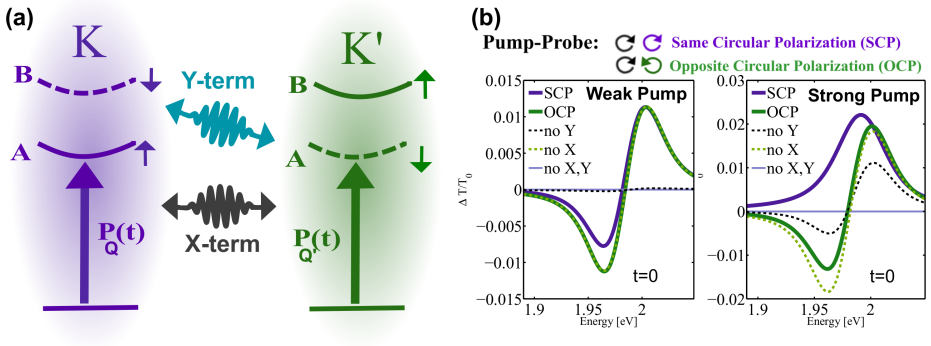

Figure 1: (a) Schematic illustration of intervalley coupling processes including the electron-hole exchange term (X) and the direct Coulomb interaction (Y). (b) Calculated differential transmission spectra as a function of energy at zero delay time in the weak and strong excitation regime illustrating the importance of X and Y intervalley coupling for pumping and probing the same valley (SCP) and different valleys (OCP).

[1] R. Schmidt, G. Berghaeuser, R. Schneider, M. Selig, P. Tonndorf. E. Malic, A. Knorr, S. Michaelis de Vasconcellos, and R. Bratschitsch, Nano Lett. 16, 2945 (2016)

Coupled spin-valley dynamics in monolayer WS_2

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Monolayer transition-metal dichalcogenides (TMDs) have recently emerged as fascinating novel materials. Like graphene, they can easily be exfoliated from bulk crystals. Unlike graphene, they have a large and direct band gap, making them attractive for potential applications in electronics or optoelectronics. They may also allow for novel device functionalities, as the spin and valley pseudospin degrees of freedom are directly coupled and stabilized by large spin splittings in the conduction and valence bands. The optical properties of these two-dimensional crystals are dominated by tightly bound electron-hole pairs (excitons) and more complex quasiparticles such as charged excitons (trions) and biexcitons.

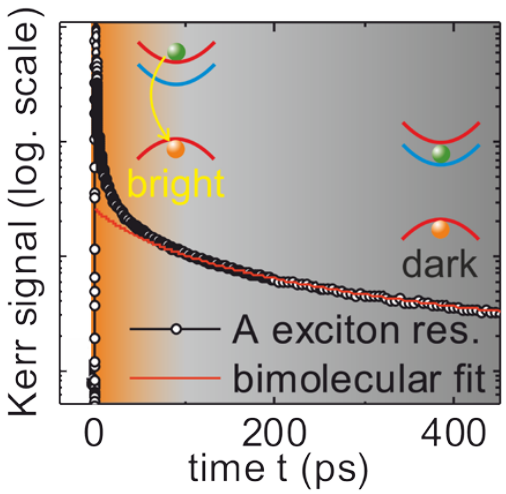

Figure 1: Time-resolved Kerr rotation trace measured on monolayer WS_2 at 4.5K under A-exciton resonant excitation.

Here, we report on the spin and valley dynamics of excitons in monolayers of WS_2. This specific TMD is characterized by a large, *negative* conduction-band spin splitting. Resonant, circularly polarized optical excitation allows us to create excitons and trions selectively either in the K^+ or the K^- valley.

We investigate the dynamics of these coupled spin-valley polarizations by time-resolved Kerr rotation (TRKR) at low temperatures. The negative sign of the conduction-band spin splitting has drastic consequences for the carrier and valley dynamics in WS_2: we observe a rapid initial decay of the valley polarization for A exciton-resonant excitation, and identify a peculiar crossover towards exciton-exciton-interaction-related decay dynamics due to the formation of a subset of optically dark A excitons. Remarkably, these dark excitons are directly observable in our TRKR measurements (see Fig. 1).

By contrast, resonant excitation of the B exciton transition leads to a very slow decay of the Kerr signal on a nanosecond timescale, making this transition highly interesting for potential valleytronic applications.

Thursday, 13.10.2016

Session Th1: 09:00 - 10:30 (Quantum Optics 2)

Session Th2: 11:00 - 12:45 (Spin Effects)

Revealing the single-exciton coherence with photonic nanostructures

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Efficient harvesting and control of the coherence generated by single emitters in solids is a prerequisite for their prospective use in optical information processing technologies. Over the last decade, four-wave mixing micro-spectroscopy (FWM) [1] has emerged as a unique approach to access coherence dynamics of excitons confined in individual quantum dots (QDs). The success of this nonlinear technique, combining optical heterodyning with spectral interferometry, relies on excellent rejection of the resonant excitation background, dominating the exciton FWM field by typically 5-6 orders of magnitude. Measuring FWM on individual strongly-confined QDs, in particular in the InAs/InGaAs QDs, is even more challenging owing to their moderate oscillator strength, thus requiring further increase of the resonant driving power. Here, we show that by embedding individual QDs in suitably designed nano-photonic devices - namely, planar microcavities [2,3], photonic waveguide antennas [4], and deterministic microlenses [5] - one can locally amplify the field around the QD dipole, permitting to drastically decrease the resonant background, and in parallel to improve the FWM collection efficiency. As a result, the sensitivity of the single-exciton coherence retrieval is outshined by up to four orders of magnitude with respect to a QD in bulk media, redefining the state-of-the-art in this field. By exploiting the three-beam FWM configuration, we demonstrate radiatively limited dephasing in InAs QDs, in the presence of a residual inhomogeneous broadening. We will then discuss the impact of acoustic phonons on the exciton dephasing, as revealed by the temperature dependence study (see Figure. 1). A novel toolbox, based on the perturbative switching between FWM and six-wave mixing responses [2], conceived to coherently control the FWM transients will be highlighted, with the emphasis on its prospective applications to control the coherence in condensed matter. As an outlook, we will focus on our current efforts to achieve the long-range radiative coupling between a pair of QDs. This is to be achieved by deterministic positioning of the QDs in a waveguide and by performing spatially-resolved FWM experiment.

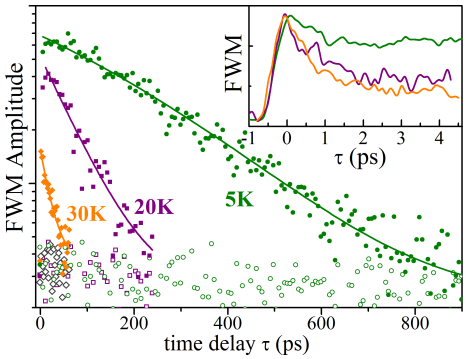

Figure 1: **Coherence dynamics of a single exciton in a deterministic InAs QD microlens measured with FWM [5]. Inset: phonon-induced dephasing during the polaron formation in the same QD [5].**

[1] W. Langbein and B. Patton, Optics Letters **31**, 1151 (2006). [2] F. Fras *et al.* Nature Photonics **10**, 155 (2016). [3] Q. Mermillod *et al.* Optica **3**, 377 (2016). [4] Q. Mermillod *et al.* Physical Review Letters **116**, 163903 (2016). [5] T. Jakubczyk *et al.* in preparation (2016).

A single-photon Fock state filter in the solid state

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One of the major roadblocks to scale optical quantum technologies is the probabilistic operation of quantum optical gates that are based on the coalescence of two indistinguishable photons. A way around this problem is to make use of the single-photon sensitivity of an atomic transition when the atom interacts with only a single mode of the optical field (one dimensional atom case [1]). In such situation, each photon sent on the device interacts with the atom: the first photon is reflected and the second one is transmitted, realizing a deterministic photon router. Such possibility has been investigated in QD-photonic crystal cavities [2], yet in an indirect way since the response was measured in crossed polarization to post-select on photons that have entered the cavity.

In this work, we demonstrate the single-photon filtering by a QD in a micropillar cavity performing as a quasi ideal one dimensional atom [3], see scheme in Fig. 1(a). The device is probed with a pulsed laser and we collect the total reflected signal in the *same* polarization. As shown in Fig. 1(b), the system presents a nonlinearity threshold for an average incident photon number as low as ~ 0.1. The $g^{(2)}(0)$ measure of the reflected light evidences that it is mostly constituted by single-photons [80% fraction of single-photons, see Fig. 1(c)] and that the multi-photon component of the field is efficiently suppressed. Three-photon correlation measurements of the reflected signal have been performed to evidence the non-poissonian statistics of the output photons.

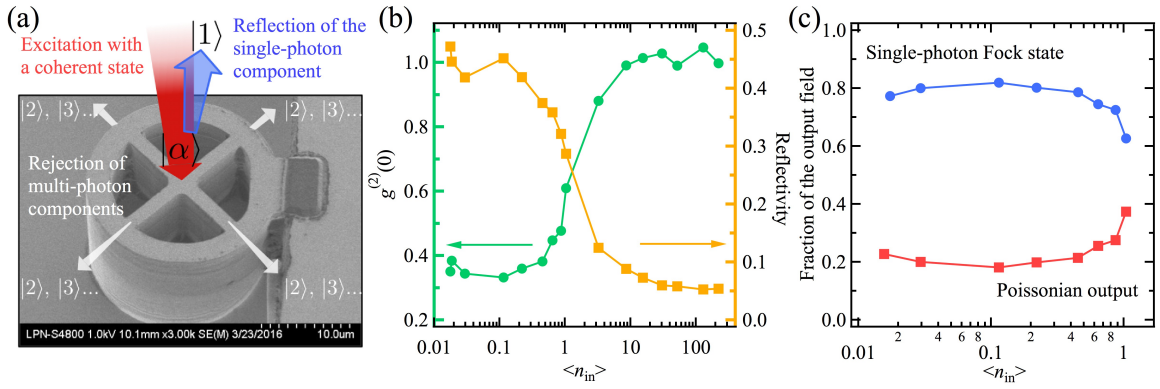

Figure 1: (a) Sketch of the working principle of the Fock state filter, $|\alpha\rangle$ represents the input laser coherent state with average photons per pulse $\langle n_{\text{in}}\rangle$ (see red arrow), the QD-cavity system scatters back mostly $|1\rangle$ Fock states (blue arrow), filtering out other multi-photon states (white arrows). (b) $g^{(2)}(0)$ (green circles, left axis) and nonlinear reflectivity curve (orange squares, right axis) as function of $\langle n_{\text{in}}\rangle$, which represents the average photon number per pulse of the poissonian input. (c) Fraction of single-photons (blue circles) and poissonian output (red squares) as function of $\langle n_{\text{in}}\rangle$.

[1] D. Valente, et al, PRA **86**, 022333 (2012).
[2] D. Englund, et al., PRL **108**, 093604 (2012); R. Bose, et al., PRL **108**, 227402 (2012).
[3] V. Giesz, et al., Nat. Comm. doi:10.1038/ncomms11986

New regimes of lasing

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Quantum-dot (QD) nanolasers hold great promise for future applications, both with respect to miniaturization and integrability, and through the possibility to exploit cavity-quantum-electrodynamical effects. In devices that operate on the basis of the interaction of individual emitters with a single mode of the electromagnetic field, questions on signatures and characteristics of lasing have to be reanswered. Quantum-optical properties, such as photon antibunching, or superthermal emission manifest from electronic correlations in the system and intermingle with regimes of thermal and coherent emission that are found below and above the threshold of any conventional laser.

We present a direct comparison of theoretical and experimental results for QD nanolasers that operate both close to the single-emitter limit yet in complementary regimes of light-matter interaction. In a QD-micropillar laser, we demonstrate the coexistence of lasing and strong coupling by combining spectroscopy, microscopic theory, and an analytic approach [1]. It turns out that the transition to weak coupling is first triggered by the onset of stimulated emission and takes place at one order of magnitude lower excitation power than predicted from conventional criteria. We explain this discrepancy by considering higher excited states that become relevant under stronger excitation needed to reach the laser threshold.

In a photonic crystal nanocavity laser, only 4 QDs are found to be close to resonance and the emission spectrum consists of their individual transition lines [2]. Nevertheless, lasing is achieved irrespective of spectral detuning of the cavity mode, indicating a dominant role of non-resonant coupling between QD-multi-exciton transitions and the cavity mode. Despite signatures of individual emitters in the spectrum, studies of the statistical properties of the emission reveal collective effects that are mediated by the light field: The emission below threshold carries signatures of subradiant suppression of spontaneous emission that is reflected both in super-thermal bunching in the photon autocorrelation function, and in a reduction of a pump-rate dependent β factor that is introduced to characterize systems, in which the emission properties are determined by the excitation-dependent interplay of different multi-exciton states.

Both realizations of few-emitter nanolasers provide insight into the role of contributions from detuned "background" emitters and into new regimes of lasing, such as in the regime of strong coupling and lasing from multi-exciton states. Microscopic theory plays an important role in identifying such new effects by accounting for electronic correlations in the gain material and their link to photon correlations that largely determine the emission properties.

[1] F. Gericke, C. Gies *et al.*, submitted for publication, arXiv:1606.05591 (2016).
[2] S. Lichtmannecker, M. Florian *et al.*, submitted for publication, arXiv:1602.03998 (2016).

Rotational Doppler Effect in Nonlinear Optics

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In 1842 Christian Doppler predicted that emitted waves by moving objects will undergo a frequency shift that directly depends on the relative speed between the observer and the object [1]. Only three years later Doppler's prediction was verified in a very spectacular experiment for acoustic waves by the Dutch physicist Buys Ballot. Since then the translational Doppler effect of electromagnetic and sound waves has been successfully applied in measurements of the speed and direction of vehicles, astronomical objects, blood flow in human bodies, and for the global positioning system (GPS). The well understanding of the Doppler effect in quantum mechanics has been used to interpret the broadened emission spectra of atoms and benefited the advanced technology in the field of cooling and trapping of atoms with laser light.

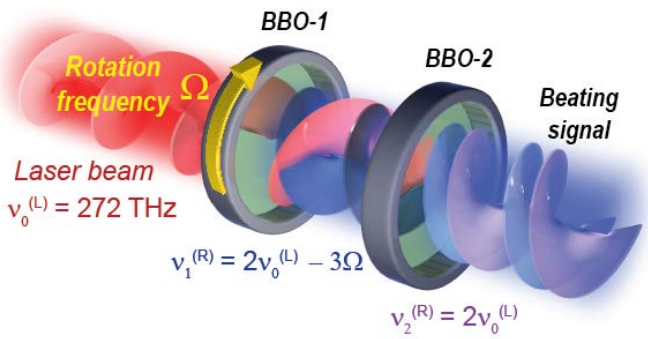

Fig.1: Schematic illustration of the rotational Doppler shift experiment for second harmonic generation. The laser beam passes through two BBO crystals, whereas one is rotating at the angular speed Ω, leading to a shifted SHG signal. At the detector the resulting beating signal of both SHG signals is measured.

Despite the numerous successful applications of the translational Doppler effect, it fails to measure the rotation frequency of a spinning object when the probing wave propagates along its rotation axis. This constraint was circumvented by deploying the angular momentum of electromagnetic waves [2] – the so called rotational Doppler effect.

Here, we will report on the first demonstration of an optical rotational Doppler shift in nonlinear optics, which was predicted nearly 50 years ago [3]. The Doppler frequency shift was determined for the second harmonic generation of a circularly polarized beam passing through a spinning nonlinear optical BBO crystal with three-fold rotational symmetry. We found that the second harmonic generation signal with a circular polarization opposite to that of the fundamental beam experiences a Doppler shift of three times the rotation frequency of the optical crystal [4]. This demonstration is of fundamental significance in nonlinear optics, as it provides us new insight into the interaction of light with moving media in the nonlinear optical regime.

[1] C. Doppler, Abh. Königlichen Böhmischen Ges. Wiss. **2**, 465-482 (1843).
[2] J. H. Poynting, Proc. R. Soc. London A **82**, 560-567 (1909).
[3] H. J. Simon, N. Bloembergen, Phys. Rev. **171**, 1104-1114 (1968).
[4] G. Li, T. Zentgraf, S. Zhang, Nature Physics **12**, 736-740 (2016).

Generating correlations between multiple spins via optical measurement

M. Atatüre

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Optically active spins confined in solids, such as semiconductors and diamond, provide interesting and rich physical systems. Their inherently mesoscopic nature leads to a multitude of dynamics within the solid-state environment of spins, charges, vibrations and light. While the quantum optics has provided the toolbox for advanced spectroscopic investigations for these interaction mechanisms, it has also offer solution possibilities for their detrimental effects for the realisation of operational quantum devices. Implementing a high level of control on these constituents and their interactions with each other creates exciting opportunities for realizing stationary and flying qubits within the context of spin-based quantum information science. In this talk, I will provide a snapshot of the progress and challenges for quantum optically interconnected solid-state spins, as well as first steps towards hybrid distributed quantum networks involving other physical systems. In particular, I will talk about how one can generate high-bandwidth quantum correlations between distant noninteracting electron spins in self-assembled quantum dots using quantum erasure concepts on the coherently scattered single photons from the two quantum dots.

Interplay of Electron and Nuclear Spin Noise in n -Type GaAs

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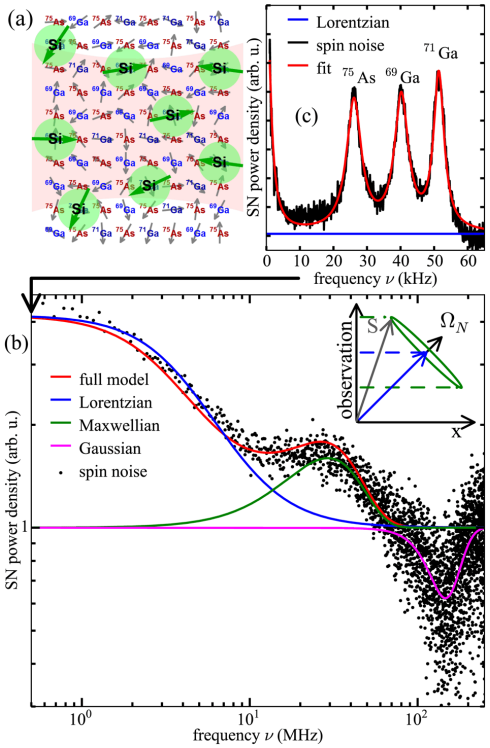
Harnessing spin coherence is one of the fundamental topics in current research concerning prospective solid state based quantum information processing. A potential system for this task are weakly interacting donor bound electrons in n-doped GaAs since the widely spaced, quasi-isolated electrons act as an ensemble of identical, individually localized atoms. However, the challenge of this approach is the inherent interaction with the nuclear spin bath. Here, we present spin-noise spectroscopy measurements on an ensemble of donor-bound electrons in ultrapure GaAs:Si covering temporal dynamics over six orders of magnitude ranging from milliseconds to nanoseconds [1]. The spin-noise spectra detected at the donor-bound exciton transition show the multifaceted dynamical regime of the ubiquitous mutual electron and nuclear spin interaction typical for III-V-based semiconductor systems. The experiment distinctly reveals the finite Overhauser shift of an electron spin precession at zero external magnetic field together with an unmodulated contribution around zero frequency stemming from the electron spin components parallel to the nuclear spin fluctuations. Moreover, at very low frequencies, features related with time-dependent nuclear spin fluctuations are clearly resolved making it possible to study the intricate nuclear spin dynamics at zero and low magnetic fields. The experimental findings are well described by a microscopic model including both of electron and nuclear spin noise. [1, 2]



(a) Polarized laser light (red) samples the spin dynamic of an ensemble of donor-bound electrons interacting with the host nuclear magnetic moments. (b) SN difference spectrum of donor-bound electrons (at B=0 minus at B=22 mT). Blue, green, and magenta curves represent the individual contributions. The spectrum is rescaled and shifted to positive noise power densities. (c) SN difference spectrum in the low-frequency range measured at B=3.75 mT. Contributions from the individual host lattice isotopes are clearly resolved.

[1] F. Berski, J. Hübner, M. Oestreich, A. Ludwig, A. D. Wieck, and M. Glazov, Interplay of Electron and Nuclear Spin Noise in GaAs, Physical Review Letters **115**, 176601 (2015) + supplemental.

[2] M. Glazov, Spin noise of localized electrons: Interplay of hopping and hyperfine interaction, Physical Review B **91**, 195301 (2015).

Optical spin orientation of an individual Fe^{2+} ion in a QD

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Processing and storing information using single dopants in semiconductors, major objectives of solotronics [1], require efficient optical pumping of an individual spin. For a single manganese ion it has been achieved by injection of spin polarized excitons into a quantum dot (QD) containing a single Mn^{2+} dopant with the use of circularly polarized optical excitation. Such an optical spin orientation was demonstrated using resonant excitation of CdTe QD pairs [2] and non-resonant excitation of CdSe QDs [3]. However, utilization of such an approach in other systems is not necessarily straightforward. In the case of recently presented system of nuclear spin-free Fe^{2+} ion in a CdSe QD [4], the zero-field splitting of the Fe^{2+} spin states may be considered as major obstacle in obtaining efficient spin orientation. In this work, however, we show that upon the application of even a small magnetic field it is possible to optically orient the spin of theFe^{2+} ion with a comparable efficiency to the one shown previously in similar systems.

The Fe^{2+} ion in bulk semiconductors exhibits a single non-degenerate ground state, which cannot be optically manipulated and used to store the quantum information. In an epitaxially strained nanostructure, however, reconfiguration of the Fe^{2+} energy spectrum leads to doubly degenerate ground state [4] split only by energy in the range of μeV. Since this splitting is much smaller than the strength of the *s,p-d* exchange interaction between the ion and the exciton, the optical orientation of the Fe^{2+} spin can be achieved in a similar way as in the case of Mn^{2+} ion, as long as the exciton is present in the QD. However, after the exciton recombination the Fe^{2+} spin undergoes fast oscillations between two spin-mixed eigenstates, which immediately cancels any exciton-induced orientation. This process can be suppressed by the application of a magnetic field as low as few tenths of Tesla. Under such conditions, the efficiency of the Fe^{2+} spin orientation becomes similar to the one obtained previously for the Mn^{2+} ion in the same QD material system (Fig. 1). Therefore the Fe^{2+} ion in a CdSe QD can be used as a robust, optically-controllable two-level system free of any nuclear spin fluctuations, thus a perfect candidate for quantum information processing.

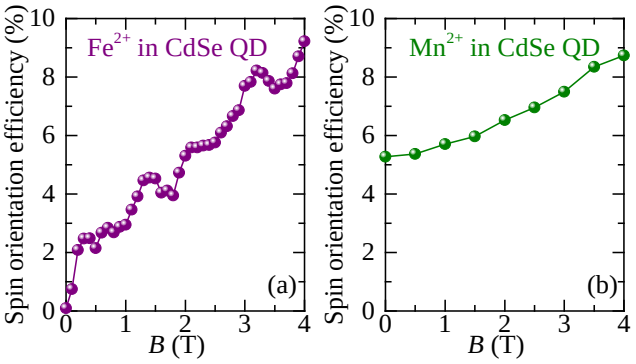

Fig. 1. Magnetic field dependence of an optical spin orientation efficiency for an individual (a) Fe^{2+} and (b) Mn^{2+} ion in a CdSe QD.

[1] J. Kobak et al., *Nature Communications* **5**, 3191 (2014).
[2] M. Goryca et al., *Physical Review Letters* **103**, 087401 (2009).
[3] T. Smoleński et al., *Phys. Rev. B.* **91**, 045303 (2015).
[4] T. Smoleński et al., *Nature Communications* **7**, 10484 (2016).

Optically probing spin qubit coherence without coherent control

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We demonstrate an entirely new method to probe quantum measurement phenomena in semiconductor quantum dot (QD) spin qubits [1]. In addition to providing direct evidence for the quantum nature of solid state qubits, we show that our method has practical importance since it provides a completely alternative route for measuring ensemble and quantum dephasing times, T_2* and T_2, using only repeated projective measurements and without the need for coherent spin control.

Our approach is based on measuring time-correlators of a spin qubit in an optically active QD beyond the second order. The measurement principle is illustrated in figure 1a. We utilize a quantum dot spin-storage structure to initialize a single electron spin in a quantum dot subject to a magnetic field applied in Voigt geometry through tunnel ionization and perform repeated projective measurements of the spin at times t_1 and t_2. This measurement is repeated, corresponding to ensemble averaging, and the resulting third order time correlations (figure 1b) reveals rich physics: For times t_1 or t_2 <T2* Larmor precession is observed which reveals the ensemble dephasing time T2*. Importantly, even though this correlation map is obtained through averaging many measurements for times t_1 and t_2 > T_2* along the diagonal oscillations are observed that decay with the dephasing time T_2 and allow its determination even without the need for coherent spin control. Finally, combining the third-order time correlator with the second-order time correlator allows to demonstrate a violation of Leggett-Garg type inequalities for certain times providing clear evidence for the quantum nature of the quantum dot spin.

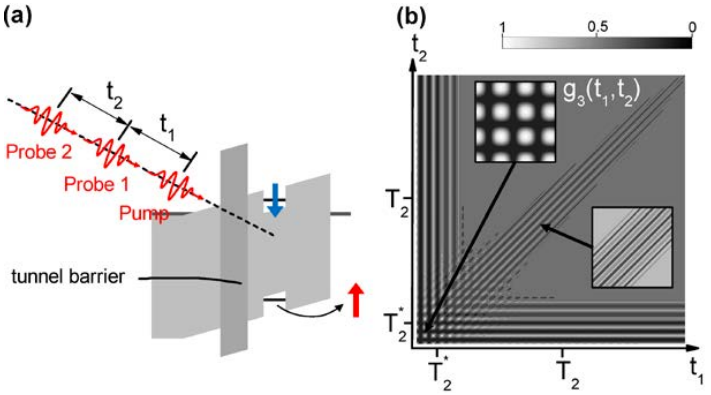

Figure 1: (a) Schematic illustration of the measurement principle. (b) Third-order time correlator of a single spin revealing T_2, T_2* and violations of Leggett-Garg inequalities.

[1] A. Bechtold et al. arXiv:1511.03684 (2015) – accepted for publication in Phys. Rev. Lett.

Picosecond control of excitons and spins in InGaAs quantum dots

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Recent progress on the control of excitons and spins in self-assembled InGaAs quantum dots by picosecond laser pulses will be reviewed. Detailed measurements of the laser-driven Rabi rotations using photocurrent read-out indicate that the dominant dephasing mechanism at high pulse areas is acoustic phonon scattering [1]. This coupling creates phonon sidebands on the neutral exciton, which allows exciton population pumping at positive detuning. At high pulse areas the population of the two-level system can be inverted by dynamic vibronic coupling, even though the pumping mechanism is incoherent [2,3]. This inversion occurs by rapid thermalization of the optically dressed states, and is relatively insensitive to small fluctuations in the excitation pulse area or frequency. For negative detunings, ultrafast de-excitation has been demonstrated, opening possibilities for ultrafast switching of the exciton state [4].

The use of photocurrent techniques also permits the initialization of single holes spins, which are particularly interesting on account of their small hyperfine interaction and hence long dephasing time. In these experiments, the different tunnelling rates of the electrons and holes are exploited to create spin-polarized holes after excitation of spin-polarized neutral excitons with circularly-polarized photons. By using sequences of time-delayed pulses, it has been possible to demonstrate picosecond preparation, full control, and read-out of a single hole spin [5]. Very high fidelity initialization has been demonstrated in a dot with small fine-structure splitting (FSS) in a regime where the hole spin lifetime exceeds the T_2^* dephasing time [6]. In another dot with larger FSS, the optical Stark effect was used to reduce the FSS and hence increase the fidelity, demonstrating the viability of hole spin control in dots with non-optimal FSS.

Resonance fluorescence techniques provide an alternative method for reading out the state of the system at the end of the pulse. I will conclude the presentation by describing very recent results in which the use of a nano-cavity is shown to strongly enhance the dynamic vibronic coupling process.

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	Sunday	Monday	Tuesday	Wednesday	Thursday	
09:00		Opening	**Kavokin**	**Gérard/Vos**	**Kasprzak**	09:00
09:15		**Efros**				09:15
09:30			Heinze	Coles	Solanas	09:30
09:45		**Dubertret**	Klembt	Pedersen	Florian	09:45
10:00			**Chatterjee**	**Müller**	**Zentgraf**	10:00
10:15		Achtstein				10:15
10:30		Coffee Break	Coffee Break	Tighineanu	Coffee Break	10:30
10:45				Schlottmann		10:45
11:00		**Potemski**	**Gershoni**	Coffee Break	**Atatüre**	11:00
11:15						11:15
11:30		Kern	**Chekhovich**	**Korn**	Hübner	11:30
11:45		Sortino			Goryca	11:45
12:00		**Jahnke**	Reiter	**Schneider**	Simmet	12:00
12:15			van der Wal		**Fox**	12:15
12:30		Lunch Break	Lunch Break	Kaniber		12:30
12:45				Berghäuser	Closing	12:45
13:00				**Marie**		13:00
13:15						13:15
13:30				Break		13:30
13:45						13:45
14:00		**Shields**	**Norris**	Conference Excursion Zollern Colliery		14:00
14:15						14:15
14:30		Snijders	Davis			14:30
14:45		Müller	Lippitz			14:45
15:00		**Moskalenko**	**Cundiff**			15:00
15:15						15:15
15:30		Poster Session P1	Poster Session P2			15:30
15:45						15:45
16:00						16:00
16:15						16:15
16:30						16:30
16:45						16:45
17:00						17:00
17:15						17:15
17:30						17:30
17:45						17:45
18:00	Welcome Reception			Stadium		18:00
18:15						18:15
18:30				Tour		18:30
18:45						18:45
19:00				Conference Dinner		19:00
19:15						19:15
19:30						19:30
19:45						19:45
20:00						20:00
20:15						20:15
20:30						20:30
20:45						20:45