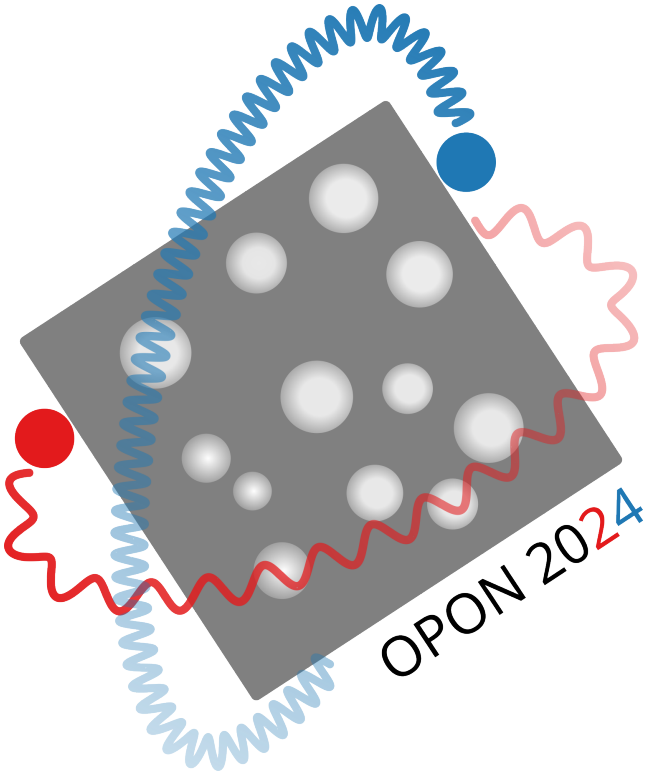
7th International Workshop on the Optical Properties of Nanostructures

Wrocław, 14-16 February 2024



Program and Abstracts

UNTERSTÜTZT VON / SUPPORTED BY

Alexander von HUMBOLDT STIFTUNG

Politechnika Wrocławska

Universität Münster

Contents

Schedule OPON 2024

	Wednesday 14 February	Thursday 15 February	Friday 16 February
09:00	Registration		
	Opening	Birowska	Cygorek
	Nysten	Bratschitsch	Villafañe
10:00	Hagen		
	Mayer	Grzybowski	Dalla
	Jürgens	Łopion	Michaelis de Vasconcellos
	Weiß	Woźniak	Mrowiński
11:00	Coffee Break	Coffee Break	Coffee Break
	Knorr	Niehues	Pieczarka
12:00	Rosati	Akimov	Goryca
	Zięba-Ostój	Dyksik	Gawełczyk
	Steeger	Kopteva	Closing
	Heckötter	Wagner	
13:00	Lunch	Lunch	Lunch
14:00			
	Reitzenstein	Bracht	
15:00	Gawarecki	Syperek	
	Vajner	Nimmesgern	
16:00	Coffee Break	Coffee Break	
	Kazimierczuk	Poster	
17:00	Wigger		
	Komar		
18:00	City walk		
19:00			
20:00			

Welcome to OPON 2024

Dear Colleagues,

In 2011 we initiated a series of workshops on the optical properties of nanostructures. The previous events (initially under the name of *Polish-German Workshops*) were organized in Wrocław (2011 and 2016), Münster (2012 and 2018), Bayreuth (2013), and Warsaw (2020). From the beginning, the idea behind these topically focused workshops was to provide a forum for the exchange of ideas related to theoretical and experimental work in the field of optical properties of nanostructures and related solid state systems. The workshops have provided an opportunity to discuss and analyze current problems in nanostructure research, to strengthen existing collaborations and create new scientific links, and to help researchers (and students) to keep track of current developments in a relatively narrow field of solid state physics.

All six previous workshops were extremely successful, with very high acceptance rate by the invited speakers and with considerable participation of students and young scientists. After some years of break, which was partly due to the Covid pandemic, we decided to organize the 7^{th} workshop of the series. This has been made possible thanks to funding from the Alexander von Humboldt Foundation within a Research Group Linkage Grant between the groups in Münster (T. Kuhn. H. Krenner) and in Wrocław (P. Machnikowski).

The 7^{th} OPON Workshop in 2024 follows the general idea of topically focused, short scientific events that have been so successful in the past but the detailed scope of the workshop has evolved, corresponding to the research interests of our community. Quantum-dot-related topics evolve more and more towards applications, although there is still much space for answering fundamental questions. The importance of 2D materials is growing, which is reflected by their share in this year's program. The evergreen topics of phonons, excitons and magnetism offer new insights into new systems and materials.

While the topical focus may shift with time, OPON 2024 remains the same workshop as it was 13 years ago: a topically focused, compact, two-and-a-half-day event with a good balance of invited and contributed talks and an opportunity to present the whole scope of activities of each research group in the form of posters, in most cases presented by PhD and MSc students. We are sure that this will offer the senior researchers an opportunity to exchange ideas, strengthen collaborations and look for new research links, while students and post-docs will be able to hear a series of excellent talks given by leading researchers in the field. At the same time, the group leaders will have an opportunity to assess and appreciate the potential of young researchers.

The Workshop is organized by the Institute of Theoretical Physics of Wrocław University of Science and Technology in collaboration with the Institute of Solid State Theory and the Physical Institute of the University of Münster.

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

The Program Committee:
Vollrath Martin Axt,
Joanna Jadczak,
Piotr Kossacki,
Hubert Krenner,
Tilmann Kuhn,
Paweł Machnikowski,
Doris Reiter.

Practical Information

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

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

Lunches and coffee breaks are provided free of charge during the three days for all the participants of the workshop. Lunches will be served at the university canteen in the "Students' Culture Zone" (Strefa Kultury Studenckiej, building C-18; move slightly left and follow straight ahead after leaving D-20). The participants will be provided with lunch vouchers at registration. Coffee breaks will be organized in the space adjacent to the conference hall (near the poster space).

We invite you to take part in a guided city walk throughout the historical city center of Wrocław. The walk will start at 18:00 on Wednesday and the meeting point is at the back (East) of the Wrocław cathedral in the heart of the Cathedral Island (Ostrów Tumski).

The members of the local groups will be happy to help you if you encounter any problem.

The Organizing Committee:
Michał Gawełczyk,
Paweł Machnikowski.

Invited Speakers

- **Ilya Akimov** (Technische Universität Dortmund)
  Coherent optical spectroscopy in perovskites semiconductors
- **Magdalena Birowska** (Warsaw University)
  Tuning magnetic and optical properties of layered MPX_3 crystals
- **Thomas Bracht** (Münster University)
  Photons from quantum dot excited by the SUPER scheme
- **Rudolf Bratschitsch** (Münster University)
  Broadband high-performance Faraday rotation spectroscopy of 2D materials and thin magnetic films
- **Moritz Cygorek** (Technische Universität Dortmund)
  Cooperative emission from solid-state quantum emitters
- **Krzysztof Gawarecki** (Wrocław University of Science and Technology)
  Atomistic and continuous media approaches to model spectral properties of semiconductor quantum dots
- **Mateusz Goryca** (Warsaw University)
  Transition Metal Dichalcogenide monolayers as a platform to study electron-electron interactions and many-body correlations
- **Tomasz Kazimierczuk** (Warsaw University)
  Ultrafast dynamics of excitons in monolayers of semiconductor TMDs
- **Andreas Knorr** (Technische Universität Berlin)
  How to make dark excitons bright
- **Iris Niehues** (Münster University)
  Investigating the properties of 2D materials with near-field techniques on the nanoscale
- **Emeline Nysten** (Münster University)
  Acousto-optoelectric spectroscopy on transition metal dichalcogenide monolayer with surface acoustic waves
- **Maciej Pieczarka** (Wrocław University of Science and Technology)
  Thermalization and Bose-Einstein condensation of light in semiconductor lasers
- **Stephan Reitzenstein** (Technische Universität Berlin)
  Deterministically fabricated single-quantum-dot devices for photonic quantum technologies
- **Roberto Rosati** (Philipps-Universität Marburg)
  Interface engineering of charge-transfer excitons in 2D lateral heterostructures
- **Marcin Syperek** (Wrocław University of Science and Technology)
  Deterministic and scalable Purcell-enhanced single-photon emitters in the telecom C-band
- **Viviana Villafañe** (Technische Universität München)
  Ultrafast electrical switching and charge state control of silicon vacancy centers in diamond
- **Daniel Wigger** (Münster University)
  Local field effects and a new destructive photon echo in a 2D semiconductor

Conference Program

Wednesday, 14 February 2024

08:45 – 09:00 Registration

09:00 – 09:15 Opening session

Session We A: *Phonons*

Chair: Tilmann Kuhn

09:15 – 09:45 We A-1 (invited)

E. D. S. Nysten[1], M. Weiß[1], B. Mayer[1], T. Petzak[2], C. Strobl[1], U. Wurstbauer[1], and H. J. Krenner[1]

[1]*Physikalisches Institut, University of Münster, Münster, Germany,* [2]*Lehrstuhl für Experimentalphysik 1, Universität Augsburg, Augsburg, Germany*

Acousto-optoelectric spectroscopy on transition metal dichalcogenide monolayer with surface acoustic waves

09:45 – 10:00 We A-2

P. C. A. Hagen[1], M. Bozzio[2], M. Cygorek[3], A. Vagov[1], D. E. Reiter[3], and V. M. Axt[1]

[1]*Universität Bayreuth, Bayreuth, Germany,* [2]*University of Vienna, VCQ, Vienna, Austria,* [3]*TU Dortmund, Dortmund, Germany*

Phonons can increase Photon Number Coherence

10:00 – 10:15 We A-3

B. Mayer, C. Strobl, M. Weiß, H. J. Krenner, U. Wurstbauer, and E. D. S. Nysten

Institute of Physics, University of Münster, Münster, Germany

Surface acoustic wave-controlled photocurrent in few-layer WSe_2

10:15 – 10:30 We A-4

K. Jürgens[1], D. Wigger[2], and T. Kuhn[1]

[1]*Institute of Solid State Theory, University of Münster, Münster, Germany,* [2]*Department of Physics, University of Münster, Münster, Germany*

Phonon sidebands in the absorption spectra of moiré exciton-polaritons

10:30 – 10:45 We A-5

D. D. Bühler[1], A. Crespo-Poveda[2], E. D. S. Nysten[3], J. J. Finley[4], K. Müller[4], P. V. Santos[2], M. M. De Lima Jr.[1], H. J. Krenner[3], and **M. Weiß**[3]

[1]*Materials Science Institute (ICMUV), Universitat de València, Valencia, Spain,* [2]*Paul-Drude-Institut für Festkörperelektronik, Berlin, Germany,* [3]*Institute of Physics, University of Münster, Münster, Germany,* [4]*Walter Schottky Institut and Electrical Engineering, TU München, Garching, Germany*

On-chip generation and dynamic piezo-optomechanical rotation of single photons

10:45 – 11:15 Coffee Break

Session We B: *Excitons*

Chair: Rudolf Bratschitsch

11:15 – 11:45 We B-1 (invited)

A. Knorr, L. Greten, H. Mittenzwey, R. Salzwedel, and M. Katzer

Nichtlineare Optik und Quantenelektronik von Halbleitern, Institut für Theoretische Physik, Technische Universität Berlin, Berlin, Germany

How to make dark excitons bright

11:45 – 12:15 We B-2 (invited)

R. Rosati[1], I. Paradisanos[2,3], L. Huang[4], Z. Gan[5], A. George[5], K. Watanabe[6], T. Taniguchi[6], L. Lombez[2], P. Renucci[2], A. Turchanin[5], B. Urbaszek[2,7], and E. Malic[1]

[1]*Department of Physics, Philipps-Universität Marburg, Marburg, Germany,* [2]*Université de Toulouse, INSA-CNRS-UPS, LPCNO, Toulouse, France,* [3]*Institute of Electronic Structure and Laser, Heraklion, Greece,* [4]*Department of Chemistry, Purdue University, West Lafayette, IN, USA,* [5]*Friedrich Schiller University Jena, Institute of Physical Chemistry, Jena, Germany,* [6]*National Institute for Materials Science, Namiki, Tsukuba, Japan,* [7]*Institute of Condensed Matter Physics, Technische Universität Darmstadt, Germany*

Interface engineering of charge-transfer excitons in 2D lateral heterostructures

12:15 – 12:30 We B-3

E. Zięba-Ostój[1], E. Rogowicz[1], A. Paralikis[2], C. Piccinini[2], R. Perea-Causin[3], E. Malic[4], B. Munkhbat[2], and M. Syperek[1]

[1]*Department of Experimental Physics, Faculty of Fundamental Problems of Technology, Wrocław University of Science and Technology, Wrocław, Poland,* [2]*DTU Electro, Technical University of Denmark, Kongens Lyngby, Denmark,* [3]*Department of Physics, Chalmers University of Technology, Göteborg, Sweden,* [4]*Department of Physics, Philipps-Universität Marburg, Marburg, Germany*

Optical properties and dynamics of neutral and charged excitons in the $MoTe_2$ monolayer in a metal-oxide-semiconductor device

12:30 – 12:45 We B-4

P. Steeger[1], J.-H. Graalmann[2], R. Schmidt[1], P. Marauhn[2], M.-C. Heissenbüttel[2], J. Nellesen[2], I. Kupenko[3], C. Sanchez-Valle[3], S. Michaelis de Vasconcellos[1], M. Rohlfing[2], and R. Bratschitsch[1]

[1]*Institute of Physics, University of Münster, Münster, Germany,* [2]*Institute of Solid State Theory, University of Münster, Münster, Germany,* [3]*Institute of Mineralogy, University of Münster, Münster, Germany*

Optical spectroscopy of intra- and interlayer excitons in atomically thin MoS_2 under high pressure

12:45 – 13:00 We B-5

J. Heckötter, M. Bergen, B. Panda, K. Brägelmann, M. Harati, S. Siegeroth, M. Aßmann, and M. Bayer

Experimentelle Physik 2a, Technische Universität Dortmund, Dortmund, Germany

Giant interactions of Rydberg excitons in Cu2O

13:00 – 14:30 Lunch

Session We C: *Quantum dots I*

Chair: Grzegorz Sęk

14:30 – 15:00 We C-1 (invited)

S. Reitzenstein

Institute of Solid State Physics, Technische Universität Berlin, Berlin, Germany

Deterministically fabricated single-quantum-dot devices for photonic quantum technologies

15:00 – 15:30 We C-2 (invited)

K. Gawarecki

Institute of Theoretical Physics, Wrocław University of Science and Technology, Wrocław, Poland

Atomistic and continuous media approaches to model spectral properties of semiconductor quantum dots

15:30 – 15:45 We C-3

D. A. Vajner[1], P. Holewa[2,3,4], E. Zięba-Ostój[2], M. Wasiluk[2], M. von Helversen[1], A. Sakanas[3], A. Huck[5], K. Yvind[3,4], N. Gregersen[3], A. Musiał[2], M. Syperek[2], E. Semenova[3,4], and T. Heindel[1]

[1]*Institute of Solid State Physics, Technical University of Berlin, Germany,* [2]*Department of Experimental Physics, Faculty of Fundamental Problems of Technology, Wrocław University of Science and Technology, Wrocław, Poland,* [3]*DTU Electro, Department of Electrical & Photonics Engineering, Techn. Univ. of Denmark,* [4]*NanoPhoton - Center for Nanophotonics, Technical University of Denmark,* [5]*Center for Macroscopic Quantum States (bigQ), Technical University of Denmark*

Progress in telecom C-band single photon generation using semiconductor quantum dots

15:45 – 16:15 Coffee Break

Session We D: *Dynamics and optical properties of 2D systems*

Chair: Magdalena Birowska

16:15 – 16:45 We D-1 (invited)

T. Kazimierczuk

Faculty of Physics, University of Warsaw, Poland

Ultrafast dynamics of excitons in monolayers of semiconductor TMDs

16:45 – 17:15 We D-2 (invited)

D. Wigger[1], T. Hahn[2], P. Machnikowski[3], T. Kuhn[2], and J. Kasprzak[4]

[1] *Department of Physics, University of Münster, Münster, Germany,* [2] *Institute of Solid State Theory, University of Münster, Münster, Germany,* [3] *Institute of Theoretical Physics, Wrocław Tech, Wrocław, Poland,* [4] *Institut Néel, University of Grenoble, Grenoble, France*

Local field effects and a new destructive photon echo in a 2D semiconductor

17:15 – 17:30 We D-3

R. Komar[1], A. Łopion[1], K. Mosina[2], A. Soll[2], Z. Sofer[2], P. Kossacki[1] and T. Kazimierczuk[1]

[1] *Faculty of Physics, University of Warsaw, Warsaw, Poland,* [2] *Department of Inorganic Chemistry, University of Chemistry and Technology Prague, Prague, Czech Republic*

Magnetically tunable reflectivity features in 2D layered magnetic semiconductor CrSBr

18:00 – 20:00 City walk

Thursday, 15 February 2024

Session Th A: *Magnetism and spin-related phenomena*

Chair: Piotr Kossacki

09:00 – 09:30 Th A-1 (invited)

M. Birowska

Faculty of Physics, University of Warsaw, Warsaw, Poland

Tuning magnetic and optical properties of layered MPX_3 crystals

09:30 – 10:00 Th A-2 (invited)

R. Bratschitsch

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

Broadband high-performance Faraday rotation spectroscopy of 2D materials and thin magnetic films

10:00 – 10:15 Th A-3

M. J. Grzybowski[1], C. Autieri[2], J. Domagala[3], C. Krasucki[1,3], A. Kaleta[3], S. Kret[3], K. Gas[3,4], M. Sawicki[3], R. Bożek[1], J. Suffczyński[1], and W. Pacuski[1]

[1]*Faculty of Physics, University of Warsaw, ul. Pasteura 5, Warsaw, Poland,* [2]*International Research Centre Magtop, Institute of Physics, Polish Academy of Sciences, Warsaw, Poland,* [3]*Institute of Physics, Polish Academy of Sciences, Warsaw, Poland,* [4]*Center for Science and Innovation in Spintronics, Tohoku University, Sendai, Japan*

Wurtzite MnSe – epitaxy and properties of an altermagnetic candidate

10:15 – 10:30 Th A-4

A. Łopion, A. Bogucki, K. E. Połczyńska, W. Pacuski, T. Kazimierczuk, A. Golnik, and P.Kossacki

Faculty of Physics, Institute of Experimental Physics, University of Warsaw, Warszawa, Poland

Temperature of magnetic ions in optically detected magnetic resonance measurement of p-type doped (Cd,Mn)Te QWs

10:30 – 10:45 Th A-5

T. Woźniak[1,2], P. E. Faria Junior[3], A. Chaves[4,5], and J. Kunstmann[6]

[1]*Wrocław University of Science and Technology, Poland,* [2]*University of Warsaw, Poland,* [3]*University of Regensburg, Germany,* [4]*Universidade Federal do Cear'a, Brazil,* [5]*University of Antwerp, Belgium,* [6]*Technische Universität Dresden, Germany*

Engineering of excitonic g-factors in van der Waals structures

10:45 – 11:15 Coffee Break

Session Th B: *Perovskites, spectroscopy*

Chair: Joanna Jadczak

11:15 – 11:45 Th B-1 (invited)

I. Niehues[1,2]

[1] *Institute of Physics, University of Münster, Münster, Germany,* [2] *CIC nanoGUNE BRTA, Donostia-San Sebastian, Spain*

Investigating the properties of 2D materials with near-field techniques on the nanoscale

11:45 – 12:15 Th B-2 (invited)

I. Akimov

Experimentelle Physik 2, Technische Universität Dortmund, Dortmund, Germany

Coherent optical spectroscopy in perovskites semiconductors

12:15 – 12:30 Th B-3

M. Dyksik[1], D. Beret[2], M. Baranowski[1], H. Duim[3], S. Moyano[2], K. Posmyk[1,4], A. Mlayah[5], S. Adjokatse[3], D. K. Maude[4], M. A. Loi[3], P. Puech[2], and P. Płochocka[1,4]

[1] *Department of Experimental Physics, Faculty of Fundamental Problems of Technology, Wrocław University of Science and Technology, Wrocław, Poland,* [2] *CEMES-UPR8011, CNRS, University of Toulouse, Toulouse, France,* [3] *Zernike Institute for Advanced Materials, University of Groningen, Groningen, The Netherlands,* [4] *Laboratoire National des Champs Magnétiques Intenses, EMFL, CNRS UPR 3228, University Grenoble Alpes, University Toulouse, University Toulouse 3, INSA-T, Grenoble and Toulouse, France,* [5] *LAAS, University of Toulouse, CNRS, UPS, Toulouse, France*

Polaron vibronic progression shapes the optical response of 2D perovskites

12:30 – 12:45 Th B-4

N. E. Kopteva[1], D. R. Yakovlev[1], E. Yalcin[1], I. A. Akimov[1], M. O. Nestoklon[1], M. M. Glazov[2], M. Kotur[1], D. Kudlacik[1], E. A. Zhukov[1], E. Kirstein[1], and M. Bayer[1]

[1] *Experimentelle Physik 2, Technische Universität Dortmund, Dortmund, Germany,* [2] *Ioffe Institute, Russian Academy of Sciences, St. Petersburg, Russia*

Optical orientation of exciton spins in perovskite crystals

12:45 – 13:00 Th B-5

M. Wagner[1,2], M. Barra Burillo[2], M. Schnell[2,3], R. Hillenbrand[2,3,4], and L. M. Liz-Marzán[1,3,5,6]

[1] *CIC biomaGUNE, Basque Research and Technology Alliance (BRTA), Donostia-San Sebastián, Spain,* [2] *CIC nanoGUNE BRTA, Donostia-San Sebastián, Spain,* [3] *Ikerbasque, Basque Foundation for Science, Bilbao, Spain,* [4] *Department of Electricity and Electronics, UPV/ EHU, Bilbao, Spain,* [5] *CIC Ciber-BBN, Donostia-San Sebastián, Spain*

Importance of analyte location in a combined surface-enhanced infrared and Raman sensor

13:00 – 14:30 Lunch

Session Th C: *Quantum dots II*

Chair: Hubert Krenner

14:30 – 15:00 Th C-1 (invited)

T. K. Bracht[1,2], M. Cygorek[2,3], V. M. Axt[4], and D. E. Reiter[1]

[1] *Condensed Matter Theory, TU Dortmund, Germany,* [2] *Institute of Solid State Theory, University of Münster, Germany,* [3] *Institute of Photonics and Quantum Sciences, Heriot-Watt University, Edinburgh, UK,* [4] *Theoretical Physics III, University of Bayreuth, Germany*

Photons from quantum dots excited by the SUPER scheme

15:00 – 15:30 Th C-2 (invited)

M. Syperek

Department of Experimental Physics, Faculty of Fundamental Problems of Technology, Wrocław University of Science and Technology, Wrocław, Poland

Deterministic and scalable Purcell-enhanced single-photon emitters in the telecom C-band

15:30 – 15:45 Th C-3

L. Nimmesgern[1], M. Cygorek[2,3], D. E. Reiter[3], A. Vagov[1], and V. M. Axt[1]

[1] *Theoretical Physics III, University of Bayreuth,* [2] *Institute of Photonics and Quantum Sciences, Heriot-Watt University,* [3] *Condensed Matter Theory, TU Dortmund*

Multimodal photon number distributions in quantum dot–cavity–systems

15:45 – 16:15 Coffee Break

Session Th P: *Posters*

16:15 – 18:15 **Poster Session**

Friday, 16 February 2024

Session Fr A: *Quantum emitters*

Chair: Stephan Reitzenstein

09:00 – 09:30 Fr A-1 (invited)

M. Cygorek

Open Quantum Systems Group, Technical University of Dortmund, 44227 Dortmund, Germany

Cooperative emission from solid-state quantum emitters

09:30 – 10:00 Fr A-2 (invited)

M. Rieger[1], **V. Villafañe**[2], L. Todenhagen[1], S. Appel[2], M. Brandt[1], K. Mueller[2], and J. J. Finley[1]

[1] *Walter Schottky Institute, School of Natural Sciences and MCQST, Technical University of Munich, Garching, Germany,* [2] *Walter Schottky Institute, School of Computation, Information and Technology and MCQST, Technical University of Munich, Garching, Germany*

Ultrafast electrical switching and charge state control of silicon vacancy centers in diamond

10:00 – 10:15 Fr A-3

N. Dalla[1], P. Kulboka[1], M. Kobecki[1], K. Oreszczuk[1], T. Kazimierczuk[1], P. Kossacki[1], R. J. Warburton[2], and T. Jakubczyk[1]

[1] *University of Warsaw, Warsaw, Poland,* [2] *Department of Physics, University of Basel, Basel, Switzerland*

High-finesse and low-mode volume cavity for novel emitters in the visible spectral range

10:15 – 10:30 Fr A-4

J. A. Preuß[1], D. Groll[2], R. Schmidt[1], T. Hahn[2], P. Machnikowski[3], T. Kuhn[2], R. Bratschitsch[1], D. Wigger[2,3,4], and **S. Michaelis de Vasconcellos**[1]

[1] *University of Münster, Department of Physics and Center for Nanotechnology, Münster, Germany,* [2] *University of Münster, Institute of Solid State Theory, Münster, Germany,* [3] *Wrocław University of Science and Technology, Department of Theoretical Physics, Wrocław, Poland,* [4] *School of Physics, Trinity College Dublin, Dublin, Ireland*

Coherent state manipulation of a single quantum emitter in hBN

10:30 – 10:45 Fr A-5

P. Mrowiński[1], M. Burakowski[1], P. Holewa[1,2,3], A. Sakanas[2,3], E. Semenova[2,3], and M. Syperek[1]

[1] *Department of Experimental Physics, Faculty of Fundamental Problems of Technology, Wrocław University of Science and Technology, Wrocław, Poland,* [2] *DTU Electro, Technical University of Denmark, Kongens Lyngby, Denmark,* [3] *NanoPhoton-Center for Nanophotonics, Technical University of Denmark, Kongens Lyngby, Denmark*

On-chip coupling of single photon emission from InAs/InP quantum dots at telecom range

10:45 – 11:15 Coffee Break

Session Fr B: *Interactions in 2D systems*

Chair: Andreas Knorr

11:15 – 11:45 Fr B-1 (invited)

M. Pieczarka[1], M. Gębski[2], A. N. Piasecka[1], J. A. Lott[3], A. Pelster[4], M. Wasiak[2], and T. Czyszanowski[2]

[1] *Department of Experimental Physics, Wrocław University of Science and Technology, Wrocław, Poland,* [2] *Institute of Physics, Lodz University of Technology, Łódź, Poland,* [3] *Institute of Solid State Physics and Center of Nanophotonics, Technical University Berlin, Berlin, Germany,* [4] *Department of Physics and Research Center OPTIMAS, Rheinland-Pfälzische Technische Universität Kaiserslautern-Landau, Kaiserslautern, Germany*

Thermalization and Bose-Einstein condensation of light in semiconductor lasers

11:45 – 12:15 Fr B-2 (invited)

M. Goryca

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Poland

Transition Metal Dichalcogenide monolayers as a platform to study electron-electron interactions and many-body correlations

12:15 – 12:30 Fr B-3

M. Gawełczyk[1,2], G. W. Bryant[3,4], and M. Zieliński[1]

[1] *Institute of Physics, Faculty of Physics, Astronomy and Informatics, Nicolaus Copernicus University, Toruń, Poland,* [2] *Institute of Theoretical Physics, Wrocław University of Science and Technology, Wrocław, Poland,* [3] *Atom Based Device Group, National Institute of Standards and Technology, Gaithersburg, MD, USA,* [4] *Joint Quantum Institute, University of Maryland, College Park, MD, USA*

Transport through dopant arrays in silicon

12:30 – 12:45 Closing session

12:45 – 14:30 Lunch

Poster Session

Th P-1 **M. S. Alam**[1], F. Gorrini[2,3], M. Gawełczyk[1], D. Wigger[4], G. Coccia[5], Y. Guo[6,7], S. Shahbazi[8,9], V. Bharadwaj[5,8,10], A. Kubanek[8,9], R. Ramponi[5], P. E. Barclay[1]1, A. J. Bennett[6,7], J. P. Hadden[6,7], A. Bifone[2,3], S. M. Eaton[5], and P. Machnikowski[1]

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Strain characterization in diamond waveguides using zero-field ODMR spectra of NV^- center ensembles

Th P-2 **M. Betke**[1], A. N. Piasecka[1], M. Gębski[2], J. A. Lott[3], T. Czyszanowski[3], and M. Pieczarka[1]

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Spectral tomography of modes in nontrivial VCSEL geometries

Th P-3 **D. Groll**[1], F. Paschen[1], P. Machnikowski[2], O. Hess[3,4], D. Wigger[5], and T. Kuhn[1]

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Readout of phonon statistics via resonance fluorescence of a single-photon emitter

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Probing the phase diagram of an optically trapped exciton-polariton condensate

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Anomalous dispersion and dissipative coupling in quantum well exciton-polariton structure

Th P-6 **F. M. Ehring**, B. Mayer, C. Strobl, M. Weiß, H. Krenner, U. Wurstbauer, and E. D. S. Nysten

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Optically gated acousto-electric effect in 2D semiconductors

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Coherence in resonance fluorescence from an acoustically modulated quantum dot with noise

Th P-8 **A. Bogucki**, A. Łopion, Z. Śnioch, K. E. Połczyńska, W. Pacuski, T. Kazimierczuk, A. Golnik, and P. Kossacki

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Characterization of Mn^{2+} spin relaxation dynamics in (Cd, Mn)Te/(Cd, Mg)Te quantum wells: Impact of magnetic field and temperature

Th P-9 **A.Dydniański**, A. Lopion, M. Raczyński, K. E. Polczyńska, T. Kazimierczuk, and P. Kossacki

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Spatial (in)homogeneity of (Cd,Mn)Te quantum well studied with the use of μ-ODMR

Th P-10 **J. Grumm** and A. Knorr

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Microscopic theory of the non-linear THz response of thin gold films

Th P-11 **M. Jaworski**[1,2], P. Mrowiński[1], M. Burakowski[1], P. Holewa[1,3,4], M. Syperek[1], E. Semenova[3,4], and G. Sęk[1]

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Fabrication of photonic structures by Xenon Plasma Focused Ion Beam for application in III telecommunication window based on InAs/InP quantum dots

Th P-12 **K. Kawa**[1], T. Kuhn[2], and P. Machnikowski[1]

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Optically controlled singlet-triplet qubit in a quantum dot molecule

Th P-13 **M. Kuniej**, M. Gawełczyk, and P. Machnikowski

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Hybrid acousto-optical control of a quantum emitter

Th P-14 **N. Spitzner**[1], P. Zhao[1], R. Liang[2], C. H. Sharma[1], L. Tiemann[1], and R. H. Blick[1]

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Optimizing electrical transport and SAW propagation in MoS_2

Th P-15 **K. Mickiewicz**[1] and M. Gawełczyk[2]

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Interplay of various transfer mechanisms for excitons in dense quantum-dot ensembles

Th P-16 **E. Olbińska** and M. Gawełczyk

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Optically active gate-defined quantum dot

Th P-17 **A. N. Piasecka**[1], M. Gębski[2], J. A. Lott[3], T. Czyszanowski[2], and M. Pieczarka[1]

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Direct probing of the local confining potential for photons in a large-area VCSEL

Th P-18 **M. Raczyński**, T. Kazimierczuk, W. Pacuski, and P. Kossacki

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Importance of photonic environment for optical benchmark of $MoSe_2$ monolayers grown by molecular beam epitaxy

Th P-19 **J. Rosiński**[1], B. Mayer[2], D. Wigger[3], M. Weiß[2], H. Krenner[2], and P. Machnikowski[1]

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Optimised phononic waveguides for quantum dot optomechanics

Th P-20 **W. Rudno-Rudziński**[1], M. Gawełczyk[2], P. Podemski[1], V. Sichkovskyi[3], J. P. Reithmaier[3], and G. Sęk[1]

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Optical properties of third telecom window emitting InAs/InGaAlAs quantum dots grown on silicon substrates

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A Bloch approach to X-ray absorption spectroscopy

Th P-22 E. Pruszyńska-Karbownik[1], D. Jandura[2], M. Dems[3], Ł. Zinkiewicz[1], A. Broda[4], M. Gębski[3], J. Muszalski[4], D. Pudiš[5,6], T. Czyszanowski[3], and **J. Suffczyński**[1]

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Concept of Inverted Refractive-Index-Contrast Grating Mirror and Exemplary Fabrication by 3D Microprinting

Th P-23 **A.K. Szczerba**[1], J. Kucharek[1], J. Pawłowski[1], T. Taniguchi[2], K. Watanabe[3], and W. Pacuski[1]

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MBE growth of CdTe structures on hBN

Th P-24 **M. Volz**, E. D. S. Nysten, M. Weiss, and H. J. Krenner

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Design of lithium niobate on silicon surface acoustic waveguide for hybrid integrated phononic circuits

Th P-25 D. A. Vajner[1], **M. Wasiluk**[2], P. Holewa[2,3,4], E. Zięba-Ostój[2], M. von Helversen[1], A. Sakanas[3], A. Huck[5], K. Yvind[3,4], N. Gregersen[3], A. Musiał[2], M. Syperek[2], E. Semenova[3,4], and T. Heindel[1]

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Single indistinguishable photons emitted at 1.55 µm by InAs(P)/InP QDs

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Direct energy transfer in optically-excited hybrid carbon nanostructures

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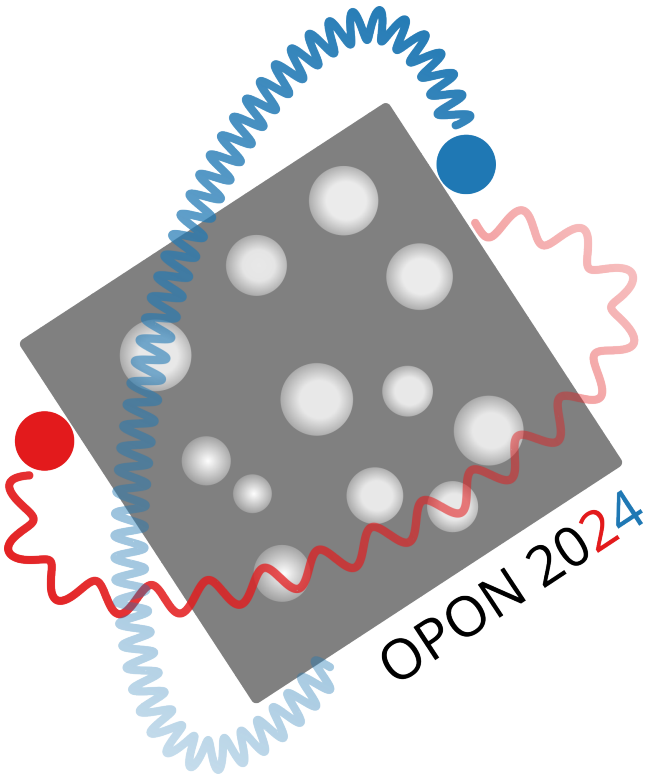
Electrically gated TMD heterostructures as a step towards 1D excitonic states

ABSTRACTS



WEDNESDAY, 14 FEBRUARY 2024

Acousto-Optoelectric Spectroscopy on Transition Metal Dichalcogenide Monolayer with Surface Acoustic Waves

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Surface acoustic waves (SAWs) have proven to be a useful tool for the manipulation, control and probing of the charge carrier dynamics inside semiconductor nanostructures [1,2,3,4]. For instance, SAW spectroscopy has already been used to probe the electrical transport inside CVD-grown MoS_2 on $LiNbO_3$ in a contact-free manner [1] and, in recent years, SAWs have been used to manipulate the emission of trions and excitons inside exfoliated TMDC monolayers [5,6,7]. In these studies, the quenching of the PL emission due to excitons dissociation under the SAW electric field was observed [5,6] as well as the excitons transport by the SAW strain field [7].

In this work, we integrated a WSe_2 monolayer flake into a $LiNbO_3$ SAW device through a classical exfoliation process. After a measurement of the static emission of the monolayer, the impact of the SAW on its photoluminescence emission was systematically studied in the time domain. The SAW is excited in a pulse scheme and a clear enhancement of the PL intensity is observed (see Figure 1(a)). This enhancement is position-dependent and tends to be larger at the edges of the monolayer and close to defects (see Figure 1(c)). Additionally, the modulation of the PL emission during the SAW pulse shows distinct differences depending on the location within the monolayer, which is not reproduced in the static PL emission measured beforehand. This indicates that the SAW induced dynamics is much more sensitive to any type of localized change in the dielectric and strain environment. The presence of two contributions to the modulation, one following the frequency of the applied acoustic field and the other twice its frequency (see Figure 1(b)), as well as their position-dependent phase and amplitude difference is a strong hint to the presence of inhomogeneities previously unseen in the static measurement [3,4]. These results show that SAW acouto-optoelectric spectroscopy can be a powerful tool to uncover the unavoidable inhomogeneities present in 2D TMDCs in experiments.

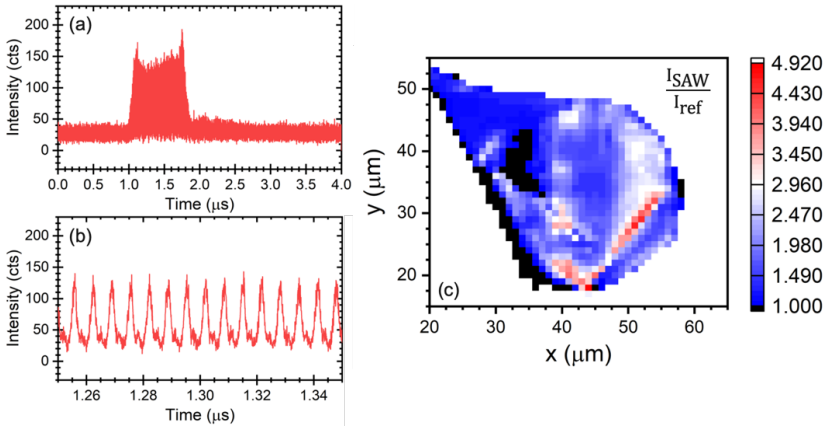

Figure 1 (a) Time-resolved measurement of the photoluminescence emission of the WSe_2 monolayer under a pulsed SAW modulation. The SAW is excited from 1µs to 1.8µs. (b) SAW modulation of the photoluminescence emission of the WSe_2 monolayer. (c) Mapping of the intensity ratio between the photoluminescence emission intensity during the SAW pulse I_{SAW} and before I_{ref}.

[1] E. Preciado et al, *Nature Communications* **6**, 8593 (2015)
[2] L. Janker et al, *Nano Lett.* **19**, 8701-8707 (2019)
[3] M. M. Sonner et al, *Nanotechnology* **32**, 505209 (2021)
[4] M. M. Sonner et al, *Phys. Rev. Applied* **16**, 034010 (2021)
[5] D. Scolfaro et al, *ACS Nano* **15**, 15371-15380 (2021)
[6] K. Datta et al, *ACS Nano* **15**, 12334-12341 (2021)
[7] K. Datta et al, *Nat. Photon.* **16**, 242-247 (2022)

Phonons can increase Photon Number Coherence

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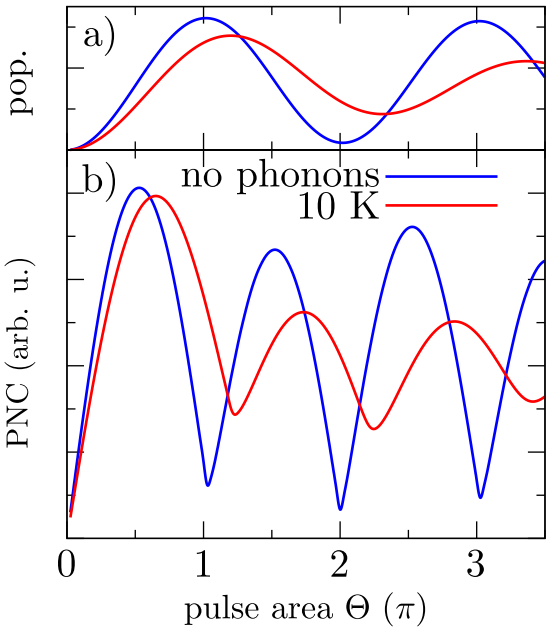
Quantum dots (QDs) have long been known to be excellent single-photon sources for applications in quantum technology, such as quantum cryptography. Quantum coherence between photon number (Fock) states occurs in the emitted light and presents a key quantity for most protocols' security [1]. Thus, it is crucial to understand the behavior of photon number coherence (PNC) of light emitted by QDs.

In this contribution, we investigate the PNC theoretically. We consider a QD in a cavity, that is excited by an external laser pulse. We model the QD as a two-level system and calculate the time dynamics of the electronic and photonic variables. We also include the coupling to phonons as well as radiative and cavity losses. The calculations are done using a numerically complete path-integral method [2]. Similarly to the Rabi rotations of the excited state occupation, the photon population, which is displayed in Fig. a), also displays Rabi rotations. We find the absolute value of the electronic coherence between the excited and the relaxed QD state to be minimal, whenever the QD is maximally or minimally excited and maximal for half-occupied states. Because under the considered conditions the PNC depends sensitively on the electronic coherence [3], we find maxima of the PNC at pulse areas equal to half integers of π, while for integer values of π, the PNC is minimal. This is portrayed by Fig. b). Thus, PNC essentially mirrors the behavior of electronic coherence for our system. When introducing phonons, this effect is damped, producing smaller coherences for $\pi/2$-pulses and boosted coherences for π-pulses. Therefore, we find that interestingly, the PNC can be increased by the QD-phonon interaction, in contrast to the typical assumption that phonons are a major source of decoherence. We attribute this to two effects: the renormalization of the light-matter coupling, leading to slower relaxation, and the damping of Rabi rotations, which lessens the excitation the laser pulse achieves and thus increases coherence. As a result, phonons can, depending on the temperature and the pulse area, increase PNC!



[1] M. Bozzio et al., *npj Quantum Inf.* **8**, 104 (2022).
[2] A. M. Barth et al., *Phys. Rev. B* **94**, 125439 (2016).
[3] Y. Karli, P. C. A. Hagen et al., *npj Quantum Inf.* accepted (2024). ArXiv:arxiv.2305.20017

Surface acoustic wave-controlled photocurrent in few-layer WSe_2

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Surface Acoustic Waves (SAWs) are a versatile tool to implement radio frequency control and sensing schemes on a chip. On the one hand, they have a wavelength in the µm range at GHz frequencies due to their 10^5 × lower propagation speed compared to photons. On the other hand, they can be easily generated on piezoelectric substrates and routed over long distances. Moreover, SAWs couple either mechanically or electrically with almost any system on the surface and, thus, are ideally suited for the implementation of hybrid device concepts [1]. For example, exploiting the electric field accompanying the SAW allows trapping or transporting charge carriers in a wide variety of materials employing the acousto-electric effect. With this, it is possible to induce an electrical current in transition metal dichalcogenide (TMDC) 2D materials [2].

The aim of this project is to investigate SAW-driven acousto-electric current (AEC) in exfoliated TMDCs. To this end, a hybrid lithium niobate-based chip is used (Fig. 1a). It comprises two interdigital transducers (IDTs) forming a SAW delay line with a design frequency of 150-250MHz (upper panel of Fig. 1b). Exfoliated few-layer WSe_2 is placed on top of the gold electrodes and the AEC is measured.

The AEC (lower panel of Fig. 1b) is observed exclusively for frequencies within the transmission band of the SAW delay line (upper panel of Fig. 1b) and increases with the applied rf power (Fig. 1c). The SAW directional dependence of this fundamental effect enables a detailed investigation of the Au-TMDC interface. Furthermore, the TMDC can be photodoped via excitation with a green laser (532nm) to deeply study the underlying charge carrier dynamics. In the low SAW-Power regime photogating leads to an enhanced AEC by up to two orders of magnitude, whereas bipolar charge carrier transport sets in for higher SAW powers.

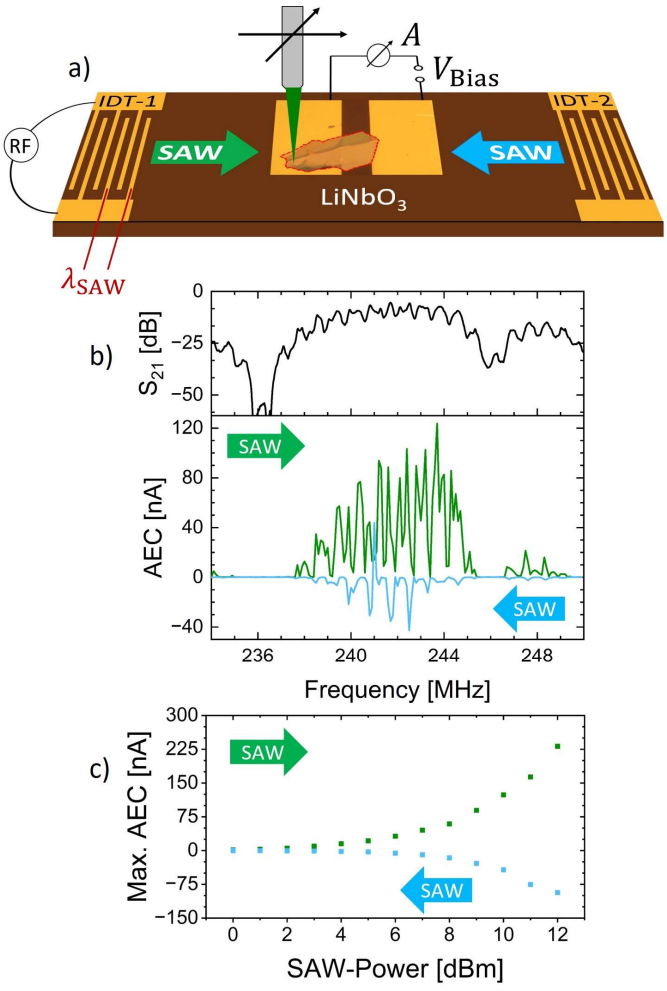

Fig.1. SAW-driven photocurrent in few-layer WSe_2.
a) Sample schematic. b) SAW delay line transmission spectrum (upper panel) and SAW-driven acousto-electric current without laser excatation (AEC, lower panel).
c) SAW-Power dependance of the AEC.

[1] P. Delsing et al, J. Phys. D: Appl. Phys. 52, 353001 (2019)
[2] E. Preciado et al, Nat. Commun. 6, 8593 (2015)

Phonon Sidebands in the Absorption Spectra of Moiré Exciton-Polaritons

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Twisted bilayers of transition metal dichalcogenides induce a spatially varying electronic environment, which manifests in the formation of a periodic and twist-angle dependent moiré potential. Excitons in these heterostructures interact with the moiré potential, resulting in delocalized moiré exciton states for large twist angles, whereas the excitons get localized at the minima of the moiré potential for small twist angles. This strong localization for small twist angles corresponds to flat exciton bands.

When placing the heterostructure in an optical cavity, the moiré excitons interact with the photonic field, leading to the formation of moiré exciton-polaritons (see red and blue curves in Fig. 1), whose dispersion also strongly depends on the twist angle between the layers. While for small twist angles the lower and upper polariton branch are separated by an energy gap, for large twist angles the gap is closed due to the curvature of the lower polariton branch. Transitions between the polariton branches can now be promoted via phonon emission or absorption (see black arrows in Fig. 1).

We calculate the linear optical absorption spectra of moiré exciton-polaritons coupled to a phonon bath. The spectra exhibit a pronounced phonon influence, leading to broadenings of the optical transitions and a rich phonon sideband structure reflecting phonon-assisted transitions. The shape of the spectra strongly depends on the twist angle. As crucial parameters for the phonon-assisted processes we identify the presence or absence of a polariton band gap, transitions to Van Hove singularities at the edge of the moiré Brillouin zone and non-Markovian processes in the dephasing dynamics. We will analyze and discuss the role of these features for the spectral shape of the transitions.

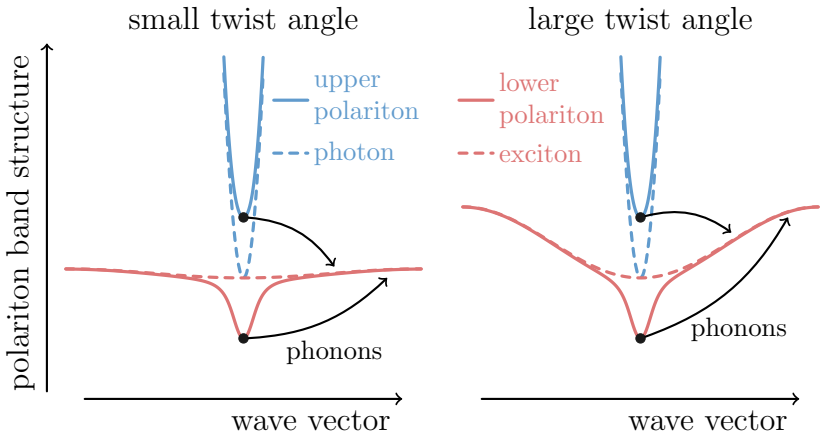

Figure 1: Sketch of phonon-assisted transition between two polariton branches for small (left) and large (right) twist angles. Dashed lines show the uncoupled exciton and photon dispersions.

On-chip Generation and Dynamic Piezo-Optomechanical Rotation of Single Photons

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Integrated photonic circuits (IPCs) are a promising platform to realize photonic quantum technologies on a chip [1]. However, the underlying schemes require reconfigurable devices which demand versa-tile tuning mechanisms. Here, we report on an acousto-optically tunable IPCs with integrated quantum emitters and demonstrate dynamic rotations of an on-chip initialized photonic qubit [2].

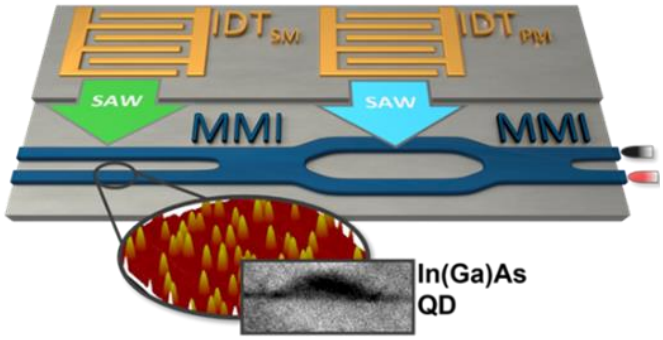

Figure 1 – Schematic of SAW-tunable Mach-Zehnder IPC with integrated QDs. IDT-SM and IDT-IM allow for the dynamic control of the QDs and the MZI. A photonic qubit is initialized by a single photon emitted by a QD.

Figure 1 shows a schematic of our device which is monolithically fabricated on a III-V heterostructure containing a layer of quantum dots (QDs). The IPC comprises a pair of ridge waveguides connecting two multimode interference (MMI) beamsplitters forming a Mach-Zehnder interferometer (MZI). Interdigital transducers (IDTs) allow for the generation of two beams of ≈ 500MHz surface acoustic waves (SAWs) to dynamically control the optical properties of the QDs (IDT-SM) [3] and the optical phase in the two arms of the MZI (IDT-PM) [4]. We initialize a rail-encoded photonic qubit by selective excitation of single QDs in one of the two waveguides. When we apply a SAW via IDT-PM, we dynamically modulate the optical phase in the MZI and, thus, perform a coherent rotation on the qubit. The angle is set simply by the electrical power applied to IDT-IM. Finally, we demonstrate programmable dynamic spectral multiplexing and demultiplexing of the photonic qubit in our device by simultaneously modulating the QD by a SAW generated by IDT-SM.

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How to make dark excitons bright

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Atomically thin semiconductors constitute a remarkable playground for exciton physics in two dimensions. This involves optically accessible (bright) as well as spin- and momentum-forbidden (dark) excitonic states for intra- and interlayer excitations. Momentum-dark excitons outside the optical light cone can typically be excited by momentum transfer resulting from (a) phonon scattering [1,2] or by (b) spatially structured optical near-fields [3-5]. In this talk, we address both aspects with respect to:
(a) the question whether -at increasing densities and under exciton-phonon scattering- dark excitons can be approximated as a weakly interacting boson gas or are possibly dominated their fermionic substructure [1], and
(b) how spatially structured near-fields can be induced by nanostructures (such as molecules [3] or metal nanoparticles [4,5]) to excite dark in-plane excitons.
Throughout the talk, a comparison with recent experiments (absorption, luminescence and angle resolved photoemission spectroscopy) will be provided.

[1] M. Katzer et al., *Phys. Rev. B* **108**, L121102 (2023).
[2] S. Dong et al., Nature Communications 14, 5057 (2023).
[3] M. Katzer et al., *Phys. Rev. B* **107**, 035304 (2023).
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Interface engineering of charge-transfer excitons in 2D lateral heterostructures

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Two-dimensional (2D) semiconductors show remarkable excitonic physics and can be integrated in heterostructures. While van der Waals heterostructures obtained by vertical stacking of different 2D materials have been largely explored, much less is known about lateral heterostructures, where two different monolayers are grown in the same plane. These lateral heterojunctions show remarkable transport both across [1,2] and along the interface [3]. The possibility of bound charge transfer (CT) excitons at their interface [4] has long been debated as their direct observation was lacking, contrary to their counterpart in vertical heterostructures, the interlayer excitons.

In this joint theory-experiment study [5], we demonstrate the appearance of the CT-exciton peak of hBN-encapsulated lateral $MoSe_2$-WSe_2 heterostructures. Our fully microscopic theory reveals the many-particle processes behind the formation of CT excitons and how they can be tuned via interface- and dielectric engineering. For interface widths smaller than the exciton Bohr radius we theoretically predict and experimentally confirm the appearance of a new CT-exciton peak in low-temperature PL spectra, boxes in Fig. 1(a) and (b), respectively. Such a peak is absent in freestanding samples or in the case of larger widths (thin line in Fig. 1(a)) or exciting away of the interface, thin in Fig. 1(b). We show that CT excitons typically exhibit small binding energies of few tens meV and large dipole moments. The resulting efficient exciton dissociation and fast dipole-driven exciton propagation makes the lateral heterostructures promising materials for optoelectronics devices.

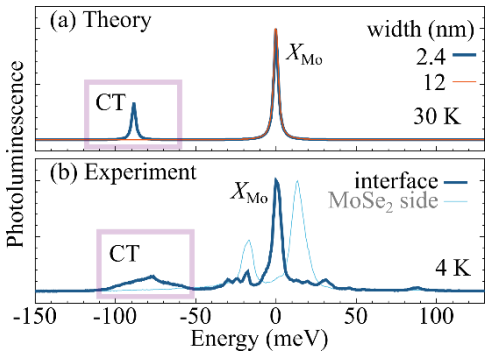

Fig. 1: Theoretical (a) and experimental (b) photoluminescence spectrum (PL) after excitation at the interface of a hBN-encapsulated lateral $MoSe_2$-WSe_2 heterostructures, showing a low-energy feature attributed to CT excitons (box). Larger junction widths (thin in (a)) or excitation on the $MoSe_2$ side (thin in (b)) do not give rise to CT excitons.

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[2] H. Lamsaadi et al., *Nat. Commun.* **14**, 5881 (2023).
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Optical properties and dynamics of neutral and charged excitons in the $MoTe_2$ monolayer in a metal-oxide-semiconductor device

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Molybdenum ditelluride ($MoTe_2$) is unique compared to other transition metal dichalcogenides (TMD) because of its narrow direct optical bandgap. A single-layer crystal gets ~1.17 eV at 5 K, which is translated to ~1.0 eV at 300 K.[1] Therefore, this is the only known TMD material with potential for application in near-infrared optoelectronic devices. In this study, we investigate the role of excess carrier density in the monolayer (ML) of $MoTe_2$ and examine to what extent one can control the optical bandgap, interactions in excitonic complexes and excitation dynamics.

The charge-tunability in the ML $MoTe_2$ is reached by making a metal-oxide-semiconductor (MOS) device with a large-area exfoliated ML of $MoTe_2$, placed on a 275-nm-thick SiO_2 deposited on a heavily-doped Si substrate, used as the back gate, and with a gold strip playing the role of the second electrode (**Figure 1**). We demonstrated the electrical modulation of excitons and trions, by applying a back-gate voltage from –30 to +30 V, tracked by the optical response from the crystal at T = 5 K, using the high-spatially-resolved photoluminescence (μPL) and contrast reflectivity experiments (μCR). After applying the fitting procedure, we extracted the maximum charge carrier density and using the Fermi-polaron model we obtained $4.7 \cdot 10^{11}$ cm^{-2} for electrons and $8.7 \cdot 10^{11}$ cm^{-2} for holes, translated to the Fermi energy ~3.3 meV in the valence band and ~2 meV in the conduction band. The trion binding energy obtained for the charge neutrality region is equals 23.5 meV, which is close to our theoretical prediction, given by the calculation with variational wave function.[2]

Additionally, we evaluated the dynamics of excitons and trions, using a non-degenerated pump-probe transient reflectivity experiment. We observe at least two fast and slow recombination channels for each species. The short decay time indicates the recombination of free complexes, while the long decay time can be interpreted as the recombination of localised excitons and trions.

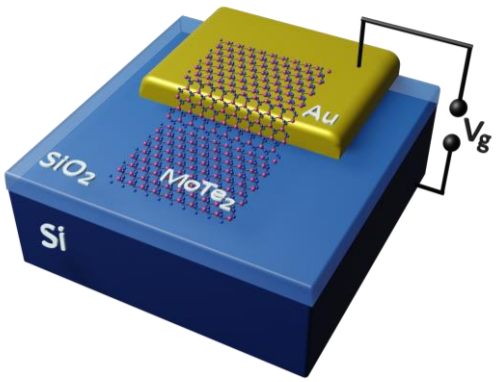

Figure 1. Schematic illustration of the MOS device.

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Optical spectroscopy of intra- and interlayer excitons in atomically thin MoS_2 under high pressure

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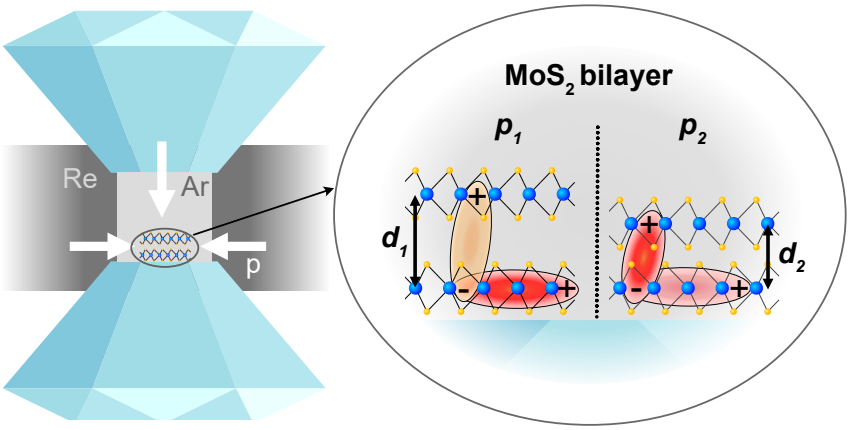
High-pressure diamond anvil cells are a recent addition to the toolkit for investigating two-dimensional materials and their heterostructures. The optical and electronic properties of multilayer samples differ significantly from their monolayer counterparts due to interlayer interactions. Exerting external pressure results in compressive strain, allowing precise manipulation of the interlayer coupling strength. Here, we present pressure-dependent optical transmission spectra of 2H-MoS_2 bilayers under pressure and extract the respective energy shift rates of inter- and intralayer excitons. These excitons exhibit distinct pressure dependent energies due to their different real-space distributions and resulting valence band contributions. Additionally, we find that the deformation of the sample differs from hydrostatic compression due to substrate effects. We discuss strategies to address this common challenge encountered in high-pressure experiments on single- and multi-layered van-der-Waals materials in conjunction with complementary DFT-based calculations.[1]



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Giant interactions of Rydberg excitons in Cu_2O

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Rydberg excitons are bound pairs of electrons and holes highly-excited quantum states in a semiconductor. The material Cu_2O hosts Rydberg excitons with principal quantum numbers up to $n = 30$ [1,2]. In such highly-excited states, excitons can reach extensions in the µm range and, therefore, are mesoscopic quantum objects. They represent the analogues of Rydberg atoms embedded in a solid-state environment and are promising candidates to transfer Rydberg physics from atoms to a semiconductor platform. Excited to states with large n, Rydberg excitons interact fundamentally different than ground state excitons: Their polarizability increases with n^7 which renders them highly-sensitive sensors of external fields. Moreover, the dipole-dipole interaction scales as n^{11} resulting in long-range inter-excitonic correlations.
We investigate Rydberg excitons experimentally with a two-color high-resolution pump-probe technique. We show that the presence of a Rydberg exciton can prevent the excitation of another within a µm-large volume, a mechanism that is referred to as Rydberg blockade (Fig. 1**a**).
Moreover, we demonstrate how to utilize Rydberg excitons to reduce the number of charged defects in the host material drastically, in turn leading to an enhancement of exciton absorption and narrower linewidths (Fig 1**b**). We show that the underlying interaction is based on a Rydberg-exciton capture process, described by a $V(r) = C_4/r^4$ potential, where r is the distance between exciton and defect and $C_4$is proportional to the polarizability.

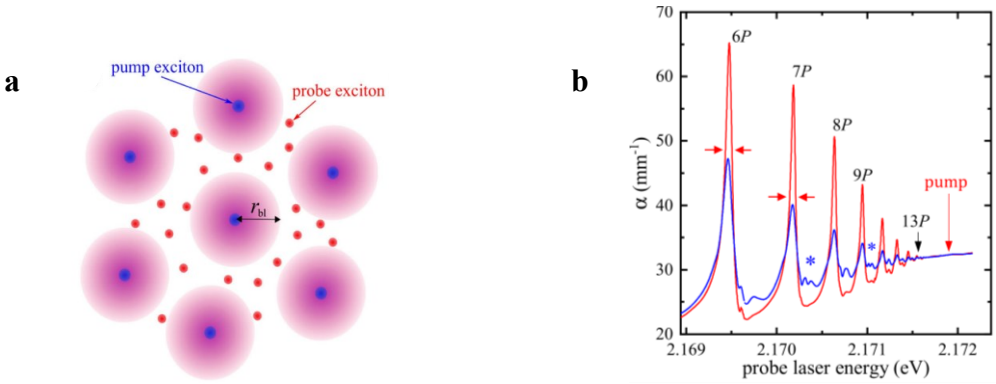

Fig. 1. a Scheme of the Rydberg blockade mechanism. Optical generation of probe excitons is blocked at separations below the blockade radius r_{bl}. **b** Optically excitation of Rydberg excitons by a pump laser leads to an enhancement of exciton absorption.

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[2] M. Versteegh et al., Giant Rydberg excitons in Cu_2O probed by photoluminescence excitation spectroscopy, PRB **104**, 245206 (2021).
[3] M. Bergen et al. Large scale purification in semiconductors using Rydberg excitons. Nat Commun **14**, 8235 (2023).
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Deterministically fabricated single-quantum-dot devices for photonic quantum technologies

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The application of solid-state quantum emitters in real-world quantum information technologies requires precise nanofabrication platforms with high process yield. Self-assembled semiconductor quantum dots (QDs) with excellent emission properties have proven to be among the best candidates to meet the needs of high-performance quantum photonic devices. However, their spatial and spectral positions vary statistically on a scale that is far too large for their system integration via conventional lithography and inflexible processing schemes. We solve this severe problem by introducing a flexible and deterministic manufacturing scheme based on precise and convenient cathodoluminescence spectroscopy followed by high-resolution electron-beam lithography to fabricate high-performance photonic quantum devices [1].

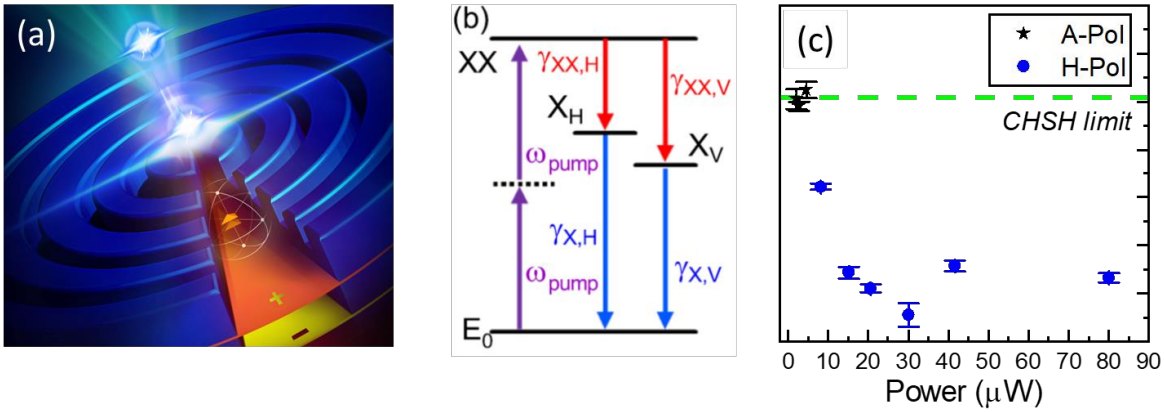

Figure 1: (a) Quantum-dot-molecule-based spin-photon interface. (b) Energy level scheme of a QD for the two-photon resonant generation of photon pairs which allow one to violate Bell's inequality in a Franson experiment (c).

In this talk, I describe basics and application examples of in situ electron-beam lithography (iEBL) acting as advanced deterministic nanofabrication platform for photonic quantum devices. Details about the iEBL process, including machine learning enhanced iEBL [2] are discussed, and its high potential for the deterministic fabrication of single-emitter devices for applications in photonic quantum technology is presented. Examples include high-performance spin-photon interfaces based on circular Bragg gratings (see Fig. 1(a)) to enhance their brightness [3], and photon pairs sources which allow us to violate Bell's inequality via energy-time entanglement in a Franson-type interferometer [4] (see Fig. 1(b, c).

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Atomistic and continuous media approaches to model spectral properties of semiconductor quantum dots

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The modeling of spectral properties of quantum dots (QDs) was the subject of many theoretical studies. The methods commonly used in such calculations can be divided into two classes. The first one contains multiband $\boldsymbol{k}\cdot\boldsymbol{p}$ models based on the continuous media approximation, and the second one involves various atomistic models.

We discuss the theoretical approaches for modeling of InAs/GaAs self-assembled quantum dots. We compare the results obtained from the 8-band $\boldsymbol{k}\cdot\boldsymbol{p}$ and the $sp^3d^5s^*$ tight-binding models, and show that discrepancies are primarily related to different treatment of strain in both methods. While the tight-binding Hamiltonian inherently accounts for strain nonlinearity via exponential factors, the standard $\boldsymbol{k}\cdot\boldsymbol{p}$ Bir-Pikus Hamiltonian is linear in strain tensor elements. Although the second-order scheme [1] was proposed, no parameters have been provided so far. In the present work, we find the values of the second-order deformation potentials [2], and calculate energy levels for electron and hole confined in a QD [2, 3]. We show that in the case of the electron, the accuracy of the continuous $\boldsymbol{k}\cdot\boldsymbol{p}$ model can be greatly improved with the second-order strain model.

Importantly, the tight binding model can explicitly take atomic disorder into account. We have recently shown that such atomic disorder can have a strong effect on the radiative Auger effect in InGaAs/GaAs QDs [4]. While the optical spectrum of a quantum dot is typically dominated by the fundamental transition, the radiative Auger process results in additional red-shifted emission lines. These lines can be used to extract information on otherwise unreachable single-particle excitation energies in the QD spectrum [5]. We present measurements of such radiative Auger lines for a range of quantum dots. We show that the atomistic tight-binding model combined with the configuration-interaction approach accounts for the intensities of the Auger lines and the changes from quantum dot to quantum dot. We emphasize the role of symmetry breaking caused by the alloy disorder, which turned out to be essential for the strength of the radiative Auger lines.

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[5] M. C. Löbl, C. Spinnler, A. Javadi, L. Zhai, G. N. Nguyen, J. Ritzmann, L. Midolo, P. Lodahl, A. D. Wieck, A. Ludwig, and R. J. Warburton, Nat. Nanotechnol. **15**, 558 (2020).

Progress in Telecom C-Band Single Photon Generation Using Semiconductor Quantum Dots

Daniel A. Vajner,[1]Paweł Holewa[2-4], Emilia Zięba-Ostój[2], Maja Wasiluk[2], Martin von Helversen[1], Aurimas Sakanas[3], Alexander Huck[5], Kresten Yvind[3-4], Niels Gregersen[3], Anna Musiał[2], Marcin Syperek[2], Elizaveta Semenova[3-4], and Tobias Heindel[1]

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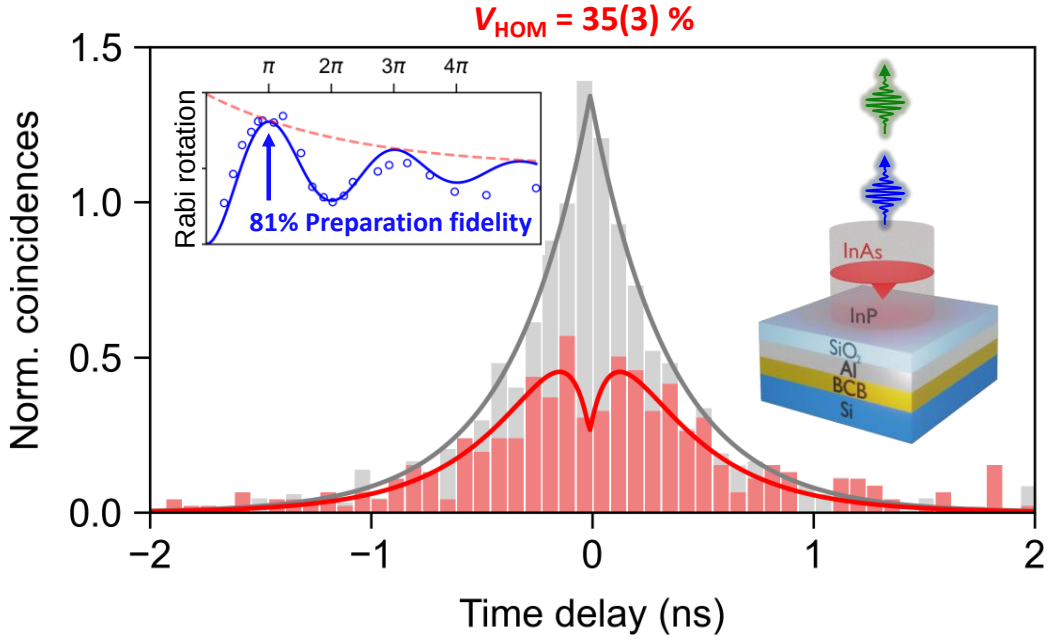
Single photons such as those from semiconductor quantum dots are needed and already employed to build the quantum internet [1]. Especially for long-distance fiber transmission high-quality Telecom C-band photons are desired. Here, we report progress towards that goal, highlighting recent work which demonstrated the coherent on-demand generation of indistinguishable photons from single QD devices consisting of InAs/InP QD-mesa structures heterogeneously integrated with a metallic reflector on a silicon wafer [2]. The coherent excitation enabled two-photon-interference visibilities > 30% as well as preparation fidelities > 80%, independently confirmed by different methods.

Furthermore, we present an analysis of the coherence time of such Telecom single photon emitters in different nanophotonic environments. Finally, we present first results from extending the employed two-photon-resonant excitation to more complex excitation regimes using chirped pulses as well as combinations of red-detuned excitation pulses.



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Ultrafast dynamics of excitons in monolayers of semiconductor TMDs

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Monolayers of transition metal dichalcogenides (TMDs) draw a lot of attention as semiconducting materials with robust optical properties, strong Coulomb interaction and an optically accessible valley degree of freedom. Extraordinary properties of exciton complexes lead to new possibilities of exploration of nonlinear effects.

In my talk, I will focus on ultrafast studies of exciton dynamics explored by time resolved photoluminescence, FWM and femtosecond pump-probe experiments. The studies of neutral and charged exciton optical response show strong interactions between different complexes. For example creation of CX population in a given K,K' valley leads to the capture of available free carriers in the opposite valley and reduces the interaction of neutral X with the Fermi sea. From the valley-resolved analysis of the observed effects we are also able to extract the spin-valley relaxation times of free carriers as a function of carrier density. The several effects related to interaction with carries such as the oscillator strength variation and energy shift will be discussed and compared to the cases of ordinary quantum wells. I will point similarities and differences in the complex landscape of exciton-exciton and exciton-carrier interactions in both two dimensional systems.

[1] Aleksander Rodek *et al* 2023 2D Mater. 10 025027

Local field effects and a new destructive photon echo in a 2D semiconductor

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Over the last several years, two-dimensional semiconductors, especially in the form of transition metal dichalcogenides, have gained considerable attention in several areas of physics. One of the reasons for this is their strong excitonic optical response, which makes them attractive for future optoelectronic or quantum applications. Their remarkable brightness allows to efficiently study them with ultrafast nonlinear spectroscopy to learn about their fundamental excitonic properties and the excitons' coupling to other quasi-particles. We have recently shown how the spectral dynamics of pump-probe [1] and four-wave mixing signals [2, 3] can be interpreted by an exactly solvable model that extends the basic optical Bloch equations by a local field effect [4]. This local field coupling takes into account the exciton-exciton interaction between the optically generated excitons in the 2D systems on a mean field level and leads to spectral shifts depending on the excitonic occupations.

We then went a step further and studied six-wave mixing (SWM) signal dynamics and discovered a peculiar temporary signal depression, depending on the considered delay between the applied laser pulses [5]. In this contribution, we will report on this new finding and demonstrate that the observed signal dynamics can be understood as a new destructive photon echo. With our local field model we are able to attribute this effect to the interaction between the excitons. We show that the two main contributions to the SWM signal interfere destructively for certain times. Already in his first report of the spin echo effect in 1950, E. Hahn has used the Bloch vector description to illustrate his newly discovered phenomenon [6]. Inspired by this, we developed a similar Bloch vector description for the destructive photon echo. Interestingly, we found that the Bloch vectors contributing to the SWM signal form Lissajous figures that get distorted with progressing time [5]. The new destructive photon echo effect allows to efficiently and systematically study the exciton-exciton interaction across 2D semiconductor samples with a spatial resolution which is only restricted by the diffraction limit of the applied laser pulses. Thereby we will be able to learn more about the potential interplay between exciton-exciton interaction and for example local strain distributions.

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[2] T. Hahn et al., Influence of local fields on the dynamics of four-wave mixing signals from 2D semiconductor systems, New J. Phys. 23, 023036 (2021).
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Magnetically tunable reflectivity features in 2D layered magnetic semiconductor CrSBr

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The discovery of 2D layered materials paved the way for investigating new quantum phenomena emerging from lower dimensionality. With the first exfoliation the these materials, they gave rise to the concept of "nano-lego" with a number of classes of 2D materials to be combined into heterostructures. In particular, in recent years a particular attention was paid to a special class of 2D materials, namely the ones exhibiting a magnetic ordering. A prominent example of such materials is chromium sulfide bromide – CrSBr, which is particularly interesting due to combination of semiconducting and magnetic properties.

With rather unusual orthorhombic symmetry[1], this semiconductor exhibits strongly anisotropic direct-band gap excitations in the near-infrared energy range. Showcasing the intriguing coupling of electronic and magnetic properties, the energy of an exciton is notably influenced by the magnetic ordering between layers. Although not all excited states observed in the reflection of the bulk material have been comprehensively examined, particularly regarding their origins and properties in a magnetic field.

In this work we present results of our investigation of optical properties of bulk CrSBr in the spectral range corresponding to the excited states. A considerable number of such states can be observed across the spectrum. For each of observed spectral feature, we quantify the shift induced by the magnetic order, which leads to characteristic behavior as a function of external magnetic field.

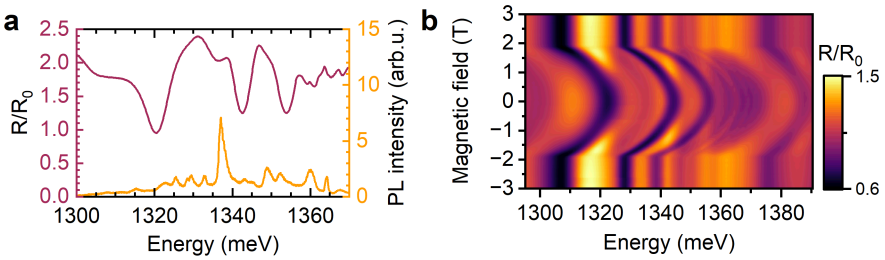
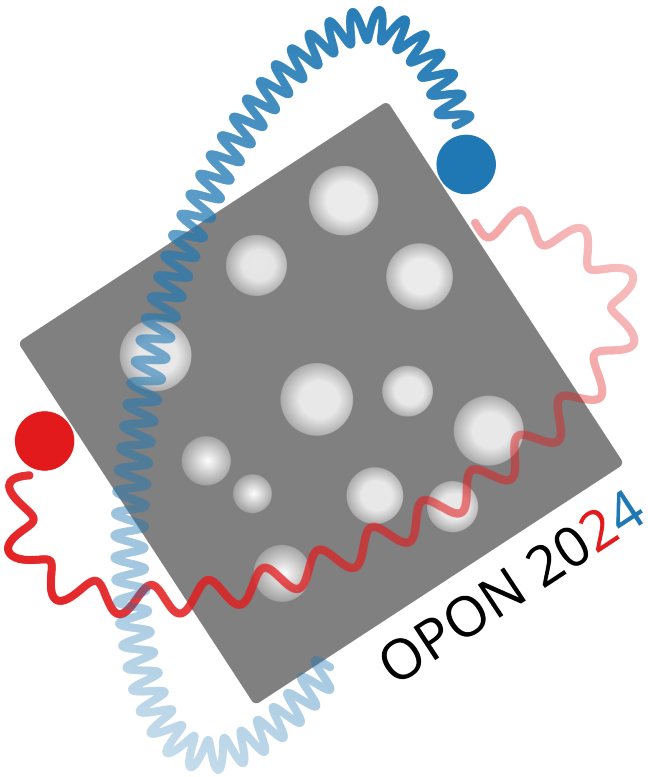


Figure 1: **a**, Comparison of reflectance with reference on substrate and photoluminescence. **b**, Magnetoreflectance of CrSBr excitons.

[1] Lee, Kihong, et al. Magnetic order and symmetry in the 2D semiconductor CrSBr. *Nano Letters* **21.8** (2021): 3511-3517.



THURSDAY, 15 FEBRUARY 2024

Tuning magnetic and optical properties of layered MPX_3 crystals

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Atomically thin, magnetic materials have recently gained a lot of attention in the field of two-dimensional (2D) materials [1]. Single magnetic layers with critical temperature above room-temperature are extremely attractive for fundamental studies and promising candidates for future spintronic applications. However, probing the magnetic order of the 2D systems by conventional magnetic experimental setups is very challenging. On the other hand, it is well known that even in the single layer limit, semiconducting two-dimensional materials strongly absorb light. Therefore, optical spectroscopy is a good method for their characterization.

In order to shed light on the intriguing phenomena of 2D antiferromagnets (AFM), I will present our recent theoretical investigations [2-7] in the framework of the density functional theory (DFT) considering magnetic and optical properties of the layered materials. In particular, I will focus on the representative AFM family, transition metal phosphorus trisulfides (MPX_3), in respect to other 2D materials. I will cover currently puzzling reaserch issues in respect to magnetic and optical properties of 2D MPX_3 crystals.

In particular, I will address following scientific questions related to the magnetic propertiesin MPX_3: what mechanism sustains the long-range AFM ordering, and whether the type of magnetic arrangement can be manipulated and effectively tuned? In this regard, I will present the results for alloy systems with magnetic [3] and nonmagnetic substitution [4]. An effective tuning of magnetic interactions and anisotropies in both $MnPS_3$ and $NiPS_3$ upon nonmagnetic substitution are revelad [4]. Regarding the optical properties, in crystals exhibiting AFM-Neel magnetic ordering, the inclusion of the spin-orbit interaction (SOI) causes an in-equivalency of the pair of valleys (K+,K-), resulting in sizable valley splitting, which can be tuned by the rotation angle of the spins [6]. Aditionaly, the direct transitions in $MnPS_3$, $MnPSe_3$ and $FePS_3$ monolayers are optically active and sensitive to the polarization of light. Finally, I will highlight the importance of the structural anisotropy in monolayer of $FePS_3$ [5].

M.B. acknowledges support from the University of Warsaw within the project “Excellence Initiative-Research University” program.

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Broadband high-performance Faraday rotation spectroscopy of 2D materials and thin magnetic films

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Faraday rotation spectroscopy is a powerful experimental technique to measure the magneto-optical response of spintronic materials and devices. However, due to speed limiting components in present-day implementations, such as polarization modulators combined with lock-in amplifiers, it can take several hours to record a high-quality Faraday rotation spectrum. In particular, these measurements become extremely challenging if (sub)micrometer spatial resolution is needed, which is required for example for encapsulated 2D materials.

We present a high-performance broadband Faraday rotation spectroscopy technique for measurements on the micron scale [1]. Spectral acquisition speeds of two orders of magnitude faster than state-of-the-art modulation spectroscopy setups are demonstrated. The experimental method is based on charge-coupled-device detection, avoiding speed-limiting components used in modulation spectroscopy. At the same time, Faraday rotation spectra are obtained with a sensitivity of 20 µrad (0.001°) over a broad spectral range (525 – 800 nm), which is on par with polarization-modulation techniques. The new measurement technique also automatically cancels unwanted Faraday rotation backgrounds.

Using the setup, we perform Faraday rotation spectroscopy of excitons in a hBN-encapsulated atomically thin semiconductor WS_2 under magnetic fields of up to 1.4 T. We resolve extremely small exciton Zeeman splittings (50 µeV at B = 0.2 T), and tiny valley polarizations (0.05% at B = 0.4 T). In addition, we perform Faraday spectroscopy and hysteresis loop measurements on a 20 nm film of the magnetic alloy TbFe to demonstrate the suitability of our setup for thin magnetic films.

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Wurtzite MnSe – epitaxy and properties of an altermagnetic candidate

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A coexistence of a magnetically compensated collinear order and spin-splitting of the bands is a peculiar phenomenon [1] that attracts a lot of attention. It is present in the class of materials, which have been recently called altermagnets [2]. Such behaviour arises from the specific symmetry operations that connect the spin sublattices. We present a novel candidate of this class, semiconductive wurtzite MnSe [3]. We demonstrate experimentally through structural characterization techniques that it is possible to obtain thin films of both the intriguing wurtzite phase of MnSe and more common rock-salt MnSe using molecular beam epitaxy on GaAs substrates. The choice of buffer layers during the growth plays a crucial role in determining the resulting phase of MnSe and consequently extends the array of materials available for the physics of altermagnetism. We present basic optical properties of structures containing wurtzite MnSe. We show that despite strong photoluminescence of MnSe close to 1.6 eV, this material can be a good barrier for CdSe quantum wells (QW) emitting at higher energies, close to 1.8 eV.

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Temperature of magnetic ions in Optically Detected Magnetic Resonance Measurement of p-type Doped (Cd,Mn)Te QWs

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In this work, we combine magnetooptical measurements and optically detected magnetic resonance (ODMR) technique to study magnetic system composed of Mn^{2+} ions in (Cd,Mg)Te/(Cd, Mn)Te QWs with carrier gas.

The advantage of the ODMR technique is the possibility to study local properties of magnetic ions incorporated in well-defined position of nanostructure. The basic information extracted from the ODMR spectra is the energy level structure of the Mn^{2+} ion, which depends, e.g., on the local strain [1]. Although the ODMR technique in diluted magnetic semiconductors is sensitive selectively to the magnetic ions, the detailed analysis of the measured signal reveals interactions within the magnetic ion system or between ions and charge carriers [2] and the temperatures of the subsystems.

The nominally undoped (Cd,Mn)Te/(Cd,Mg)Te quantum wells are typically p-type [3]. The hole gas originates from the background doping of the (Cd,Mg)Te barrier material or the surface states. By covering the (Cd,Mn)Te/(Cd,Mg)Te QW structure with a nickel metallic layer, we produced a sample with different carrier gas properties. As we observe by magnetooptical measurements, the hole gas is replaced by electron gas in the QW. Depending on the conditions, we have observed that the ODMR signal is affected by the carriers present in the sample in two ways. The first effect is the shift between the ODMR signals obtained on neutral and charged exciton (Knight shift). The second one is a change in the spin-lattice relaxation (SLR) rate in the presence of the carriers.

At the same time, the shape of the ODMR signal keeps the information about the temperature of the magnetic ions involved in the absorption of the MW. Studying it in detail can provide even more information about interactions with charge carriers.

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Engineering of excitonic g-factors in van der Waals structures

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We develop a fully ab-initio based method of calculation of excitonic g-factors, which describe their energy dependence on external magnetic field, and apply it to 1L TMDs and $MoSe_2/WSe_2$ heterobilayers, obtaining excellent agreement with experimental data for intra- and interlayer excitons. A proper inclusion of stacking-dependent selection rules allows to assign the measured optical peaks to specific transitions in the band structure and regions of the samples [1]. We identify a series of magneto-PL peaks in 1L WS_2 based on the calculated g-factors of excitons, trions and biexcitons, as well as phonon replicas of the dark trion. We obtain a perfect agreement of the individual bands g-factors with the values derived from experimental data [2]. We explain the reduction of a g-factor measured in $MoSe_2/WS_2$ by the spatial confinement of the mixed exciton in the moiré potential [3]. We analyze the influence of uniaxial and biaxial strain on 1L TMDs, finding a large strain dependence of excitonic g-factors and dipole strengths. The calculated trends of direct and indirect exciton g-factors in WS2 micro-bubbles allow us to explain the strain-induced exciton hybridization in WS2 monolayers unveiled by Zeeman splitting measurements [4,5]. We investigate a new class of hexagonal 2D materials with formula MSi_2Z_4 (M: Mo, W; Z: N, P, As, Sb), which are isosymmetric to 1L TMDs. We find a new set of circularly polarized excitonic transitions with high binding energies and large positive g-factors [6].

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Investigating the properties of 2D materials with near-field techniques on the nanoscale

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Scattering-type scanning near-field optical microscopy (s-SNOM) and nanoscale IR point spectroscopy (nano-FTIR) allow for nanoscale optical mapping of manifold material properties. Both techniques are based on elastic light scattering at an atomic force microscope tip that is illuminated with monochromatic or broadband laser light. Acting as an optical antenna, the tip converts the illuminating field into a strongly concentrated near field at the very tip apex. Interferometric recording of the tip-scattered field as a function of sample position yields near-field amplitude and phase s-SNOM images (employing monochromatic laser illumination), which encode information about the local dielectric function of the sample, while Fourier-transform spectroscopy of the tip-scattered field (employing IR broadband illumination) allows for nano-FTIR spectroscopy [1,2].
Intercalation of 2D layered semiconductors with molecules can drastically change the electric, optical, and magnetic properties of the host crystal. Recently, we found that MoS_2 bulk crystals become superconducting when intercalated with Tetraethylammonium (TEA) molecules [3]. To get a deeper understanding of the molecule distribution in the material we performed IR and THz s-SNOM and nano-FTIR spectroscopy to map the local carrier density of the intercalated MoS_2. In the s-SNOM images we find a Drude-like response in amplitude and phase signals. Furthermore, the optical images are not homogeneous, indicating a spatial variation of the conductivity, i.e., the carrier concentration. In addition, we use nano-FTIR to confirm the Drude-like response and to measure the molecular vibrations. By modeling the near-field spectra we can extract the local conductivity of the sample.
For dielectric samples such as biological materials or polymers, the near-field amplitude and phase signals of the scattered field reveal the local reflectivity and absorption, respectively. Importantly, absorption in s-SNOM imaging corresponds to a positive phase contrast relative to a non-absorbing reference sample. Interestingly, a negative phase contrast (NPC) can be observed when imaging a non-absorbing material on a highly reflecting substrate, which can hinder the recognition of materials with a weak infrared absorption [4]. We explore the origin of the NPC using representative test samples and demonstrate straightforward simple correction methods that remove the NPC and that allow for the identification of weak absorption contrasts.

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Coherent optical spectroscopy in perovskites semiconductors

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Perovskite semiconductors are appealing for optoelectronic and photonic applications. The knowledge currently available about the energy structure of photoexcited electrons, holes and exciton complexes, their interaction, binding energy, and relaxation dynamics are far from being complete. Conventional time-integrated reflectivity or photoluminescence (PL) techniques alone often do not allow one to make unambiguous conclusions about the energy structure due to inhomogeneous broadening of optical transitions and complex dynamics of photoexcited carriers. Here, nonlinear optical techniques based on photon echoes or two-dimensional Fourier spectroscopy provide unique access to the energy structure of perovskite semiconductors.

We investigate the coherent dynamics of excitons in halide perovskites materials of different composition and dimensionality. Most importantly, the exciton itself serves as a probe for the interaction with the crystal lattice, local potential fluctuations, other excitons and charge carriers in our studies. First, the results on single bulk crystals are presented. Here, the magnitude of fluctuations of the energy bandgap is evaluated. We observe exceptionally long exciton coherence time up to 80 ps at low temperature of 1.5K in mixed mixed-halide perovskite crystals due to the localization of excitons at the scale of tens to hundreds of nanometers [1]. Next, the role of exciton-exciton interactions in bulk crystals is discussed. In particular, polarization resolved transient signals provide rich information about the biexciton binding energy and spin dependent interactions in dense exciton ensembles [2]. Finally, we study coherent optical response from lead-halide nanocrystals where quantum beats in the photon echo signal are observed due to excitons fine structure and interaction with optical phonons.

[1] S. Grisard, A.V. Trifonov, I.A. Solovev, D.R. Yakovlev, O. Hordiichuk, M.V. Kovalenko, M. Bayer, I.A. Akimov, *Nanolett.* **23**, 7397 (2023).

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Polaron vibronic progression shapes the optical response of 2D perovskites

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2D layered perovskites constitute a rather unique semiconducting material system very different from the well-known family of epitaxial structures [1] The coexistence of organic and inorganic sublattices within the crystal structure bridges the worlds of *classic* and organic semiconductors. The resulting hybrid material is characterized by a soft and ionic lattice significantly enhancing the coupling of charge carriers to the ions in the lattice. Such a coupling has a pronounced impact on their opto-electronic properties, giving rise to complex absorption and emission spectra.

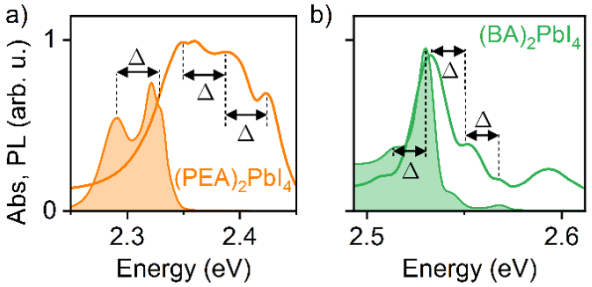

Figure 1: Comparison of absorption and PL spectra of (a) $(PEA)_2PbI_4$ and (b) $(BA)_2PbI_4$. Dashed vertical lines indicate the energy of individual optical transitions. The black arrows indicate the Δ energy spacing between the optical transitions.

An exemplary optical response of prototypical 2D perovskites namely $(PEA)_2PbI_4$ and $(BA)_2PbI_4$ is presented in Fig. 1a and b. The absorption spectra (solid line) consist of equally-spaced distinct transitions indicated with dashed vertical lines and separated by an energy Δ (black arrows). Associated spectral features, separated by Δ, are also present in photoluminescence (PL) response (shaded curves). A multitude of explanations [2] have been offered in an attempt to rationalize the complex optical spectra, however, neither interpretation is able to explain the magnitude of the Δ spacing quantitatively.

In our recent work [3] we show that the formation of polaronic states with their characteristic vibronic progression are responsible for complex line shapes observed in 2D perovskites. Crucially, we explain the magnitude of the Δ spacing by correlating the absorption/PL with the resonant Raman scattering response.

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Optical orientation of exciton spins in perovskite crystals

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Lead halide perovskite semiconductors are attracting research interest due to for their photovoltaic efficiencies and optoelectronic properties. They also show remarkable spin properties, well suitable for the spintronic applications [1]. The optical orientation of the exciton spins and charge carriers is a fundamental phenomenon in spin physics [2]. Circularly polarized photons generate spin-oriented excitons and carriers whose spin polarization and spin dynamics can be detected by polarized photoluminescence, Faraday/Kerr rotations, etc. The perovskite band structure and selection rules provide 100% spin polarization of the carriers at optical orientation and allow for 100% polarized photoluminescence, compared to a maximum of 25% circular polarized emission in conventional III-V and II-VI semiconductors.

Here, we demonstrate a giant degree of optical orientation up to 85% can be achieved for excitons in $FA_{0.9}Cs_{0.1}PbI_{2.8}Br_{0.2}$ perovskite crystals in time-resolved photoluminescence [3]. It is remarkably stable against laser excitation energy detuning from exciton resonance up to 0.5 eV, which proves the suppression of the mechanisms of spin relaxation of carriers characteristic of the usual III-V and II-VI semiconductors. This is also confirmed by non resonantly excited coherent spin beats of the exciton in the magnetic field.

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Importance of Analyte Location in a Combined Surface-Enhanced Infrared and Raman Sensor

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Infrared and Raman spectroscopy are powerful biochemical analysis tools as they extract chemical information about samples in a fast and label-free manner. The two techniques are complementary and thus the combination of them yields a more complete picture of the sample. However, both techniques have extremely low sensitivity and thus require enhancement of the signal, which can be performed via technique-specific gold plasmonic antennas [1]. The substrates used for surface enhanced Raman scattering (SERS) have a length scale of tens of nanometers, while surface-enhanced infrared absorption (SEIRA) substrates have dimensions of micrometers. The challenge of combining SEIRA and SERS lies in the combination of these length scale elements, while minimizing compromises in the efficiency of both methods [2].

In this work we present a combined SERS and SEIRA substrate based on infrared antennas produced by electron-beam lithography and metal evaporation, which act as the SEIRA element of the substrate. As a proof-of-principle demonstration, these antennas were used to detect the cellular metabolite adenine. We then functionalize these IR antennas with SERS resonant nanoparticles which enables the simultaneous detection of adenine with SERS and SEIRA at the same location. The key idea behind this approach is to use the IR resonance of a long metal nanorod, while simultaneously enhancing the field enhancement at visible frequencies by additional nanospheres that coat the nanorod.

Our results show that SEIRA rods produced with electron-beam lithography functionalized with gold nano-spheres are a suitable substrate for combined SEIRA and SERS. Furthermore, our results and simulations indicate that the location of the molecule within the combined sensor, and thus the method of assembly, are paramount to the efficiency of the sensor.

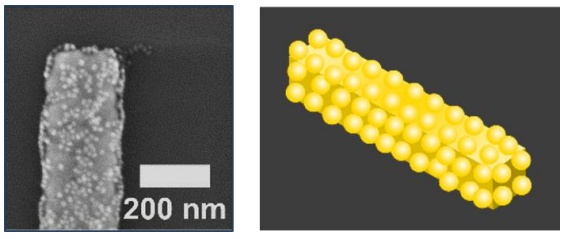

Figure 1. Left: SEM image of a SEIRA antenna functionalized with nanoparticles. Right: schematic image of the sensor concept.

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Photons from quantum dots excited by the SUPER scheme

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Controlling the properties of light from quantum emitters is essential for reliable quantum communication. In this context, quantum dots have emerged as a promising platform, offering excellent photon properties and controllability.
In this talk, I give an overview on different approaches for optically exciting a quantum dot, comparing their strengths and drawbacks, especially focussing on the Swing-Up of quantum EmitteR (SUPER) scheme [1], which has been experimentally verified by several groups [2,3]. Further, I explain the dynamics of two-color excitation and how it can be used to efficiently generate entangled photon pairs from a quantum dots biexciton-exciton cascade in optical cavities [4], overcoming previous boundaries set by two-photon excitation [5].
An important aspect of this approach is the decoupling of the preparation process from the subsequent photon emission, enabling an effective initial-value problem, which was previously inaccessible in two-photon absorption settings. As shown in Fig. 1, using this approach one can achieve an entanglement with unprecedentedly high fidelity, even when accounting for phonon interaction at elevated temperatures up to 80K. This brings quantum dots one step closer to real-world quantum applications.

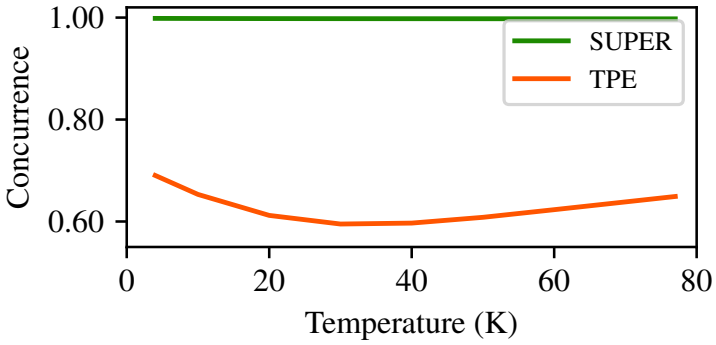

Figure 1: Simulated concurrence of entangled photon pairs from a quantum dot in an optical cavity, under influence of LA phonons at various temperatures. For SUPER, the concurrence maintains a high value while for two-photon excitation (TPE), the value declines.

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Deterministic and scalable Purcell-enhanced single-photon source in the telecom C-band

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Self-assembled semiconductor quantum dots (QDs) are structures that have the potential to generate single photons and entangled photon pairs. These are fundamental components of quantum photonics devices that can be used for quantum communication, computation, and simulation, which have the potential to revolutionise information processing speed, efficiency, and security. However, the self-assembly process of QDs remains a considerable drawback, hampering device fabrication with deterministic, scalable, and material-efficient technology.

In this talk, I will present the ways to provide determinism and scalability in fabricating self-assembled InAs/InP QD-based single-photon sources dedicated either for silica fibre optical networks or on-chip nanophotonic systems operating at the telecom C-band (near 1550 nm photon wavelength).[1-4] The sources utilise the Purcell effect, requiring a precision location of a QD with respect to an optical mode of a microcavity system, providing elevated photon extraction efficiency, enhanced spontaneous emission, and good quantum statistics. To achieve this, the far-field optical imaging of QD emission in the near-infrared is used combined with the electron beam lithography for the cavity fabrication process. An example of a QD in a circular Bragg grating cavity will illustrate this part of the talk.[2]

Once the cavity-coupled quantum dot device is fabricated, it can be positioned at a specific location on a quantum photonic chip.[3,4] This can be achieved through a pick-and-place technique using micro-transfer printing. This technology allows for the combination of multiple material systems. The process will be demonstrated by implementing a QD in a one-dimensional nanobeam cavity device to a silicon-based photonic platform.

[1] **P. Holewa** et al. *Optical and electronic properties of low-density InAs/InP quantum-dot-like structures designed for single-photon emitters at telecom wavelengths*, Phys. Rev. B 101(19),195304 (**2020**);

[2] **P. Holewa** et al. *Scalable quantum photonic devices emitting indistinguishable photons in the telecom C-band*, arXiv:2304.02515 [quant-ph] (**2023**);

[3] **P. Mrowiński** et al. *Optimization of heterogeneously integrated InP-Si on-chip photonic components*, Optics Express 31, 1541 (**2023**);

[4] **M. Burakowski** et al. *Heterogeneous integration of single InAs/InP quantum dots with the SOI chip using direct bonding*, arXiv:2311.13961 [physics.optics](**2023**);

Multimodal photon number distributions in quantum dot–cavity–systems

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In recent times, advances in quantum information processing lead to a significant rise of efforts trying to make practical, scalable applications a reality. Among the many challenges yet to be fully overcome the preparation of suitable nonclassical quantum states stands out as one of the central problems and thus still attracts a great deal of research interest. Both the generation and control of conventional nonclassical states often necessitate the use of complicated experimental protocols.

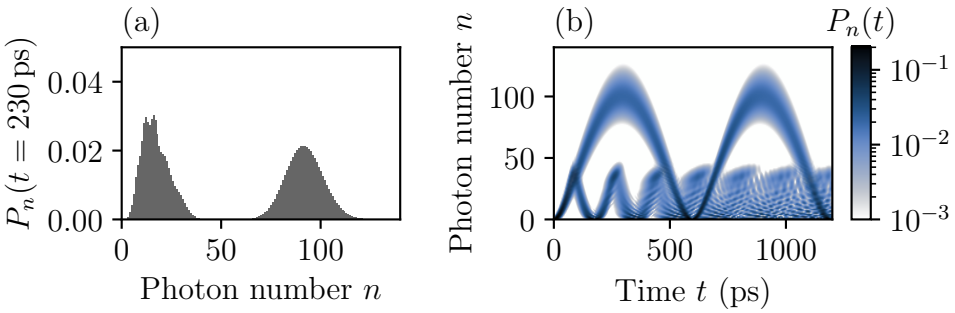
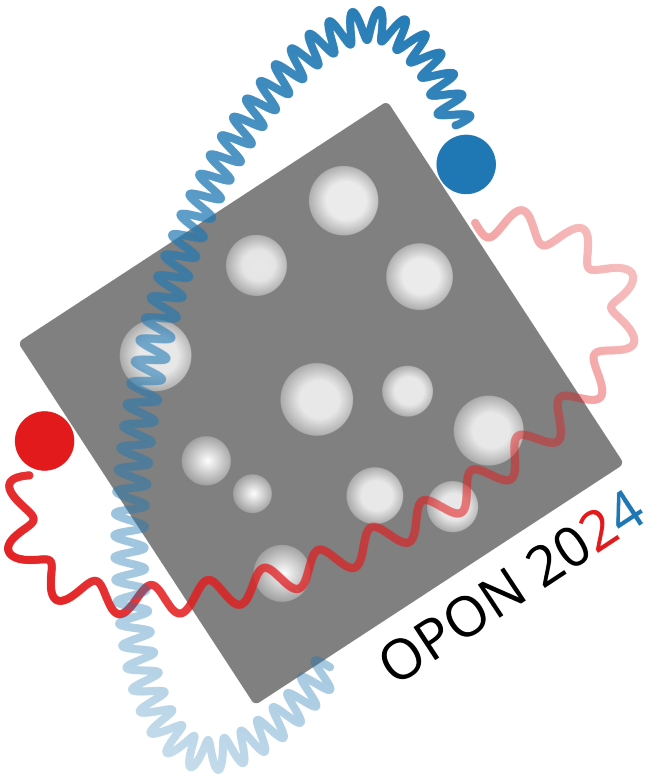


Figure 1: Photon number distribution $P_n(t)$ at fixed time t (a) and resolved in both time and photon number n (b).

In this contribution, we present theoretical investigations of novel highly nonclassical states, which are characterised by multiple wave packet-like structures oscillating independently in the photon number space (Fig. 1). Much of their appeal stems from the simplicity of their generation consisting merely of strong, slightly off-resonant cw driving of a quantum dot embedded inside a microcavity [1]. In addition, their properties, such as oscillation amplitude and frequency of the individual wave packets, exhibit simple relations to the system's parameters and thus can be controlled in straightforward fashion. Dissipative effects will eventually lead to a stationary distribution, which displays equivalent bimodality under the right circumstances [2].

Leaving behind the realm of cw driving, the control of the states can even be extended to the number of simultaneously present wave packets. Through sudden increases of the laser intensity new packets can be generated. It is largely due to this amount of controllability that we believe that the proposed states could lead to novel ways to process quantum information.

[1] L. Nimmesgern *et al.*, Phys. Rev. B (submitted), arXiv:2312.03402
[2] M. Cygorek *et al.*, Phys. Rev. B **96**, 201201 (2017).



FRIDAY, 16 FEBRUARY 2024

Cooperative emission from solid-state quantum emitters

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Novel growth and fabrication technologies allow for an unprecedented level of control over nanoscale semiconductor quantum devices. Recently, several groups have demonstrated samples where multiple quantum dots can be tuned into resonance [1,2]. When multiple quantum emitters become indistinguishable, collective quantum effects like superradiance and measurement-induced cooperative emission [2] emerge due to entanglement between the emitters.

A detailed understanding of the signatures of cooperative emission is challenging for several reasons: First, close-to-identical emitters operate in a regime where non-degerate perturbation theory breaks down. Second, real-world quantum devices typically strongly interact with local phonon baths as well as with a global photonic environment, and the different environments generally influence each other. Moreover, the presence of additional imperfections like spectral wandering further obfuscates the physical picture. Nevertheless, for few emitters, the problem of cooperative emission in the presence of multiple environments can be solved numerically exactly using the process tensor (PT) formalism [3,4].

Here, I report on recent theoretical and experimental findings and summarize the current understanding of cooperative emission in semiconductor nanostructures. This includes the discussion of how genuine superradiance can be distinguished from measurement-induced cooperative emission, how to interpret peaks in $g^{(2)}$ photon correlation experiments, how to obtain analytical expressions for superradiant decay rates in the presence of strong coupling to phonons, and why inter-emitter correlations remains strong for long times despite strong local interactions with phonons.

[1] J.-H. Kim, S. Aghaeimeibodi, C. J. K. Richardson, R. P. Leavitt, E. Waks, *Nano Lett.* **18** 4734 (2018).
[2] Z.X. Koong, M. Cygorek, E. Scerri, T. S. Santana, S. I. Park, J. D. Song, E. M. Gauger, B. D. Gerardot, *Sci. Adv.* **8**, abm8171 (2022).
[3] M. Cygorek, M. Cosacchi, A. Vagov, V. M. Axt, B. W. Lovett, J. Keeling, E. M. Gauger, *Nature Physics* **18**, 662 (2022).
[4] J. Wiercinski, E. M. Gauger, M. Cygorek, *Phys. Rev. Research* **5**, 013176 (2023).

Ultrafast electrical switching and charge state control of silicon vacancy centers in diamond

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Optically-active point defects in diamond feature atomic-sized two-level systems, constituting a promising solid-state platform for the development of novel quantum technologies. Specifically, group IV vacancy complexes in diamond (G4V) (with silicon, germanium, tin or lead) show excellent optical properties due to their crystallographic symmetry which favors emission into ZPL[1]. In this group, the silicon vacancy (SiV−) has been so far the most studied complex and T2 spin coherence times exceeding ~10ms have been demonstrated at low operation temperatures (T~100mK)[2]. Even though the energy levels of the G4V, forming a double-lambda system with spin S=1/2, can be used to store and process quantum information, their optical readout is often inefficient due to internal total reflection of light in the diamond.

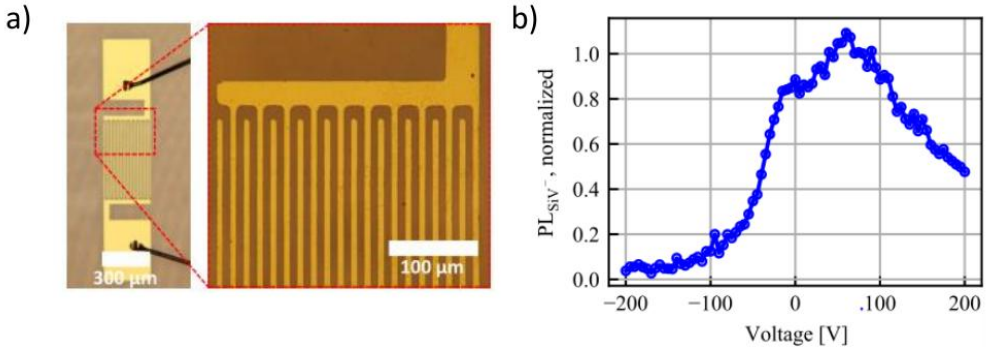

Fig. 1. a) *Optical micrograph of the diamond in planar-interdigital configuration.* ***b)*** *SiV- photoluminescence intensity upon changes in the applied voltage between V=±200 V.*

In this talk, we present our efforts towards controlling and understanding the SiV− charge state mechanisms towards implementing spin-to-charge conversion protocols[3]. By means of voltage pulses applied from a pair of interdigital metal contacts on the diamond surface we develop a method to dynamically manipulate the charge state of SiV− centers and demonstrate that they can be switched reversibly between SiV^0 and SiV− at MHz-rates (see Fig. 1). We furthermore fully explore the charge cycle of the SiV− center spectroscopically and find that it is aided by the presence of P1 and divacancy centers in the host lattice. Our results shed light on the charge cycle mechanisms on G4V and elucidate the potential for realizing an opto-electronic readout of their spin state.

[1] Pingault, B., Jarausch, D. D., Hepp, C., Klintberg, L., Becker, J. N., Markham, M., Becher, C. and Atatüre, M. Coherent control of the silicon-vacancy spin in diamond. Nature Communications, 8(1), 15579 (2017)
[2] Sukachev, D. D., Sipahigil, A., Nguyen, C. T., Bhaskar, M. K., Evans, R. E., Jelezko, F., and Lukin, M. D. Silicon-vacancy spin qubit in diamond: a quantum memory exceeding 10 ms with single-shot state readout. PRL 119, 223602 (2017)
[3] Rieger, Manuel, et al. "Fast optoelectronic charge state conversion of silicon vacancies in diamond." arXiv preprint arXiv:2310.12288 (2023).

High-finesse and low-mode volume cavity for novel emitters in the visible spectral range

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Efficient single-photon generation devices require optimized attributes of purity, indistinguishability, and brightness. The two latter parameters can be improved by incorporating single-photon emitters inside a photonic cavity. Here, we present a cavity platform, where the top mirror consists of a concave Gaussian-like shape, while the bottom mirror is planar. This cavity geometry achieves high finesse values since the upper wavefront of the Hermite-Gaussian beam matches the mirror geometry and is reflected into the cavity mode with minimal losses. It also facilitates achieving low-mode volume since the beam waist rests at the bottom mirror. Both factors are crucial for high-Purcell Factors. The bottom mirror rests on a piezo stage while the top rests on a tunable kinematic mount. The elements are connected by a stiff and lightweight cage mount to shift the mechanical resonance frequencies above the typical acoustic and seismic environmental noise frequencies.

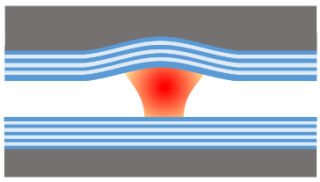

Figure 1. Schematics of the cavity design.

The cavity length was scanned to characterize the cavity setup with an oscillating voltage applied to the piezo, which holds the bottom mirror. Two lasers, one acting as a reference and the other tunable, were shined upon the cavity. The resulting distance between the two corresponding peaks for a cavity mode was utilized to provide information about the slopes of the cavity modes. With that, we could determine the broadening of the cavity modes in the wavelength domain, which led to the information about the Q-factors of the cavity. Since, for a cavity without internal losses, the Q-factor varies linearly with the mode numbers thus, we were able to calculate the finesse parameter. For our mirrors with 500 ppm transmission, we were able to achieve Q-Factors up to 10^5 and Finesse of $6 \cdot 10^3$, which is comparable to the theoretical values for the mirrors.

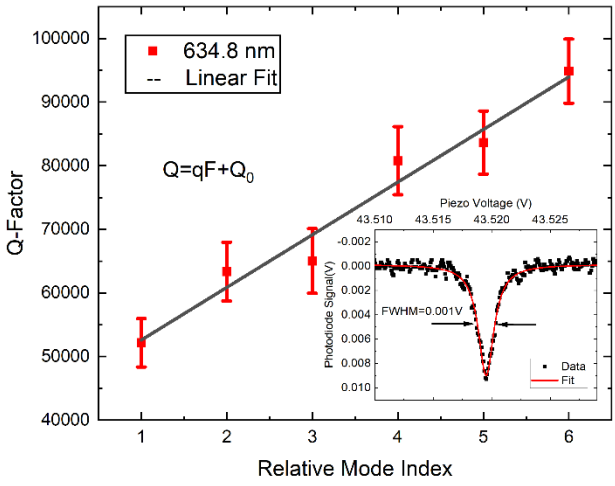

Figure 2. Q-Factors for different modes. In subset, photodiode voltage with cavity length detuning.

As candidates for the single-photon source that is suitable for the cavity, we analyze relevant properties of atomic-defects in GaN: linewidth, spectral stability and optimal excitation parameters.

[1] Tomm, N., Javadi, A., Antoniadis, N.O. et al. A bright and fast source of coherent single photons. *Nat. Nanotechnol*. 16, 399–403 (2021).

Coherent state manipulation of a single quantum emitter in hBN

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[1] *University of Münster, Department of Physics and Center for Nanotechnology, Wilhelm-Klemm-Str. 10, 48149 Münster, Germany*
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[3] *Wrocław University of Science and Technology, Department of Theoretical Physics, 50-370 Wrocław, Poland*
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Single-photon sources are crucial components for building quantum networks. However, achieving optimal optical coherent control poses a substantial challenge in advancing quantum technologies. Recently, solid-state quantum light emitters have been discovered in atomically thin 2D materials like transition metal dichalcogenides and hexagonal boron nitride (hBN) [1]. The efficient single-photon emission, even at room temperature, the wide variability of the emission wavelength, and tunability of the emitters in hBN make them particularly interesting for quantum sensing and wavelength division multiplexed quantum communications. Moreover, these emitters, readily available in commercially produced hBN nanocrystals, prove ideal for the fabrication of large arrays of single-photon sources [2], and efficient coupling to photonic structures such as 3D printed microlenses [3].

Here, we demonstrate the optical ultrafast coherent state manipulation of a single hBN quantum emitter in a double-pulse experiment [4]. We measure the emitted photons as a function of the laser pulse delay to detect the coherence properties of the two-level system. Our comprehensive experiment-theory study reveals the impact of different sources of spectral jitter on the ultrafast coherence dynamics. Additionally, we show that coherent control can be exerted not only on the direct optical transition but also phonon-assisted, providing insight into the internal phonon quantum dynamics. We find that increased decoherence rates in optical phonons are due to dephasing processes of the phonon states, partly due to their anharmonic decay. Similarly, dephasing induced by acoustic phonon generation results in a rapid decrease in coherence when propagating phonon wave packets are emitted. Our experiments on phonon-assisted coherent control of individual hBN color centers are a significant step towards hybrid quantum technologies that combine electronic and phononic excitations.

[1] S. Michaelis de Vasconcellos, et al., "Single-Photon Emitters in Layered Van der Waals Materials," *physica status solidi (b)* **259**, 2100566 (2022)
[2] J. A. Preuß, et al., "Assembly of large hBN nanocrystal arrays for quantum light emission," *2D Materials* **8**, 035005 (2021)
[3] J. A. Preuß, et al., "Low-Divergence hBN Single-Photon Source with a 3D-Printed Low-Fluorescence Elliptical Polymer Microlens," *Nano Lett.* **23**, 407 (2023)
[4] J. A. Preuß, et al., "Resonant and phonon-assisted ultrafast coherent control of a single hBN color center," *Optica* **9**, 522 (2022)

On-chip coupling of single photon emission from InAs/InP quantum dots at telecom range

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Integrated Quantum Photonic Circuits (IQPC) in which semiconductor-based components, like emitters, waveguides (WGs), detectors, can all be integrated on a compact photonic chip, could provide a better performance in complex tasks such as computing, energy conversion, biomedical sensing, and cryptography. In this work we present modelling, fabrication, and experimental studies related to a hybridized InP/Si WG system with InAs/InP quantum dots (QDs) heterogeneously integrated with the silicon-on-insulator platform. Numerical studies of such WGs demonstrate efficient QD coupling with multimode propagation in a hybrid InP/Si part of the system, as well as efficient transfer of light to Si WG via a linear taper structure [1]. The optimized system promises of approx. 30 % of on-chip directional copuling which might be further enhanced via Bragg grating system. Single-photon source is based on low density 3.1×10^{8} cm^{-2} epitaxially grown InAs/InP QDs with high single photon emission purity, high extraction efficiency when coupled with photonic microstructures [2]. The quantum emitter is integrated with SOI wafer by wafer bonding technique and via subsequent photo and e-beam lithography to process the WGs.

We investigated experimentally both the on-chip coupling efficiency and the quantum nature of emission by orthogonal microphotoluminescence configuration allowing for collection of outcoupled light from the cleaved facet. In this way, we obtain a high-quality quantum device with broadband on-chip coupling to Si WG of 10.2% preserving a good suppression of multiphoton emission events with background corrected $g^{2}(0) < 0.05$. The outcomes of our study underscore the potential benefits of this approach for advancing the development of quantum on-chip photonics using single-photon sources which are also easily combined with external fiber optics network.

[1] P. Mrowiński, et al., *Opt. Express* **31**, 1541-1556 (2023)
[2] P. Holewa, et al., *ACS Photonics* ***9****, 2273 (2022)*

Thermalization and Bose-Einstein condensation of light in semiconductor lasers

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Historically, photons were the first particles considered under the Bose-Einstein statistics. Surprisingly, photonic gases were among the latest to demonstrate the direct consequence of this quantum statistics - the Bose-Einstein condensation (BEC) [1]. On the other hand, laser operation is typically understood under the nonequilibrium setting of optical gain overcoming loss in a device, in contrast to BEC in thermodynamic equilibrium.

Here, we present our recent observation of a BEC phase transition in a broad-area (23-μm diameter) oxide-confined vertical-cavity surface-emitting laser (VCSEL) designed for 980-nm optical data communication [2]. We tested devices with different cavity mode-quantum well energy detuning $\Delta = \varepsilon_0 - \varepsilon_{QW}$, to operate the device below the Bernard-Duraffourg lasing condition and achieve photon gas thermalization. For more positive detuning $\Delta>0$, we observed fundamental transverse-optical mode condensation, followed by a thermalized distribution of higher-order modes, in agreement with the Bose-Einstein distribution, which suggests that the BEC is not in perfect equilibrium with the active medium and reaches the stimulated cooling regime. Nevertheless, we experimentally extracted the parameters of the equation of state (EOS) of the photon gas in the VCSEL. We found perfect agreement with the EOS of a textbook 2D Bose gas, confirming its thermodynamic properties. On the contrary, for a more negatively detuned device $\Delta<0$, we observed a standard broad-area VCSEL behavior, with multi-mode lasing at higher-order modes above the threshold current.

Our results show a new perspective on understanding semiconductor VCSELs, which can be used to test the BEC physics in table-top room-temperature devices. We offer that VCSELs can operate in a thermalized regime below reaching positive gain. Moreover, our demonstration allows observing effective photon-photon interactions and collective superfluid phenomena in photon BECs. This would eventually link the worlds of exciton-polariton and photon superfluid physics into one device. Finally, the thermalization mechanism and the BEC effect allow one to achieve single-mode coherent operation in a broad-area VCSEL, strongly contrasting the common belief.

[1] J. Klaers et al., Nature 468, 545 (2010);
[2] M. Pieczarka et al., arXiv:2307.00081 (2023);

Transition Metal Dichalcogenide monolayers as a platform to study electron-electron interactions and many-body correlations

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Electron-electron (e-e) interactions underpin many interesting phenomena in 2D layers of mobile charges, including the fractional quantum Hall effect, spin textures (skyrmions), and quantum Hall ferromagnetism. These phenomena arise from the Coulomb repulsion between charges, which in turn typically enhances the susceptibility of spin or related pseudospin (*e.g.*, valley, layer, subband) degrees of freedom, and can even cause instabilities and spontaneous transitions to broken symmetry phases. An excellent platform to study e-e interactions and many-body correlations is provided by electrostatically doped monolayers of transition-metal dichalcogenide (TMD) semiconductors such as WSe_2 and $MoSe_2$. This is because of their extreme 2D quantum confinement, reduced dielectric screening, and heavy carrier masses. In addition to those features, thanks to the valley-specific optical selection rules in TMD monolayers, interactions and correlations between particles with different spin and valley quantum numbers can be revealed using circularly polarized light.

The talk will cover several experiments that made significant contributions to the understanding of e-e interactions and many-body correlations in monolayer TMDs. Employing state-of-the-art optical spectroscopy in high magnetic fields, we have elucidated a number of puzzling phenomena that defy explanation within a single-particle framework, which has traditionally been quite successful in describing the fundamental properties of TMDs. Noteworthy examples include the spontaneous transition to a broken-symmetry phase [1], triggered by leveraging the interaction-enhanced carrier magnetic susceptibility [2], as well as the exploration of many-body nature and intervalley correlations of quasiparticle states evident in the optical spectra of specific material systems [3].

[1] J. Li, M. Goryca, N. P. Wilson, A. V. Stier, X. Xu, and S. A. Crooker, Phys. Rev. Lett. **125**, 147602 (2020).
[2] K. Oreszczuk, A. Rodek, M. Goryca, T. Kazimierczuk, M. Raczyński, J. Howarth, T. Taniguchi, K. Watanabe, M. Potemski, and P. Kossacki, 2D Materials **10**, 045019 (2023).
[3] J. Li, M. Goryca, J. Choi, X. Xu, and S. A. Crooker, Nano Letters **22**, 426 (2022).

Transport through dopant arrays in silicon

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The recent development of precise phosphorus donor placement in silicon [1,2] has attracted attention to chains and arrays of such sites. They have already proven well suited for quantum simulation of the Extended Hubbard [3] and SSH [4] models and are of major interest for future quantum-information devices.

In the experiment, gated systems of a few sites are studied electrically in terms of stability and Coulomb-blockade diagrams by measuring the current while sweeping gate voltages. The theory aims to simulate such diagrams and provide a two-way correspondence between the system and the simulated model. Thus, the need for a non-equilibrium transport theory of dopant systems arises.

Our approach based on combining exact diagonalization with non-equilibrium Green's functions allows for calculating currents and other observables in the arrays. Typically, by resorting to Green's functions, one loses the information on the underlying eigenstates. We preserve this knowledge and can back-trace states responsible for features of interest. Thus, we can, e.g., characterize the many-body configurations that contribute to the current or determine current magnitudes for different channels. We study some of these effects to better understand transport studies of experimentally realized 3×3 arrays [3].

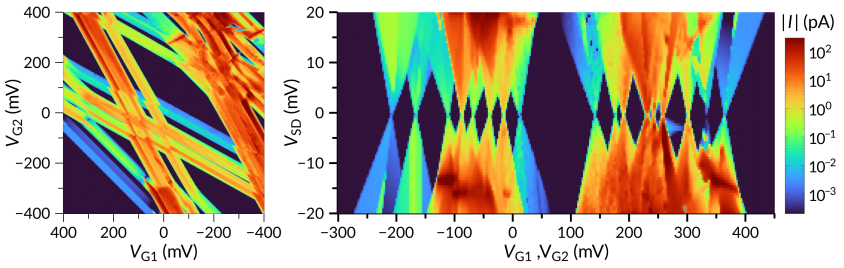
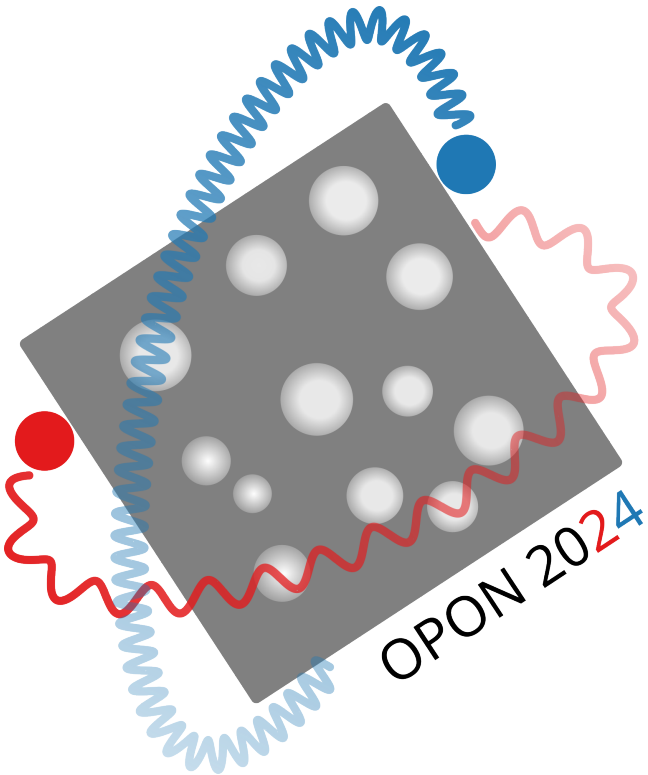


Figure 1: Stability and Coulomb blockade diagrams calculated for a disordered 3×3 array.

We consider the influence of several factors on transport properties and show that the current flow in the system is highly resilient to disorder. We explain this by decomposing the disorder into effects related to a disorder of individual sites and pairs of sites and we try to map the paths for local currents. We observe that the electron transverse hopping plays a minor role, and thus a 3×3 array has very similar transport properties to three long-range Coulomb-interacting but tunnel-uncoupled parallel 3-site chains. These insights provide important feedback for the creation of future devices of this kind.

[1] M. Fuechsle et al., *Nature Nanotech.* **7**, 242 (2012).
[2] J. Wyrick et al., *Adv. Funct. Mater.* **29**, 1903475 (2019).
[3] X. Wang et al. *Nature Commun.* **13**, 6824 (2022).
[4] Y. Chung et al. *Nature* **606**, 694 (2022).



POSTERS

Strain Characterization in Diamond Waveguides Using Zero-Field ODMR Spectra of NV$^-$ Center Ensembles

M. S. Alam[1], **F. Gorrini**[2,3], **M. Gawełczyk**[1], **D. Wigger**[4], **G. Coccia**[5], **Y. Guo**[6,7], **S. Shahbazi**[8,9], **V. Bharadwaj**[5,8,10], **A. Kubanek**[8,9], **R. Ramponi**[5], **P. E. Barclay**[11], **A. J. Bennett**[6,7], **J. P. Hadden**[6,7], **A. Bifone**[2,3], **S. M. Eaton**[5], **P. Machnikowski**[1]

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The negatively charged nitrogen-vacancy center (NV$^-$) in diamond has shown great potential in nanoscale sensing and quantum information, based on its field-sensitive ground spin states. These states are detected by the optically detected magnetic resonance (ODMR), which depends on efficient fluorescence detection. Laser-written waveguides in diamond have recently been used to improve the coupling of NV$^-$ centers to light, hence enhancing fluorescence signal [1]. However, in the waveguides, the ODMR spectra are consistently asymmetric.

Here, we show that this asymmetry is caused by strain induced by the laser-writing of the waveguide. We exploit this fact to characterize strain across the structure based on zero-field ODMR spectra. We find a dominant compressive axial component transverse to the waveguide, with smaller longitudinal and shear strain components.

To understand the impact of strain on ODMR spectra features, we first simulate a single microwave-driven NV$^-$ center and check how its optical response is tuned by specific strain components. We then model the experimental spectra from ensembles of NV$^-$ centers, assuming an even distribution of the four NV$^-$ orientations in the crystal. We exploit the translational symmetry of the waveguide structure, which reduces the number of relevant strain components to three. Based on numerically calculated four NV$^-$ centers' eigenstates and corresponding excitation probabilities for microwave-driven transitions, we compose a simulated ODMR spectrum from pairs of weighted Lorentzians for each NV$^-$ orientation. Finally, we extract the strain components by fitting the model to the experimental data.

Our results reasonably quantify the strain distribution in the studied waveguide structures with results comparable to polarized micro-Raman spectroscopy results [2] but provided via a more accessible experimental method.

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Spectral tomography of modes in nontrivial VCSEL geometries.

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Typical vertical-cavity surface-emitting lasers (VCSELs) are designed with circular apertures embedded in a cylindrical laser mesas. Most commonly, VCSELs have a small mesas because large aperture devices are known to suffer from multimodal and unstable lasing, as well as current crowding effects. Recently, chaotic cavities have returned to the area of research interest, as the VCSELs in these shapes are characterized by higher quantum efficiency, better coherence, and stability [1, 2, 3].

In this contribution, we present a newly implemented method for characterization of individual modes in photonic structures. In our technique, we want to focus on the characterization of individual modes by introducing an automated process of tomography in both momentum and real space. So far, attempts at spectral tomography of modes have mainly consisted of point-by-point scanning of the sample with an optical fiber. Our approach is to use a two-dimensional camera and scan a sample emission slice-by-slice across the monochromator entrance slit, which is presented in Figure 1. We characterized and compared a standard circular and broken-symmetry crescent-shape apertures and showed that breaking the geometrical symmetry leads to more even lasing spatially, and using k-space tomography, we can characterize the chaotic character of the modes.

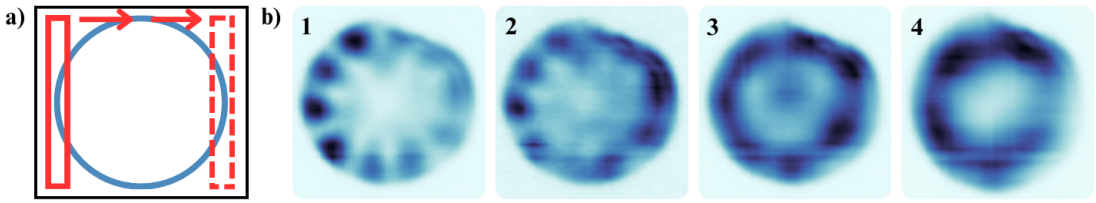

Figure 1: (a) The rectangle depicts the area from which light is incident on the entrance slit of the monochromator. (b) Spatial distribution of modes as a result of data processing for symmetrical mesa and aperture.

Our technique is very important for the development of VCSEL technology, as it allows us to characterize the homogeneity of the luminescence in a fast and automated way, as well as to obtain the spatial distribution of the modes.

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Readout of Phonon Statistics via Resonance Fluorescence of a Single-Photon Emitter

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An excellent tool for the acoustic control of solid state single-photon emitters is provided by surface acoustic waves (SAWs). In the classical regime these are routinely used to manipulate light that is scattered off a single-photon emitter by modulating its transition frequency [1, 2]. Furthermore it has been shown that one can in principle create and control the quantum state of SAW resonators [3]. We combine both of these aspects here and investigate theoretically the interplay between the phonon quantum state of a mechanical resonator and the resonance fluorescence (RF) spectrum of a single-photon emitter which is located inside that resonator [4].

We derive analytical expressions for the RF spectrum, depending explicitly on the quantum statistics of the phonon mode. We show that in most cases it is possible to invert this relation and obtain information on the initial phonon mode occupations from the RF spectrum. The exceptions to this rule are cases where relevant optical transitions in the coupled emitter-phonon system are forbidden due to vanishing Franck-Condon factors, i.e., overlap matrix elements of the phonon states. We discuss two solutions to this problem, which are (i) combining different laser detunings, changing the relevant optical transitions and selection rules, and (ii) using emitters with sufficiently large decoherence rates, which promote off-resonant optical transitions and allow for light scattering even in cases where the relevant resonant transitions are forbidden. We thus establish a simple and direct connection between the optical and acoustic components of such a hybrid system, paving the way for using single-photon emitters as quantum transducers between the optical and the acoustic domain.

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Probing the phase diagram of an optically trapped exciton-polariton condensate

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Cavity exciton polaritons, part-light and part-matter quasiparticles, can undergo Bose-Einstein (BEC) condensation transition, forming a macroscopically coherent state. Those condensates are intensively studied systems, where the nature of equilibrium and non-equilibrium BEC can be explored in a single structure. In order to spatially separate the condensate from the reservoir one can shape the excitation laser beam into a ring. Due to the repulsive interactions with excitons a circular potential trap is formed, which allows to obtain condensation at lower pumping powers than when excited with a Gaussian or homogenous spot [1]. Despite the vast literature on polariton condensation, the phase diagram of condensation [2-5] in a trap has not yet been investigated.

In this contribution, by using a GaAs-based strong-coupling microcavity sample, we experimentally study the process of polariton condensation at various detunings, determining the photon-like or exciton-like character of investigated quasiparticles. The studied structure is nonresonantly excited with the pumping pulsed laser shaped into a ring to obtain an effective potential created by the photo-excited excitonic reservoir. The sample is characterised with a thickess wedge, hence, we measure the condensation threshold powers at various positions on the sample (which corresponds to different exciton-photon detunings), and using several ring diameters.

Determining the threshold power over a range of detunings and sizes of optical traps leads to optimalization of obtaining BEC of exciton polaritons. It therefore defines the optimum region where a polariton laser - a novel kind of coherent light source - should operate.

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Anomalous dispersion and dissipative coupling in quantum well exciton-polariton structure

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Strong light-matter coupling in semiconductor microcavities leads to the formation of quasiparticles called exciton polaritons, in which the energy is coherently exchanged between quantum-well (QW) excitons and bound photons. As it is typical for many interacting systems, the levels of these interacting constituents repel one another, leading to the eigenstate anticrossing and characteristic polaritonic dispersion. However, continuous photon loss due to the mirror imperfections, together with the exciton decay via radiative and nonradiative channels, makes microcavities a lossy, dissipative system. It has been shown before how dissipation and dissipative light-matter coupling can strongly affect polariton dispersions, particularly when it is strong enough in comparison to the inherent exciton-photon coupling [1,2]. In other contexts it has been shown how an additional dissipative resonance, acting as a channel of loss, can effectively lead to level attraction [3] – a phenomenon rarely observed in polaritonic research. The attraction would visualize itself in the eigenstate energy dispersion as an inverted shape of one of the polaritonic branches. Such anomalous energy-wavevector dependence, linked to negative particle mass and group velocity, would offer great potential in dispersion engineering and studies of non-Hermitian phases of quantum matter in a solid state.

In this work, we demonstrate the level attraction manifested as an anomalous, inverted dispersion in the AlGaAs exciton-polariton system. We investigate the mechanism of dissipation in our structure, which is crucial for the attraction to occur. Unlike previous studies, our sample hosts both standard Γ-excitons in the QWs, coherently coupled to photons, but also lower-energy spatially and momentum indirect X-excitons, prone to dissipation. We show how the source of dissipation in our structure is the lower-energy indirect state, acting as a draining channel for both photons and electrons. This highly dissipative mode allows for the lossy coupling to become sufficiently strong to surpass the inherent exciton-photon coupling, resulting in inverted eigenstate dispersion. We present the evolution of polaritonic level attraction observed in a photoluminescence measurement and demonstrate the change of the anomalous dispersion shape with the exciton-photon detuning. We model our findings using the three coupled oscillators model, offering an insight into effective coupling strengths. Finally, we demonstrate the superiority of our material system in comparison to scarce previous observations, owing to its high tunability, ease of design and huge potential for non-Hermitian phases engineering.

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Optically gated acousto-electric effect in 2D semiconductors

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With wavelengths in the micrometer range at GHz frequencies, surface acoustic waves (SAWs) are a versatile tool for radio frequency control and probing of charge carrier dynamics in novel semiconductor nanostructures. They are generated on a piezoelectric chip and routed over long distances to couple either mechanically or electrically with almost any nanosystems. In our experiments we fabricated hybrid lithium niobate SAW-devices including SAW delay lines with design frequencies of 150-250MHz containing gold electrodes on which different mechanically exfoliated transition metal dichalcogenide (TMDC) 2D materials can be placed. The dynamic electric field of the SAW induces a SAW power-dependent Acousto-Electric Current (AEC) in the different TMDC structures. The dependence of this fundamental effect on the direction of the SAW enables a detailed investigation of the metal-TMDC interface. Through the spatially-resolved photodoping of the TMDC with a focused green laser (532nm), this setup can be utilized to study the charge carrier dynamics in a variety of different TMDCs, spanning from mono- to few-layer samples.

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Coherence in resonance fluorescence from an acoustically modulated quantum dot with noise

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Quantum dots (QDs) modulated by surface acoustic waves (SAWs) offer a promising solution for miniaturized on-chip multifunctional acousto-optic hybrid quantum systems [1]. Resonance fluorescence (RF) is a common tool to investigate their properties and to map the characteristics of the acoustic field to the optical signal [2-4] with a possible extension to the quantum domain [5,6]. The spectrum of light scattered from an acoustically modulated QD contains a series of sidebands [2], whose intensities oscillate in the time domain [4]. The scattered photons are antibunched [3,7], demonstrating the single-photon nature of the scattering process.

In this contribution, we theoretically study the coherence between different spectral sidebands (frequency channels) in the RF from a weakly optically excited and acoustically modulated QD. We propose an experiment, in which light scattered into two different sidebands is filtered out and interfered, with the resulting signal observed in the time domain. We show that the resulting time-domain interferograms are qualitatively different depending on the presence of coherence between the two sidebands (see Fig. 1). The dependence on the relative phase is a fingerprint of the mutual coherence of these beams. We also include background white noise that leads to fluctuations of the transition energy [8] and demonstrate the noise resilience of the interference effect.

The coherence indicates that a single scattered photon is in a coherent superposition of two frequency modes or that the two modes are entangled. This opens the way to controlling quantum acoustic waves, and in the limit of quantized phonon fields, it may allow the transfer of entanglement from phonons to photons.

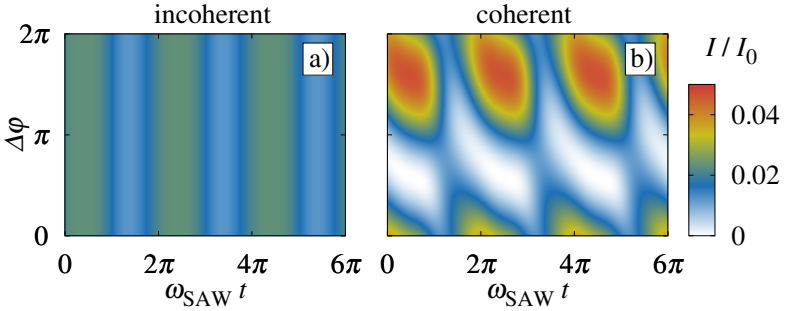

Figure 1: Interferogram in the case of an incoherent (a) or coherent (b) sum of zero phonon line and the first phonon sideband. $\Delta\varphi$ is the relative phase between the two scattered beams derived from the two spectral lines and I_0 is the RF intensity in the weak excitation limit.

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Characterization of Mn^{2+} Spin Relaxation Dynamics in (Cd, Mn)Te/(Cd, Mg)Te Quantum Wells: Impact of Magnetic Field and Temperature

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The rate of spin-lattice relaxation is a critical factor in evaluating the suitability of magnetic ions for use in information processing. Specifically, the form of this rate variation with temperature and magnetic field gives insights into the mechanisms driving energy loss.

In our study, we report on measuring the spin-lattice relaxation rate in a (Cd, Mn)Te/(Cd, Mg)Te quantum well. We employed the time-resolved optically detected magnetic resonance (ODMR) method, recognized for its sensitivity [1], to measure the relaxation time of Mn^{2+} ions located in the quantum well, considering variations in magnetic field and temperature (see Fig. 1).

The obtained results align with a revised model outlined in [2]. This model accounts for the uneven spacing of manganese energy levels, noting that the separation between Mn^{2+} energy levels varies with the magnetic field and strain within the sample. The model accurately describes the dependencies on temperature and magnetic field observed in our study. The findings indicate that the primary energy dissipation mechanism in the system studied is the 'direct process', involving the emission or absorption of a single phonon.

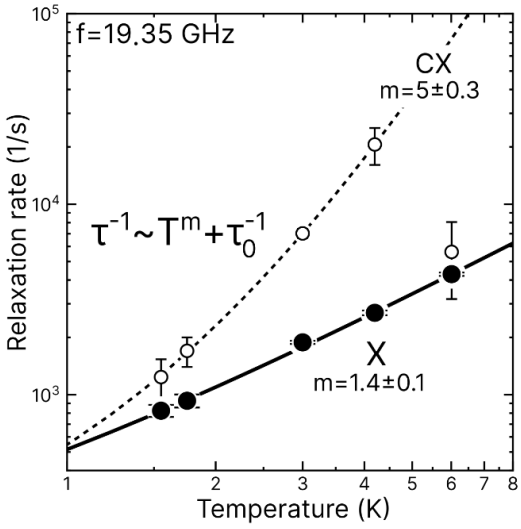

Figure 1 The spin-lattice relaxation rate of the Mn^{2+} ions in CdTe quantum well vs temperature can be described with the power function. The relaxation rate dependence of the neutral exciton (X) is dominated by the direct mechanism. In contrast, the charged exciton (CX) dependency suggests multi-phonon processes.

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Spatial (In)homogeneity of (Cd,Mn)Te Quantum Well Studied with the use of μ-ODMR

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Optically Detected Magnetic Resonance (ODMR) is an incredibly effective technique for studying the local properties of quantum wells (QWs) doped with paramagnetic ions [1]. ODMR takes advantage of the selectivity provided by optical detection methods while maintaining the sensitivity of paramagnetic resonance. A common practice in optical studies of QWs is focusing the light with relatively low-NA lenses, which results in spatial resolution of tens of micrometers. Such an approach makes it easier to integrate the optical experiment with the microwave antenna in ODMR experiments. In our studies, to get better access to local properties revealed in the optical spectrum, we employed μ-photoluminescence and μ-reflectance techniques, followed by μ-ODMR based on those.

(Cd,Mn)Te quantum wells are intrinsically p-doped, with the hole gas derived from the structure's surface [2]. The previous studies show that the interactions with carriers can affect manganese ions in at least two different ways [3]. We observe a shift of the magnetic resonance towards lower magnetic fields (Knight shift) and acceleration of the spin-lattice relaxation time in the presence of carriers. Coincidently, the carrier concentration can be tuned by applying additional above-barrier illumination [4,5], which also affects Coulomb disorder in the plane of the QW. We exploit these effects in our study to explore the effects of carrier gas on manganese ions in the microscale via mapping of (magneto)optical properties of the sample and by μ-ODMR.

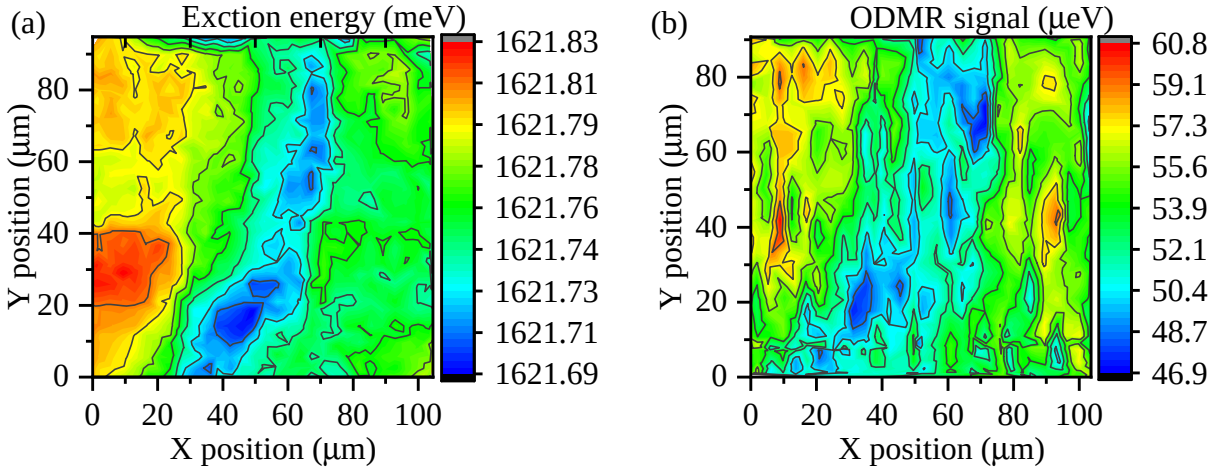

Figure 1: Maps across the sample of: (a) neutral exciton energy, (b) neutral exciton ODMR shift.

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Microscopic theory of the non-linear THz response of thin gold films

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An understanding of the optical response of noble metal nanostructures and its underlying microscopic origins is crucial for the investigation and realization of plasmonic devices. We study the interaction of strong THz and infrared pulses with thin gold films with focus on the excitation, dynamics and decay of non-equilibrium electron distributions.
The theoretical model is based on the Boltzmann kinetic equations involving intraband light-matter coupling and electron-phonon scattering. While the excitation of the electron gas closely follows the dynamics of the external field, the decay of excited states by electron-phonon scattering occurs on a picosecond time scale. Using a self-consistent solution of Maxwell's equations and the kinetic material equations, the radiative self-interaction of the electron gas in thin film approximation is included.
In the linear regime, our numerical results reproduce the classical Drude model including radiative and non-radiative decay channels. For non-linear excitations, we predict a dynamics beyond the relaxation time approximation and with increasing intensity of the incident field a redshift of the transmitted signal.

Fabrication of photonic structures by Xenon Plasma Focused Ion Beam for application in III telecommunication window based on InAs/InP quantum dots.

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Nowadays, one of the many promising ways to produce single photons is to use semiconductor quantum dots integrated into a photonic structure, which can be, for example, micro-pillars or mesas, used to improve emission collection. The advantage of using Xe-PFIB (Xenon Plasma Focused Ion Beam) technology is that it is a technique that allows deterministic and direct fabrication of the structure in the material even without the use of protective masks. In addition, compared to Ga ions, the implantation effect is reduced so that no emission degradation through defect formation is observed. In this research, we focus on processing and spectroscopy measurements of sample with InAs/InP semiconductor quantum dots with low surface density [1, 2, 3]. Series of mesas in range of 3 to 5 μm in diameter were milled. Fabrication of mesas was performed with the beam accelerating voltage was set to 10 kV and the beam current to 1nA then the fabricated microstructures were characterized by low-temperature micro-photoluminescence (μ-PL) measurements – see Fig. 1. Next, we characterized the single QD emission in terms of purity of single photon emission with clear anitibunching for the charged exciton emission. In addition, we also attempted deterministic processing of such microstructures using the PL imaging step [4] which allows preselecting a suitable QD for bright emission spectrally matched to 1.55 μm wavelength.

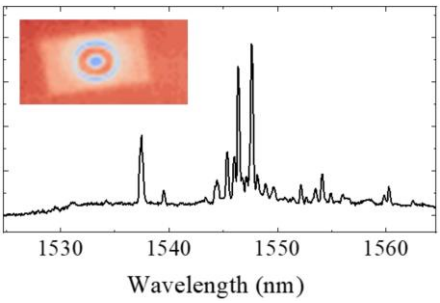

Figure 1. Low-temperature microphotoluminescence spectra from a single InAs/InP quantum dot selected by Xe-PFIB processed micro mesa structure

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Opticaly controled singlet-triplet qubit in a quantum dot molecule

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The spin of an electron confined within a quantum dot continues to be a promising choice for physically realizing a qubit. Our theoretical investigations revolve around an experimentally realized qubit [1] within a self-assembled double quantum dot structure [Fig. (a)], based on two-electron states (one electron per dot). These states include a spin singlet $|S\rangle = (|\uparrow\rangle_1 \otimes |\downarrow\rangle_2 - |\downarrow\rangle_1 \otimes |\uparrow\rangle_2)/\sqrt{2}$ and a spin triplet $|T\rangle = (|\uparrow\rangle_1 \otimes |\downarrow\rangle_2 + |\downarrow\rangle_1 \otimes |\uparrow\rangle_2)/\sqrt{2}$. To achieve optical control of the quantum bit, allowing for the arbitrary rotation of its Bloch vector around a specified axis, we employ the off-resonance coupling of $|S\rangle$ and $|T\rangle$ to a shared excited state $|X\rangle = |\uparrow\rangle_1 \otimes |\downarrow\uparrow\Downarrow\rangle_2$ (a doubly charged exciton state, forming a Λ-system) [Fig. (a)]. This control is implemented using either two spectrally narrow pulses [Fig. (b)] that meet resonant Raman conditions or a single spectrally broad pulse positioned at the midpoint of the singlet-triplet energy splitting [Fig. (c)].

Our examinations focus on quantitatively characterizing imperfections in the gating procedure arising from nonadiabatic evolution and limited spectral selectivity in a real system, in comparison to the ideal adiabatic Raman transfer of occupation in the Λ-system employing the formalism derived in [2]. Subsequently, we investigate the effects of decoherence induced by coupling to crystal lattice phonons and radiative recombination. Consequently, we pinpoint the optimal compromises between various error sources and highlight the most favorable conditions for quantum control over the singlet-triplet qubit in both optical control schemes [Figs. (b) and (c)].

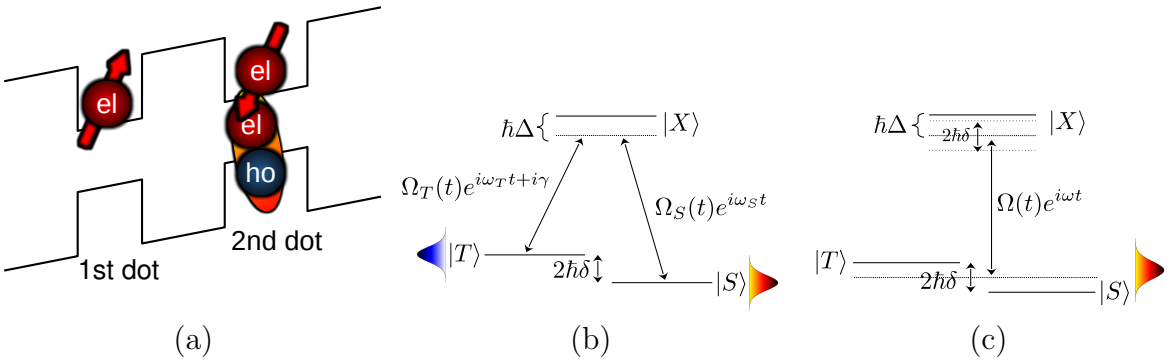

FIG. (a) The band-edge diagram for the investigated system. Optical stimulation couples the two-electron states to the excited state, generating an additional exciton in the 2nd dot. (b) The Λ-system designed for optical manipulation of the singlet-triplet qubit in a two-color protocol, i.e. through the application of two laser pulses that selectively couple $|S\rangle$ and $|T\rangle$ to $|X\rangle$ while satisfying Raman conditions. (c) The Λ-system devised for optical spin control in a one-color protocol, i.e. using a single broad laser pulse that simultaneously couples both $|S\rangle$ and $|T\rangle$ to $|X\rangle$.

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Hybrid acousto-optical control of a quantum emitter

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Recent years brought the idea of hybrid systems [1], in which quantum degrees of freedom of various kinds, due to controlled couplings, allow the transfer of quantum information and may lead to the emergence of new generation devices. A hybrid system may include quantum information processing, storage, and transmission components. Optically active quantum dots (QDs) are at the forefront of systems for applications in quantum technologies. The wide tunability of optical properties, and the available interfaces with light, microwaves, and mechanical waves make QDs a great candidate for a component of hybrid systems.

QDs generate polarization-entangled photon pairs by exploiting indistinguishable emission paths within the biexciton-exciton cascade. However, deterministic and high-fidelity preparation of the state is needed. There are methods like resonant excitation [2] or adiabatic rapid passage [3], but all resonant schemes need cross-polarization filtering to distinguish emitted photons from the resonant excitation pulse, which limits the photon yield significantly. Thus, non-resonant excitations schemes are needed. Recently, novel approach has been proposed, where the state is prepared by effectively periodically switching between two detunings [4]. The main challenge in this scheme is that precise control of two pulses is needed because the evolution strongly depends on their relative timing. Thus, replacing the double-pulse scheme with direct modulation of detuning is desirable.

In this contribution, we propose a new version of the swing-up method of exciton and biexciton state control. We take advantage of the acoustic modulation that allows achieving the intended goal with just one mode of vibration and one optical pulse or even continuous optical driving with single acoustic pulse. In this hybrid acousto-optical approach, selectively exciting either exciton or biexciton state is possible, as well as controlling the exciton-biexciton superposition of states. The results enable the protocol's operation for both single-photon or entangled photon sources.

We model the system using the two- and three-level Hamiltonians in the dipole and rotating wave approximations. Apart from directly finding the evolution for Gaussian optical pulses by numerically solving the Liouville-von Neumann equation, we provide analytical considerations for flat-top optical and acoustic pulses to understand the system's evolution better. Additionally, we estimate the impact of phonon-induced decoherence processes in a non-Markovian approach.

A significant advantage of this method is possibility of implementation for both positive and negative detunings, where the only limitation is caused by the availability of the needed acoustic field frequencies. The scheme is almost phonon decoherence-free even for liquid nitrogen temperatures. More importantly, the scheme may pave the way for generating entanglement between an emitter and a quantum acoustic mode using an acoustic pulse as a trigger for the transitions, leading to subsequent state transfer via an acoustic bus.

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Optimizing electrical transport and SAW propagation in MoS_2

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2D materials offer a plethora of interesting new research and industry applications. Especially few-layered and monolayer MoS_2 has gained increasing significance in recent years, due to its large band gap of up to 1.9 eV at the K and K′ valley of the hexagonal Brillouin zone [1]. Further distinguishing it from other van der Waals materials, such as graphene, are its strong spin-orbit coupling and broken inversion symmetry resulting in coupled valley and spin physics, opening up the field of valleytronics [2]. As has been demonstrated for CVD graphene [3], surface acoustic waves (SAW) and transport measurements allow non destructive probing of the physics governing the material.

In this work we exfoliated MoS_2 flakes of a few layers onto a specially tailored substrate with $LiNbO_3$ as piezoelectric top layer and doped silicon as back gate [Fig. 1a)]. We can pass surface acoustic waves through the MoS_2 flake via an interdigitated transducer (IDT) electrode configuration [Fig. 1b), left] and study the electrical response for different carrier concentrations. To facilitate electron flow at low temperatures, liquid nitrogen physical vapor deposition (LNPVD) was utilized to deposit metals in a Hall bar design with six electrical contacts as shown in [Fig. 1b), right]. The cooled deposition reduces Fermi level pinning (FLP) in the contact interface and empowers us to measure longitudinal and transversal voltages with better contact quality.

Under acoustic excitation at 4.2 K, we observed acoustic currents and voltages in MoS_2 that depend on the power and frequency of the SAW. Hence, we were able to observe the acoustoelectric and acoustogalvanic effect. We also studied magnetotransport under perpendicular magnetic fields and the weak localization phenomenon.

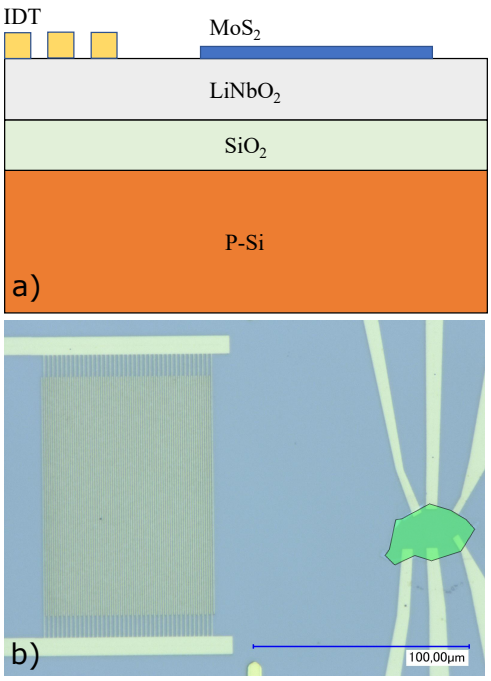

Figure 1: a) Scheme of substrate design, b) picture of IDT (left) and MoS_2 flake (right, black line encloses flake)

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Interplay of various transfer mechanisms for excitons in dense quantum-dot ensembles

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Quantum nanostructures such as quantum dots (QDs) have many different applications in the modern world. From light-emitting diodes through solar cells to implementations of quantum computers. The sought-after properties of QDs are related to the confined electrons, holes, and their complexes, with the exciton (electron-hole pair) being the basic one. Self-assembled QDs can form different ensembles on a plane, from very sparsely scattered dots to densely packed ensembles. This affects the interplay of differently ranged interactions and couplings. It is therefore important to understand, what processes are responsible for carrier behavior in particular for exciton transfer among QDs. Three possible channels for this transfer are the Förster and Dexter mechanisms, as well as single-particle tunneling that becomes important in dense ensembles.

Förster transfer of an exciton in QDs is quite well understood. The dynamics of a single exciton for this interaction were investigated [1]. Also, the dependence of the coupling magnitude on the properties of QDs is known [2]. From the optical spectra of QDs, it is also possible to differentiate Förster and Dexter interactions [3]. Having said that, there is much to explore about how these processes compete with each other. Here, we look at the interplay of Förster and Dexter exciton transfers with the single-particle hopping mechanism.

We investigate QDs arranged in a square lattice with one or two excitons in the system. By describing the system with our extended Hubbard model with two particle species and exactly diagonalizing the Hamiltonian, we quantify different regimes of dominant Förster, Dexter, or hopping process. We study the energy level structure, electron and hole densities, particle correlations, and optical transition dipoles to characterize those regimes.

Our study gives a better understanding of how different exciton transfer mechanisms compete with each other with a special focus on dense QD ensembles with enhanced tunneling. The model is applicable to other lattices of various quantum emitters including disordered systems.

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Optically active gate-defined quantum dot

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Quantum dots (QDs) of various types are currently used in many areas of quantum technologies and quantum information. Gate-defined QDs, which are created by applying electrodes over a quantum well allow for manipulation of their properties by adjusting the potentials applied to the electrodes. High-quality many-qubit devices have been demonstrated within this approach [1]. However, dots of this kind can typically only confine one type of carrier simultaneously which means that they cannot directly couple with light and thus exchange information with flying photonic qubits. Conversely, self-assembled QDs can confine both electrons and holes and therefore can be optically active. Although easier to manufacture than gate-defined QDs, their properties tend to be harder to control, as they are characterized by randomness in their arrangement and defining features (size, shape, and details of chemical composition). Thus combining the advantages of both kinds of QDs, i.e., easily adjustable QD properties and controlled couplings between QDs with optical activity would be desirable.

Here, we propose to use the simplest possible geometry of circular electrodes whose combined potential would confine both holes and electrons. By numerical simulations, we show that for this geometry it is theoretically possible to create an optically active gate-defined QD.

Our calculations are carried out by numerically solving the Schrödinger equation in cylindrical coordinates. Direct discretization of the problem leads to carrier wave functions exhibiting nonphysical behavior near the origin. We implement the improved discretization [2] to avoid this problem. Then we calculate the overlap integral of carrier wave functions, with a nonzero result indicating a theoretical possibility of both carriers occurring in the same area of the QD, which is essential for optical transitions to take place. After we achieve a nonzero overlap of the wave functions, we carry out an optimization process for the dimensions of the system and potentials applied to the electrodes to maximize the result. A key step in the optimization is to reject dot-defining parameters that result in electron wave functions that are not well-localized, meaning that in a real system, the electron would not get confined in the dot at all. From the optimized QD parameters we obtain an overlap of ~ 0.2 which is a very promising result.

Our results can be an introductory step in creating optically active gate-defined QDs. We expect the potential for optical activity to turn out to be even higher after including the electron-hole interaction in the model. If this kind of dot was added to a linear array or a matrix of standard gate-defined QDs it could act as an interface with light for such a device. This additional component could open the door for long-distance quantum communication between gate-defined QD matrices.

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Direct probing of the local confining potential for photons in a large-area VCSEL

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Bose-Einstein condensation (BEC) of photons was achieved in dye microcavity systems [1]. Recently, growing interest in the field motivated work in semiconductor cavities, and signatures of a thermalized BEC have been observed [2,3]. The confining potential provided by the optical microcavity is crucial for BEC, as photons propagating in free space would have linear dispersion. Thus, the minimum energy state would be a state with zero particles. Therefore, detailed knowledge of the confining potential for photon gas is necessary to quantify semiconductor lasers as BEC of photons.

The local emission of large-area electrically pumped vertical-cavity surface-emitting lasers (VCSELs) strongly depends on the inhomogeneity of the local temperature distribution and the nonuniform current density. Those inhomogeneities also change the effective local width of the cavity, which is directly related to the confining potential for the photons. Thus we can expect a change in the density of the states function and in the extracted values of the Bose-Einstein distribution. Because of this effect, the assumption that the density of states has a purely 2D-like character and a fixed value over the whole VCSEL cavity may be an insufficient approximation. Here, we present a new measurement method for determining the local resonant energy of the fundamental mode in wide aperture oxide-confined VCSELs by filtering the spontaneous emission spectrum in the wavevector space close to the normal incidence $k_{||} \approx 0$, which allowed us to deduce the local effective potential change of the microresonator. We observe a constant value of the effective cavity energy for low current densities. In contrast, for higher current densities, the thermal effects and inhomogeneity in local current densities start to play a significant role, changing the planar confining potential for photons into a parabolic potential. The resulting data can be compared to theoretical simulations of the influence of current and temperature on the local potential shape.

Studies on the thermalized photon gas in semiconductor microcavities may provide devices that act as Bose-Einstein condensates of photons, allowing for new research possibilities in Bose-Einstein condensation physics.

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Importance of photonic environment for optical benchmark of $MoSe_2$ monolayers grown by molecular beam epitaxy.

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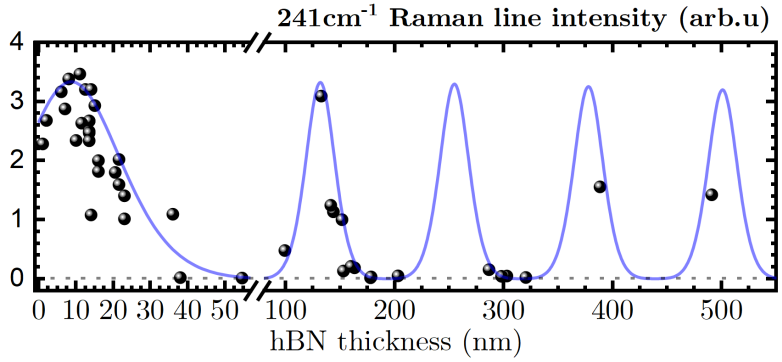
The growing interest in the physics of two-dimensional semiconducting layers has one major inconvenience. In most cases, studied systems are not, in fact, two-dimensional. Exfoliated flakes of transition metal dichalcogenides (TMDs) are relatively small and highly spatially inhomogeneous due to strains originating from the layer transfer process. On the other hand, the samples produced by the epitaxial techniques in a bottom-up approach show a supreme advantage of large-scale homogeneity and the reproducibility. Scalable methods give hope for them being applied in industry applications in the near future.

In our work, we investigated samples of monolayer $MoSe_2$ grown by molecular beam epitaxy on the manually exfoliated hexagonal boron nitride flakes that were deposited onto silicon–silicon oxide wafer. The samples we have obtained exhibit robust homogeneity not only on a scale comparable to single exfoliated $MoSe_2$ flakes but, moreover, on the scales of the whole silicon dice. That fact was observed as the consistency of the low–temperature photoluminescence and room–temperature Raman scattering spectra measured at dozens of spots of different h–BN flakes. The energy, linewidth, as well as shape of the excitonic lines in PL spectra, remained very similar across each MBE–grown sample.

Although the PL spectra shape remained fairly, spatially unchanged, its intensity varied substantially within the given sample and between samples obtained in different growth processes. In this work, we explore the reasons standing behind the observed phenomena. By analyzing the h-BN thicknesses and monolayer filling–factor with an atomic force microscope we were able to pinpoint the main differences affecting light emission intensity between $MoSe_2$ monolayer samples and to develop the model that explains PL and Raman scattering intensity as function of a below lying h-BN thickness.



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Optimised phononic waveguides for quantum dot optomechanics

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Hybrid quantum architectures aim to integrate the advantageous features of different systems while avoiding their individual limitations [1]. In the pursuit of these architectures, surface acoustic waves (SAWs) can play a crucial role. They possess the ability to robustly interact with virtually any other quantum system and, notably, can be directed across millimeter distances with remarkably low dissipation.

The investigation presented here involves a finite element method study of optomechanical coupling between quantum dots (QDs) and Lamb modes (SAW mode propagation in thin membranes) within a phononic waveguide. Here, we consider two kinds of waveguides that are based on a phononic crystal, which, in our study, is a hexagonal lattice of snowflake holes in a GaAs membrane. The first waveguiding structure is formed by removing one row of holes from the hexagonal lattice in the Γ-K direction in reciprocal space (referred to as W1). The second is a modification of W1 achieved by cutting the two arms of the snowflakes that extend into the waveguide core. We focus on the deformation potential (DP) coupling, given its dominance in comparison to the relatively weak piezoelectric potential coupling observed in GaAs materials [2].

In our study, we first adjust the geometric parameters of the phononic crystal to generate a comprehensive band gap that covers the entire k-space within the GHz regime. Based on the found parameters, we optimize the operation of the waveguides by adjusting the spacing between the remaining rows of holes (hole-to-hole center width of the waveguide), described by the geometric parameter Δ. For both types of waveguides, we find the parameter Δ, which reduces the number of modes within the band gap to 2 or 3 and simultaneously maximizes the DP coupling. We take into account both the conduction-band DP, which relies on volumetric strain that vanishes in the symmetry plane in the middle of the membrane thickness, and the valence-band deformation potential that involves shear strain. In the optimized structure and for QDs shifted off the symmetry plane, we observe that the regions of efficient coupling for the two mechanisms do not overlap in the waveguide plane, thus allowing one to select the coupling mechanism through the QD position. The coupling strength in both cases is of the same order of magnitude and, in the case of coupling by valence bands, it exceeds the previously reported values [3] by approximately one order of magnitude at ten times higher frequencies. Throughout the entire optimization process, we take the constraints imposed by realistic experimental conditions into account and keep the QDs within a safe distance from the interfaces.

Our findings determine the optimal photonic waveguide geometry for efficient coupling between QDs and guided modes in the GHz range and reveal a rich structure of position-dependent coupling mechanisms that may allow one to control the desired properties of the coupling.

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Optical properties of third telecom window emitting InAs/InGaAlAs quantum dots grown on silicon substrates

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The amount of information generated every day increases in a very fast rate. The fastest means of its transfer involves light transmitted over networks of optical fibers. However, thus far it is used predominantly for long-haul communication. To take advantage of photons also locally, e.g. directly between computers, it is crucial to integrate emitters and detectors with silicon electronics. However, since indirect band gap forbids direct generation of light in silicon, hybrid structures are required, combining efficient light emission in III-V semiconductors with traditional electronics. Due to the large mismatch of lattice constants and thermal expansion coefficients, smart strategies of integration must be adopted. The most practical seems to be the direct growth of III-V compounds on Si substrates, however, the mismatches between materials of different groups require mitigating strategies to prevent propagation of unavoidable defects.

We present here the effects of incorporation of different defect filtering layers, based on strained superlattices and/or supplementary quantum dot (QD) layers, on the growth of InAs/InGaAlAs QDs for emission in the third telecom window, to take advantage of established technological platform [1]. Complementary optical spectroscopy techniques, i.e. photoreflectance and temperature-, time- and polarization-resolved photoluminescence, are employed to determine optical quality and application potential of obtained structures by comparison to analogical results measured on excellent quality QDs grown on a native InP substrate [2]. Experimental observations are supported by calculations of energy structure, combining multiband $\boldsymbol{k \cdot p}$ and configuration-interaction methods. We confirm that the design of structures indeed limits the density of defect in the proximity of optically active QDs, as intended, since the obtained optical characteristics are comparable to the reference ones. However, the emission of Si-based structures exhibit much larger broadening, related most probably to the nucleation of two different dot populations, as suggested by the unusual dispersion of carrier lifetimes. It is unfavorable for laser devices but may be beneficial for e.g. optical amplifiers. A structure with QD-based defect filtering layers is identified as the most promising and its application prospect is discussed.

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A Bloch approach to X-ray absorption spectroscopy

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In this contribution, we present a combined theory of X-ray Bloch - and Maxwell's equations to describe X-ray absorption experiments like XANES and EXAFS. Particularly crucial in the calculation of EXAFS spectra is a detailed knowledge about the electronic structure and the electron - X-ray interaction matrix elements. In contrast to prior work, where a semi-empirical tight-binding approach was employed [1], we have improved our methodology by including *ab initio* electronic structure calculations.[2] As a proof of principle we calculated the absorption spectrum of graphene which recovers now spectral signals missing in the previous approach [1].

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Concept of Inverted Refractive-Index-Contrast Grating Mirror and Exemplary Fabrication by 3D Microprinting

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A subwavelength grating (SWG) is a photonic structure made of dielectric stripes of subwavelength thickness spaced periodically in one-dimension, typically either suspended in air or deposited on a low-refractive index material substrate. Such grating acts as a highly effective and compact mirror, offering an appealing substitute to multilayer and bulky Distributed Bragg Reflectors. In addition, it may host a peculiar type of a mode called a Bound State in a Continuum exhibiting in principle an infinitely large quality factor. As such, SWGs are very promising for studies and applications of light-matter coupling phenomena.

We present a completely new approach to the design and fabrication of SWGs, breaking two paradigms hitherto in force. First, in our design a SWG made of a low refractive index material is deposited on a cladding layer made of a high refractive index material. We call the proposed design an "inverted refractive-index-contrast grating". Second, we use a technique of 3D micro-printing to produce an exemplary inverted refractive-index-contrast grating based mirror.[1,2] So far, SWGs have been produced by technologically demanding, subtractive-type methods, such as "wet" or "dry" etching combined with electro-lithography.

Our numerical analysis shows that the inverted refractive-index-contrast grating enables nearly total power reflectance, regardless of the refractive index of the cladding layer, as long as the refractive index of the grating material is larger than $\sim$1.75. Reflectivity of around 0.9 is predicted even in the case when the refractive index is as low as 1.5. Moreover, the grating enables efficient polarisation discrimination and phase tuning of the reflected light, properties that are not obtainable using DBRs.

In our proof-of-concept 3D micro-printed inverted refractive-index-contrast gratings, thin stripes of IP-Dip photoresist are deposited on a Si cladding. Qualitative and quantitative comparison of measured and calculated power reflectance spectra reveals very good agreement, indicating, in particular, almost 90% reflection into all diffraction orders and efficient polarization control.

The proposed design and fabrication method open wide perspectives for research and applications in (nano)photonics, optics, and optoelectronics. In particular: (i) the production of highly reflective mirrors in the form of 3D micro-printed gratings is greatly facilitated and accelerated, as no high-vacuum techniques such as vapor deposition or epitaxy are required; (ii) 3D micro-printing offers the advantage of scalability, which is beneficial for possible industrial production; (iii) the method relaxes the requirements for the refractive index of the cladding layer hosting the grating, extending the range of materials that can be applied, so it becomes possible to use a monolayer of transition metal dichalcogenide as a cladding/active layer.

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MBE growth of CdTe structures on hBN

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Hexagonal boron nitride (hBN) is a perfect substrate for the growth of high optical quality 2-dimensional materials such as $MoSe_2$[1]. Moreover, hBN exhibits a very high energy gap (5.9 eV[2]) and ultra-low roughness in the case of exfoliated hBN. The motivation of the present work is based on the observation that such properties of hBN could be also useful for the epitaxy of 2D structures formed from 3D materials, such as e.g. CdTe quantum wells (QWs). In such a case hBN could act both as a flat substrate and barrier material with a high energy gap.

The growth was realized by Molecular Beam Epitaxy on exfoliated hBN flakes deposited on Si (100) substrates covered by 90 nm of SiO_2. Despite the use of relatively small hBN flakes, the Reflection High-Energy Electron Diffraction (RHEED) was applied to observe the evolution of the surface during the growth of the structure. We tested the growth of various tellurides: CdTe, ZnTe, (Cd,Mg)Te, and their heterostructures. After the growth, samples were examined with Atomic Force Microscopy (AFM) and low-temperature photoluminescence (PL) was investigated. Several samples were grown in various temperatures of the substrate during growth.

For typical growth temperatures of tellurides (350-450˚C) there was no observable deposition of material on hBN. The best results were obtained for the lowest temperatures, below 300˚C. The AFM scans of hBN covered by II-VI materials revealed a polycrystalline structure with two different areas: with and without the influence of the electrons from RHEED. In the photoluminescence spectrum of samples with CdTe quantum wells with (Cd,Mg)Te barrier a sharp peak of a CdTe quantum well was observed in the area influenced by RHEED. Experiments have shown that the electron beam from RHEED has a huge impact on the substrate even before the growth. Additionally, on the samples grown on a preheated area with a temperature of 800°C, the influence of RHEED was not visible, and the PL signals of CdTe QW on various spots on hBN were detected. This suggests that the impact of RHEED is similar to annealing the substrate before growth. Also presence of hBN for the formation of high optical quality QWs is important, because areas where CdTe was deposited directly on SiO_2 (not on hBN flakes) revealed only PL of (Cd,Mg)Te barriers, not CdTe quantum wells[3].

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Design of lithium niobate on silicon surface acoustic waveguide for hybrid integrated phononic circuits

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Surface acoustic waves (SAWs) have proven to be effective in the control and manipulation of elementary excitations in condensed matter [1, 2]. In particular, SAWs have been efficiently used to interact with spin waves in magnetic thin film, which shows great potential for the realization of novel microwave devices [3]. In this work, the design of a lithium niobate on silicon (LNoSi) phononic waveguide is presented. The localization of the SAW propagation inside a phononic waveguide will enhance the coupling to hybrid quantum mechanical systems, such as spin waves. Furthermore, the used LNoSi platform offers many other advantages such as high piezoelectric coupling, the capability of photonic waveguiding in addition to the phononic modes, as well as the possibility of non-linear optics. The fundamental phononic waveguide modes determined by the waveguide geometry will be simulated using finite element methods and the phononic dispersion will be studied by varying the waveguide width and height.

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Single indistinguishable photons emitted at 1.55 µm by InAs(P)/InP QDs

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Non-classical light sources, crucial elements in the development of quantum technologies, are revolutionizing our approach to computing, communication, and information security. One of the challenges is to create sources emitting single, indistinguishable photons on demand. An essential practical aspect of such sources is their ability to emit photons in the telecom spectral range. Epitaxial quantum dots (QDs) present promising potential as single-photon sources within these spectral ranges [1, 2].

Here we investigate the quantum optical characteristics of single photons emitted by InAs(P)/InP QDs grown via metalorganic vapor-phase epitaxy in the Stranski-Krastanow mode and heterogeneously integrated with silicon. The QDs exhibit emission at ~1.55 µm, crucial for long-haul, low-loss optical transmission through standard silica fibers [3]. The photon extraction efficiency is enhanced to ~10% by employing a metallic mirror beneath the QDs in combination with a top mesa structure [4].

We confirm the single-photon emission from QDs through measurements of the second-order autocorrelation function, revealing $g^{(2)}(0) = 0.005(4)$ for the biexciton under two-photon resonant excitation. Through the Hong-Ou-Mandel type two-photon interference (TPI) experiment, we evaluate the indistinguishability of emitted photons. TPI visibility, which quantifies this indistinguishability, is pivotal in assessing the coherence of carriers within the QD [5]. Here we show TPI visibility of 35(3)% obtained directly from raw experimental data and 73(6)% when fitted to a model [6]. This significant progress in generating single, indistinguishable photons within the telecom C-band provides valuable insights for potential integration of investigated emitters into devices required for quantum information technologies.

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Direct energy transfer in optically-excited hybrid carbon nanostructures

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In the resonant energy transfer process between a molecule adsorbed on graphene and the graphene surface, the energy is transferred non-radiatively from an excited state of the molecule to the ground state of graphene. The transfer rate depends on the molecule-surface distance and decays with a R^{-4} dependence. The deviation from R^{-6} dependence found in such a process occurring between interacting dipoles is characteristic of systems with delocalized charge densities. The understanding of this property is essential in developing nanometrology methods based on spectroscopic observation of the energy transfer effect.
The transfer rate has an analytical formula [1] which is dependent on the electronic properties of the nanographene fragment and the graphene surface. The increase of the transition dipole moment of nanographene excitation increases the rate, while the molecular band gap exhibits and optimal value of approximately 3.20 eV at which the energy transfer rate is the highest. This allows for tunability of the resonant energy transfer vs. other competing processes, such as charge transfer and Dexter energy transfer.
We consider nanographene donor molecules that can be classified into threefold centrosymmetric systems (C_{42}, C_{96} depicted below) and systems without threefold symmetry (C_{54}, C_{60}, C_{78}). The non-centrosymmetric systems are gradually elongated along their twofold symmetry axis. We find that while some trends scale simply with system size, or can be classified according to molecular symmetry, not all effects can be easily attributed to one of these molecular features. As an example, the decay parameters fitted to short-range (exponential decay) and long-range interactions (R^{-4} decay), which cannot be simply categorized based on symmetry or molecule size. This highlights the need for further computational research to improve the theoretical description of the FRET process in π-conjugated systems and other systems with delocalized charge density.

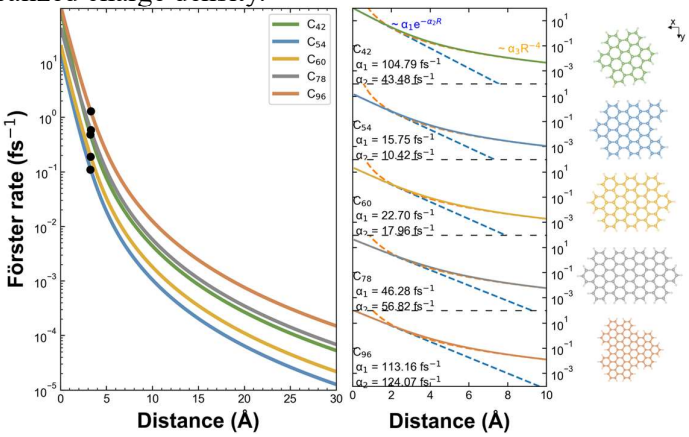

Figure 1: Calculated FRET rates and fitted exponential short-range (blue dashed curve, α_1 decay parameter) and R^{-4} long-range (yellow dashed curve, α_2 decay parameter) decay parameters for nanographene molecules adsorbed on graphene.

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Electrically gated TMD heterostructures as a step towards 1D excitonic states

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Due to their layered crystal structure, Transition Metal Dichalcogenides (TMDs) are an excellent platform to study behaviour of free electric carriers in a 2D regime, especially optical properties caused by emergence of different excitonic states. However, to study more intricate states, such as charged excitons, a sophisticated multilayer structures are required. Process used to fabricate such structures must ensure high accuracy in placement of subsequent layers as well as reasonably high success rate. In this work we present such method, which uses a PDMS stamp covered in polycarbonate film. As a proof of concept, an electrically gated WSe_2 structure encapsulated in hBN was prepared and its photoluminescence and reflectivity were measured as a function of applied voltage.

The goal of the ongoing research is to study excitons confined in a 1D space due to local lowering of exciton binding energy in nonuniform electric field. Such confinement is possible to obtain in a structure similar to the already fabricated one by proper electrode positioning [1].

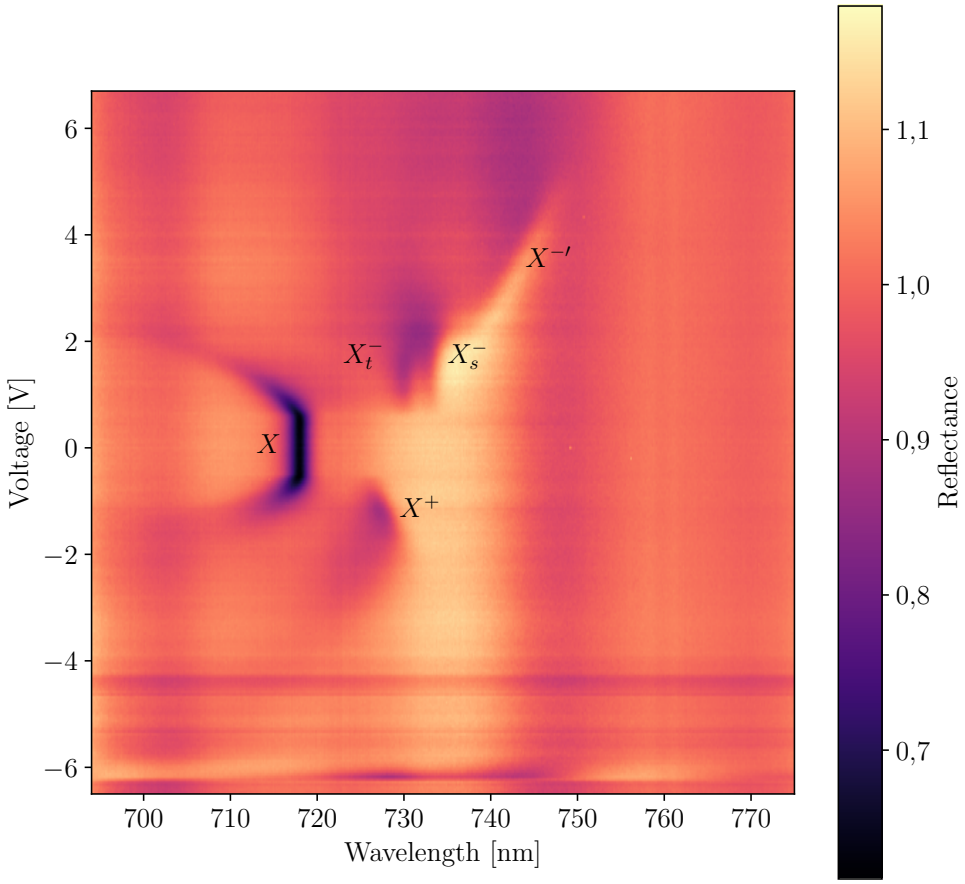

Figure 1: Reflectance of the fabricated sample as a function of applied voltage. Signatures of several different excitonic states are clearly visible.

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