2D Materials for Photonic Quantum Technologies

716. WE-Heraeus-Seminar

27 - 28 May 2021
ONLINE

WILHELM UND ELSE
HERAEUS-STIFTUNG

Introduction

The Wilhelm und Else Heraeus-Stiftung is a private foundation that supports research and education in science with an emphasis on physics. It is recognized as Germany's most important private institution funding physics. Some of the activities of the foundation are carried out in close cooperation with the German Physical Society (Deutsche Physikalische Gesellschaft). For detailed information see https://www.we-heraeus-stiftung.de

Aims and scope of the 716. WE-Heraeus-Seminar:

After the discovery of the first 2-dimensional material in 2004, a single layer of carbon called graphene, which led to the Nobel prize in 2010, enormous research efforts have emerged to find new types of atomically flat materials and characterize their unique properties. Due to their strong interaction with light they are expected to have numerous applications in optics and electronics. This is fostered by the possibility to stack different monolayers of van der Waals materials generating artificial heterostructures.

Since quantum emitters were found in various 2D materials in recent years there is an increasing interest in their quantum optical properties and 2D materials became a key enabling technology for applications in photonic quantum technologies. Compared to other solid-state quantum emitters, 2D emitters' advantages lie in their deterministic position control, their straight forward integration into complex photonic circuits and devices, and their tailorable electronic band structure. In addition, 2D materials can be used as non-linear optical on-chip elements and to build new types of quantum sensors and detectors.

This new research field has just started to explore its endless possibilities. During this workshop we want to bring together the leading researchers of this new field, educating the next generation on this fascinating topic and discuss the future directions of 2D materials for photonic quantum technologies, preparing for the next phase of the European Quantum Technology Flagship.

Introduction

Scientific Organizers:

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Program

Program *(CEST)*

Thursday, 27 May 2021

9:00 – 9:15	COFFEE gathering	
9:15 – 9:30	Klaus Jöns Andreas W. Schell Vincenzo D'Ambrosio	**Introduction and organization**
Session 1 - Chair: Andreas W. Schell		
09:30 – 10:00	Rudolf Bratschitsch	**Single-Photon Emitters in 2D Materials**
10:00 – 10:30	Alexander Tartakovskii	**Tunable van der Waals Nano-Photonics**
10:30 – 11:00	*COFFEE break & networking opportunity*	
Session 2 - Chair: Rudolf Bratschitsch		
11:00 – 11:30	Paulina Plochocka	**Energy and Charge Transfer in Hybrid Transition Metal Dichalcogenide/2D Perovskite Heterostructures (MX2/(PEA)2PbI4)**
11:30 – 12:00	Ursula Wurstbauer	**Degenerate Many-Body States and Multi-Valley Physics of Excitons in vdW Hetero-Bilayers**
12:00 – 12:30	Alexander Högele	**Excitons in van der Waals Heterostructures**
12:30 – 14:00	*LUNCH break*	

Program *(CEST)*

Thursday, 27 May 2021

Session 3 - Chair: Paulina Plochocka

14:00 – 14:30	Araceli Venegas-Gomez	**Why are We Still Talking about Diversity in STEM?**
14:30 –15:00	Ilja Gerhardt	**Understanding the Coherence of Single Emitters by Ramsey Spectroscopy**
15:00 – 15:30	Brian Gerardot	**Quantum Light and Strongly Correlated Electronic States in a Moiré Heterostructure**
15:30 – 16:00	*COFFEE break & networking opportunity*	

Session 4 - Chair: Brian Gerardot

16:00 – 16:30	Bernhard Urbaszek	**Engineering Optical Transitions in 2D Nanostructures**
16:30 – 17:00	Christian Schneider	**Strain Engineered Single Photon Sources with Atomically Thin Crystals**
17:00 – 17:30	Kai Müller	**Quantum Emitters in 2D Materials**
17:30 – 19:00	**Poster Session**	

Program *(CEST)*

Friday, 28 May 2021

Session 5 - Chair: Klaus Jöns

9:00 – 9:30	Prineha Narang	**Predicting Interactions in Correlated Low Dimensional Quantum Systems**
9:30 – 10:00	Igor Aharonovich	**So What Do We Really Know about Quanutm Emitters in hBN?**
10:00 – 10:30	Niko Nikolay	**Revealing the Electronic Structure of Color Defects in Hexagonal Boron Nitride by Correlation Measurements and Spectroscopy**
10:30 – 11:00	*COFFEE break & networking opportunity*	

Upgraded talks - Chair: Igor Aharonovich

11:00 – 11:15	Aidan Campbell	**Strongly Correlated Electronic States in a MoSe2/WSe2 Moiré Superlattice**
11:15 – 11:30	Nadine Leisgang	**Giant Stark Splitting of an Exciton in Bilayer MoS2**
11:30 – 11:45	Kai-Qiang Lin	**Excitonic Quantum Interference in 2D Semiconductor**
11:45 – 12:00	Katja Barthelmi	**Precisely Positioned Single Photon Emitters in Monolayer MoS2**
12:00 – 12:15	Julien Renard	**Investigation of Polariton-Polariton Interactions in Monolayer MoSe2**
12:15 – 12:30	Discussion	
12:30 – 14:00	*LUNCH break*	

Program *(CEST)*

Friday, 28 May 2021

Session 6 - Chair: Vincenzo D'Ambrosio

14:00 – 14:30	Dirk Englund	**2D Quantum Materials for Quantum Information Processing and Sensing**
14:30 – 15:00	Alexandra Carvalho	**Graphene Oxide: Adding Function to Graphene**
15:00 – 15:30	Miriam Serena Vitiello	**Quantum Devices at THz Frequencies Exploiting 2D Materials**
15:30 – 16:00	*COFFEE break & networking opportunity*	

Session 7 - Chair: Miriam Serena Vitiello

16:00 – 16:30	Alexander Kubanek	**Mechanically Isolated Quantum Emitter in Hexagonal Boron Nitride**
16:30 – 17:00	Agnieszka Kuc	**Interlayer Exciton Diffusion in Twist-Angle-Dependent Moiré Potentials of WS2-WSe2 Heterobilayers**
17:00 – 17:15	Klaus Jöns Andreas W. Schell Vincenzo D'Ambrosio	**Closing remarks**

End of the seminar

Posters

Posters

1	Suvi-Tuuli Akkanen	**Graphene Plasmons in Optically Forged Structures**
2	Minh Bui	**Modifying Optical Properties of Monolayer Molybdenum Dichalcogenides by Low Energy Ion Implantation**
3	Ioannis Caltzidis Oscar Camacho Ibarra Federico Fabrizi	**Coupling 2D Single-Photon Emitters and Nano-Beam Cavities**
4	Ulrich Czopak	**Unconventional Photon Blockade – Single Photons from Weak Nonlinearities**
5	Falk Eilenberger	**Direct Growth of 2D-Materials on Optical Fibers: a Novel and Scalable Route to Integrated Photonics with 2D-Materials**
6	Michael Förg Thomas Hümmer	**Ultra-Stable Open Micro-Cavity Platform for Closed Cycle Cryostats**
7	Miriam Gerstel	**Lanthanide Complexes: Luminescence Properties and Morphological Characterizations**
8	Jonas Göser	**Synthesis of Laterally Interfaced Homo- and Heterobilayers of Transition Metal Dichalcogenide Semiconductors**
9	Julia Heupel	**Fabrication of Single-Crystal Diamond Membranes for Quantum Photonics**
10	Katja Hoeflich	**Ion Beam Based Direct Writing of Single Photon Sources**
11	Michael Hoese	**Mechanically Isolated Quantum Emitters in Hexagonal Boron Nitride**

Posters

12	Yossef Khattab	**Nanostructured MoS2 Thin Films as Optical Metasurface**
13	Lukas Lackner	**Tunable Exciton-Polaritons Emerging from WS2 Monolayer Excitons in a Photonic Lattice at Room Temperature**
14	Micaela Laini	**Integration of TMD-Based van der Waals Heterostructure with a Nanobeam Cavity**
15	Battulga Munkhbat	**Exploring TMDC Nanophotonics**
16	Jonathan Noé Manuel Nutz	**Beyond Fluorescence: An Ultra-Senstive Cavity Absorption Microscope for New Insights into 2D Materials**
17	Patrick Pertsch	**Electrically Driven Optical Nano-Antennas**
18	Maximilian Ruf Matthew Weaver	**Enhancing the Spin-Photon Interface of Color Centers in Diamond for Quantum Networks**
19	Sina Saravi	**Photon-Pair Generation Mediated by Coupling of Emitters to Nonlinear Photonic Nanostructures**
20	Marc Sartison Eva Schöll	**Resonance Fluorescence from Waveguide-Coupled Strain-Localized Two-Dimensional Quantum Emitters**
21	Matteo Savaresi	**Site-Controlled and Energy-Tuneable Single Photon Emitters in WSe2 Monolayers**
22	Johannes Scherzer	**Open Cavity in Closed-Cycle Cryostat as a Quantum Optics Platform**
23	Luca Sortino	**Bright Single-Photon Emitters in a Two-Dimensional Semiconductor Coupled with Dielectric Nano-Antennas**

Posters

24	Lukas Sponfeldner	**Capacitively-Coupled and Inductively-Coupled Excitons in Bilayer MoS2**
25	Pablo Tieben	**Spectroscopic Analysis of Defect Centers in hBN**
26	Mikko Turunen	**Deterministic Optical Modification of Monolayer MoS2**
27	Benjamin Vest	**Temperature-Dependent Spectral Emission of Hexagonal Boron Nitride Quantum Emitters on Conductive and Dielectric Substrates**
28	Tobias Vogl	**Quantum Advantage in Interferometry Using Single Photons Emitted from 2D Hexagonal Boron Nitride**
29	Shen Zhao	**Cryogenic Photoluminescence Spectroscopy of Interlayer Excitons in TMD Heterostructures**

Abstracts of Lectures

(in alphabetical order)

Title: “So what do we really know about Quanutm Emitters in hBN?”

Igor Aharonovich

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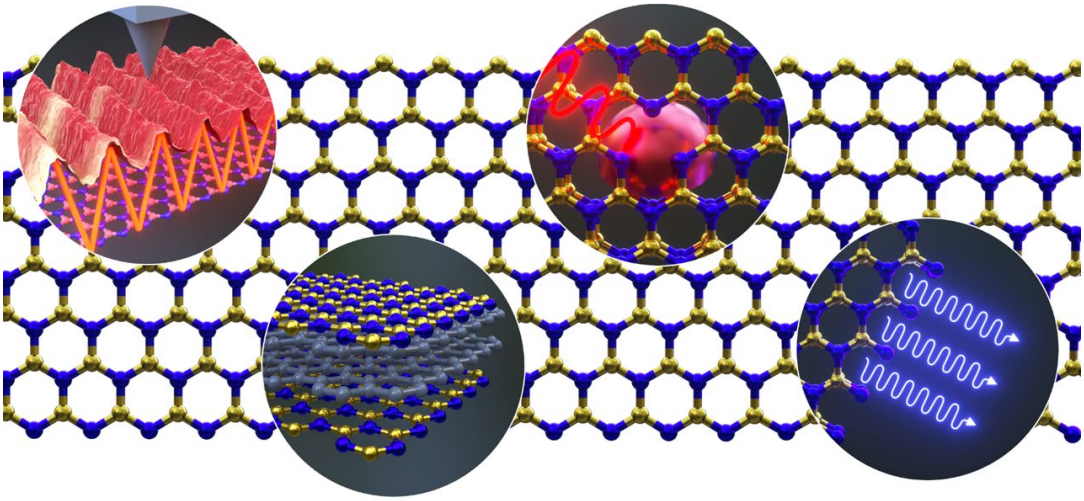
Engineering robust solid-state quantum systems is amongst the most pressing challenges to realize scalable quantum photonic circuitry. While several 3D systems (such as diamond or silicon carbide) have been thoroughly studied, solid state emitters in two dimensional (2D) materials are still in their infancy.

In this presentation I will discuss single defects in an emerging 2D material – hexagonal boron nitride (hBN) that as promising qubits for quantum photonic applications. In particular, I will focus on the fundamental question of what is the origin of the emitters, and provide an overview of their unique photophysical properties. I will also highlight the recently discovered spin defects in this material and present the challenges of moving forward with their applications.



Precisely positioned single photon emitters in monolayer MoS_2

K. Barthelmi[1], A. Hötger[1], J. Klein[1], L. Sigl[1], F. Sigger[1], S. Gyger[2], T. Taniguchi[3], K. Watanabe[3], M. Lorke[4], M. Florian[4], F. Jahnke[4], V. Zwiller[2], K.D. Jöns[2], U. Wurstbauer[1,5], C. Kastl[1], K. Müller[1], J.J. Finley[1] and A.W. Holleitner[1]

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[2]KTH Royal Institute of Technology, Sweden, and University of Paderborn, Germany
[3]National Institute for Materials Science, Tsukuba, Japan
[4]Jacobs University Bremen, Germany
[5]Westfälische Wilhelms-Universität Münster, Germany

We demonstrate the deterministic generation of single photon emitters (SPE) in a monolayer MoS_2 van der Waals heterostack [1-5]. The emitters are naturally confined axially in the monolayer while having a lateral creation accuracy of less than 10 nm generated by highly local helium ion irradiation only limited by secondary ion events [6]. We reach defect creation efficiencies close to unity in larger irradiated spots and up to 18% for single shot irradiation. We spectroscopically investigate single SPEs by performing photoluminescence excitation spectroscopy and temperature dependent measurements. The implantation of defects in readily assembled van der Waals heterostacks results in very homogeneous statistical emission of single defects at 1.75 eV within a narrow energy window (FWHM ~ 28 meV) [3,5]. The optical line shape reveals a strong asymmetry resembling the interaction with LA/TA phonons. Employing the independent Boson model to our emission lines, we find that the emitters are spatially localized to a length scale of 2 nm, which is consistent with scanning tunneling microscopy STM on the samples [6]. The demonstrated methodology allows positioning SPEs with a precision of a few nanometers. Our work paves the way towards the controlled and deterministic generation of SPEs in monolayer TMDC van der Waals heterostructures and quantum photonic devices.

References

[1] J. Klein et al., 2D Mater. **5**, 1 (2017)
[2] J. Klein et al., Nature Comm. **10**, 2755 (2019)
[3] J. Klein and L. Sigl et al., ACS Photonics 8, 669 (2021)
[4] A. Hötger et al., Nano Lett. **21**, 1040 (2021)
[5] K. Barthelmi et al., Appl. Phys. Lett. **117**, 070501 (2020)
[6] E. Mitterreiter et al., *Nano Lett.,* **20,** 6 (2020)

Revealing the electronic structure of color defects in hexagonal boron nitride by correlation measurements and spectroscopy

Niko Nikolay[1], Florian Böhm[1], Oliver Benson[1]

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Optically active point defects in hexagonal boron nitride have been studied extensively over the last years [1]. They are promising candidates as single photon sources in integrated devices for optical quantum technologies [2]. However, it is often difficult or impossible to reveal the electronic level structure for a defect in a specific sample. Besides the spectrum, we have investigated the Stark tunability [3] and quantum efficiency [4] in order to evaluate suggestions for the exact structure of the defects. In this presentation we will introduce polarization-sensitive photon correlation measurements [5] to shine light on the defect properties. We provide recent experimental results and compare them to a multi-level rate equation model. As future perspective, we discuss the potential of correlation measurements for the observation of structural dynamics in individual defects.

References

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[2] Hybrid integrated quantum photonic circuits, A.W. Elshaari, W. Pernice, K. Srinivasan, O Benson, V Zwiller, Nature Photonics **14**, 285-298 (2020).

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Single-photon emitters in 2D materials

R. Bratschitsch[1]

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Atomically thin transition metal dichalcogenides serve as a promising new material class for opto-electronics. In contrast to thicker crystals, monolayers of MoS_2, WS_2, $MoSe_2$, and WSe_2 exhibit prominent photoluminescence. Recently, we have discovered bright and stable single-photon emitters in single layers of WSe_2 [1], which renders atomically thin semiconductors also interesting for quantum optics. In my talk, I will show that these quantum light sources are strain-induced and demonstrate deterministic positioning of the emitters on the nanoscale [2]. Furthermore, I will present single-photon emission from the layered monochalcogenide semiconductor GaSe [3], and demonstrate that the photons can be routed in dielectric waveguides on a photonic chip [4]. Finally, I will discuss the nature and prospects of single-photon emitters in hBN by focusing on the role of phonons [5] and how large emitter arrays can be created [6].

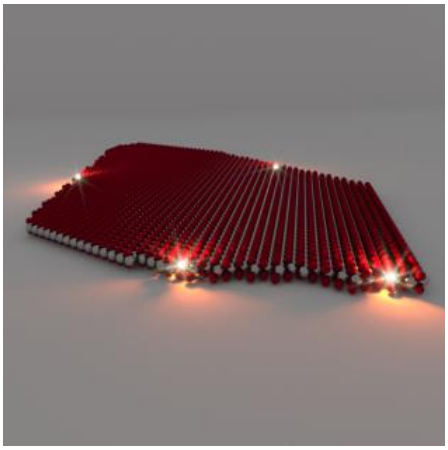

Figure 1: Artistic impression of a WSe_2 monolayer with several single-photon emitters.

References

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[3] P. Tonndorf et al., 2D Materials **4**, 021010 (2017)
[4] P. Tonndorf et al., Nano Letters **17**, 5446 (2017)
[5] D. Wigger et al., 2D Materials **6**, 035006 (2019)
[6] J. A. Preuß et al., 2D Materials, in press (2021)

Strongly correlated electronic states in a $MoSe_2/WSe_2$ moiré superlattice

A. J. Campbell[1], M. Brotons-Gisbert[1], H. Baek[1], K. Watanabe[2], T. Taniguchi[2], and B. D. Gerardot[1]

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TMD moiré superlattices have been shown to host hybrid excitonic states [1], localised quantum emitters [2] and tuneable correlated electronic states including Mott insulating and Wigner crystalline phases [3-5]. $MoSe_2/WSe_2$ heterostructures have been widely studied as a host of band-edge interlayer excitons. However, optical signatures of moiré flat band formation in these structures have thus far proved elusive. In this work we perform resonant absorption spectroscopy of intralayer excitons in a dual-gate tuneable $MoSe_2/WSe_2$ heterostructure with a $57.2^o \pm 0.3^o$ twist angle at 4 K. We observe the formation of moiré intralayer excitons, as well as correlated electronic states at multiple fractional fillings of the first conduction and valence mini-bands. In the hole-doping regime, we observe the WSe_2 charged exciton exhibits doping dependent extraordinary g-factors. We measure the magnetic phase diagram by tuning the fractional filling and observe a peak in the g-factor around 1 hole per moiré site. A Curie-Weiss fit to the temperature dependence of the g-factor at 1 hole per site suggests the formation of an anti-ferromagnetic Mott insulator. Our results show the potential of $MoSe_2/WSe_2$ heterostructures to probe a widely tunable, two-dimensional Hubbard system.

References

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[4] E. Regan et al., Nature **579,** 359 (2020)
[5] Y. Xu et al., Nature **587** 214 (2020)

Graphene oxide: adding function to graphene

A. Carvalho,[1] M. C. F. Costa,[1] V. S. Marangoni,[1] M. Trushin,[1] R. K. Donato,[1] A. H. Castro Neto[1,2]

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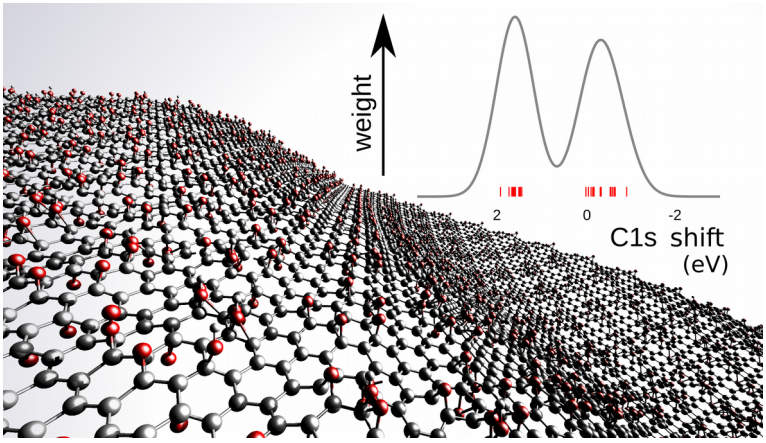
Graphene has been the stage of discovery of numerous novel physical phenomena due to its relatively perfect crystal lattice and purity, and resistance to oxidation. In contrast, graphene oxide is loathed by theorists due to its material complexity, but has a great demand for industrial applications. This stems from the fact that it can be (1) dispersed in water (2) easily functionalised with organic functional groups.

However, graphene oxide, different from most 2D materials, has no crystalline order and can have a range of different compositions, and this makes experiments and processes difficult to reproduce. For this reason, the research in graphene oxide is often of an empirical nature. In this talk, we will consider some of the present challenges in the characterisation of the chemical composition of graphene oxide.[1] We will show how the production of graphene oxide by direct oxidation of graphene is a fast alternative to conventional methods of graphene oxidation and yields high quality material with uniform oxidation[2].

Finally, we will demonstrate how functional materials with morphology responsive to the environment can be created from graphene oxide[3].



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Title: 2D Quantum Materials for Quantum Information Processing and Sensing

Abstract: It was recently shown that 2D materials can be assembled into entirely new types of heterostructures, enabling optoelectronic properties that were impossible using bulk semiconductors. These atomically engineerable heterostructures hold particular promise for quantum technologies. Here, we review our recent work on graphene-based photodetection, with a particular focus on single-photon resolving devices [1–4], and on engineered "artificial atom" emitters in 2D materials [5–9].

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Bio: Dirk Englund received his BS in Physics from Caltech in 2002, and an MS in EE and a PhD in Applied Physics from Stanford University in 2008. He was a postdoctoral fellow at Harvard University until 2010, when he became Assistant Professor of E.E. and Applied Physics at Columbia University. He joined the MIT EECS faculty in 2013. Major recognitions include PECASE, Sloan Fellowship in Physics, DARPA Young Faculty Award, the OSA's Adolph Lomb Medal, the Bose Research Fellowship, and in 2020 a Humboldt Research Fellowship.

Quantum Light and Strongly Correlated Electronic States in a Moiré Heterostructure

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The unique physical properties of two-dimensional materials, combined with the ability to stack unlimited combinations of atomic layers with arbitrary crystal angle, has unlocked a new paradigm in designer quantum materials. For example, when two different monolayers are brought into contact to form a heterobilayer, the electronic interaction between the two layers results in a spatially periodic potential-energy landscape: the moiré superlattice. The moiré superlattice can create flat bands and quench the kinetic energy of electrons, giving rise to strongly correlated electron systems. Further, single particle wave packets can be trapped in the moiré potential pockets with three-fold symmetry to form 'quantum dots' which can emit single photons. Here I will present magneto-optical spectroscopy of a 2H-$MoSe_2$/WSe_2 heterobilayer device with ~3° twist. I will discuss the unique properties of moiré-trapped interlayer excitons, which can emit highly tunable quantum light, and their spectral evolution with exciton density and carrier doping. Finally, I will report the observation of large number of strongly correlated electron and hole states as a function of fractional filling, with a particular focus on the hole moiré superlattice band which exhibits giant g-factors indicative of magnetic ordering.

Understanding the coherence of single emitters by Ramsey spectroscopy

Yijun Wang, Guilherme Stein, Vladislav Bushmakin, Jörg Wrachtrup, Andreas W. Schell and Ilja Gerhardt

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High-quality single photon emitters are an important building block in the field of quantum technologies. Some organic dye molecules, most notably highly condensed aromatic systems, exhibit lifetime limited linewidth at liquid helium temperatures. Here, we study the organic dye dibenzanthanthrene (DBATT, $C_{30}H_{16}$) which offers a remarkable single photon purity, high photon flux and narrow-band emission simultaneously.
In this work, we validate if the spectral linewidth can reach the Fourier limit under cryogenic conditions. Beside an analysis of the linewidth, we analyze the photon statistics and derive the transverse relaxation time T_2.
Furthermore, we perform optical Ramsey Spectroscopy. For this we apply a set of consecutive $\pi/2$ pulses with a varying delay τ. This reveals a measure of optical coherence while the molecule is undisturbed.
We confirm that the T_2-time is governed by the longitudinal relaxation time T_1, and conclude that the dephasing processes in the system are negligible. Subsequently, the linewidth of the emitted photons is truly Fourier limited, which makes the emitter ideal for quantum interference experiments.

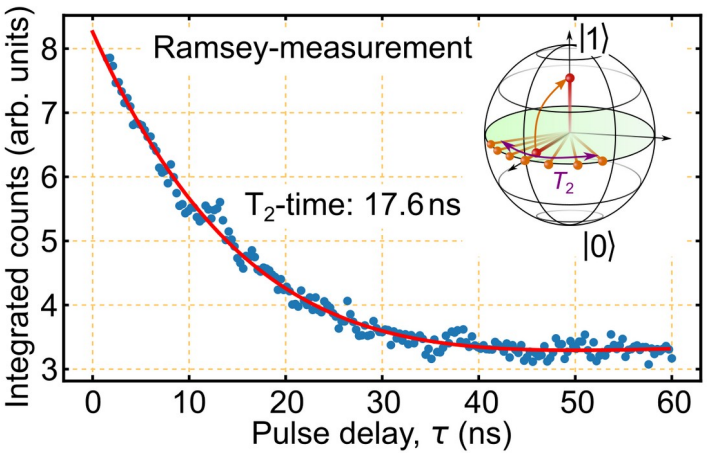

Figure 1: Ramsey spectroscopy on a single organic molecule.

Excitons in van der Waals heterostructures

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Van der Waals crystals of transition metal dichalcogenide (TMD) semiconductors have evolved as an increasingly significant material platform for condensed matter research. The crystals can be routinely exfoliated down to the monolayer limit, or assembled into rationally designed vertical van der Waals heterostructures. In analogy to semiconductor monolayers, such TMD heterostructures exhibit remarkable optical properties with valley-contrasting dipolar selection rules dominated by strongly bound interlayer excitons. I will discuss the results of our recent studies of interlayer excitons in various heterobilayer and heterotrilayer TMD assemblies as a function of layer material, number, twist angle and atomic registry.

Mechanically isolated quantum emitter in hexagonal Boron Nitride

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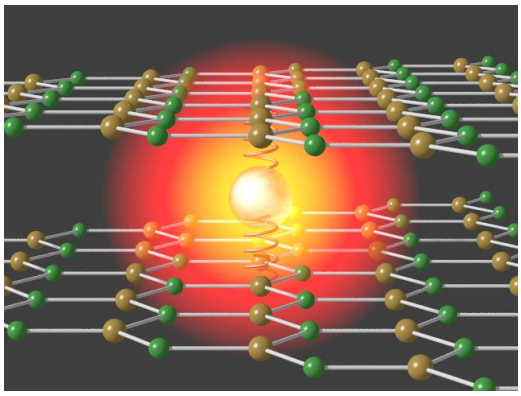

Single photon sources are among most crucial constituents of photonic quantum technology. Solid-state based quantum emitters are of particular importance since they offer robust and scalable platform development with applications in quantum information and quantum sensing. All solid-state emitters have in common, that they interact strongly with the thermal bath and with lattice phonons reducing the optical and spin coherence. Therefore, solid-state quantum optics experiments are restricted to operate at cryogenic temperatures in order to suppress interactions with the solid-state environment. A measure for the optical coherence is the linewidth of an optical transition. Perfect coherence is achieved when all incoherent processes arising from interactions with the environment are suppressed. Once suppressed, the spectral line of a single photon emitter matches the Fourier Transform of its excited state decay.

In this talk I will discuss our recent investigations on defect center in hexagonal Boron Nitride. We studied more than 1000 defect centers with emission frequencies across almost the complete visible spectrum. For some of these emitters, we have observed Fourier-Transform limited lines at cryogenic temperatures under resonant excitation. We interpret our findings with the absence of any dephasing mechanism on the timescale of the scan. Surprisingly, we have discovered that these narrow optical transitions persist when increasing the temperature up to ambient conditions. Such behavior could be explained by a defect center that is decoupled from in-plane phonon modes which, in turn, could be explained by an out-of-plane defect center. I will introduce the audience to our model and understanding of the underlying physics. Furthermore, I will define characteristic features on how to identify these remarkable emitters among others. If time permits, I will discuss applications in optical cavity experiments and as quantum random number generators.

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Interlayer Exciton Diffusion in Twist-Angle-Dependent Moiré Potentials of WS_2-WSe_2 Heterobilayers

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The nanoscale periodic potentials introduced by so-called moiré patterns in semiconducting van der Waals (vdW) heterostructures provide a new platform for designing exciton superlattices. To realize these applications, a thorough understanding of the motion of the excitons in the moiré potentials is necessary. Here, we investigated interlayer exciton dynamics and transport modulated by the moiré potentials in WS_2/WSe_2 heterobilayers, with twist angles of 0° and 60°, in time, space, and momentum domains using transient absorption microscopy combined with first-principles calculations. Exciton transport deviates from normal diffusion, due to the interplay between the moiré potentials and strong many-body interactions, leading to exciton-density- and twist-angle-dependent behavior. Experimental results verified the theoretical prediction of energetically favorable K-Q interlayer excitons and unraveled exciton-population dynamics that was controlled by the twist-angle-dependent energy difference between the K-Q and K-K excitons. These results have important implications for designing vdW heterostructures for exciton and spin transport as well as for quantum communication applications.

Giant Stark splitting of an exciton in bilayer MoS_2

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Transition metal dichalcogenides constitute a versatile platform for atomically thin optoelectronic devices and spin-valley memory applications. In monolayers, optical absorption is strong, but the transition energy is not tunable as the neutral exciton has essentially no out-of-plane electric dipole [1]. In contrast, interlayer exciton transitions in heterobilayers are widely tunable in applied electric fields, but their coupling to light is considerably reduced. In homobilayer MoS_2, the situation is different: Recent studies have shown a strong absorption feature up to room temperature, interpreted as an interlayer exciton [2].

Here, we integrate homobilayer MoS_2 in a dual-gate device structure allowing independent control of the electron density and out-of-plane electric field [3]. On increasing the electric field at close-to-zero electron concentration, we observe two well-separated features in our absorption measurements: the energy degeneracy of the two interlayer exciton configurations is lifted. This result reveals the large in-built electric dipole and proves the interlayer character of the transition; the electron is localized in the top or the bottom layer, while the hole is delocalized across the bilayer, as confirmed by beyond-DFT calculations. We further tune the energy splitting between these two interlayer excitons by as much as 120 meV, more than 10 times their linewidth. Due to their very large opposing dipole moments, we are able to bring the interlayer excitons energetically close to resonance with the intralayer states. While the interaction with the intralayer A-exciton is weak, we observe an avoided crossing of the upper interlayer exciton with the intralayer B-exciton, indicating a strong mixing between the two different states.

For optoelectronics, these highly tunable excitonic transitions with large oscillator strength and in-built dipoles hold great promise for non-linear optics with polaritons on account of strong exciton-exciton interactions.

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Excitonic quantum interference in 2D semiconductor

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Few solid-state systems exhibit optical phenomena related to quantum interference such as electromagnetically induced transparency (EIT). We demonstrate a cavity-free, atom-like EIT effect in the optical transitions of strongly bound excitons formed in single-layer crystals of WSe_2 [1]. We probe EIT by second-harmonic generation (SHG), which is possible because of broken inversion symmetry. Under the condition of double resonance of the driving and radiated field with the fundamental excitonic transitions, the SHG spectrum splits due to excitonic quantum interference. As shown in Fig. 1, the number of dips in the SHG spectrum relates directly to the number of Rabi flops the strongly driven system undergoes within a single laser pulse. The coherent dynamics are accurately described by a ladder-type three-level model. We further demonstrate the ability to control EIT through twist angle in bilayer WSe_2 and $MoSe_2$ [2]. Such a degree of freedom does not exist in conventional dilute atomic-gas systems, where EIT was originally established, and allows us to shape the frequency dependence, i.e., the dispersion, of the optical nonlinearity.

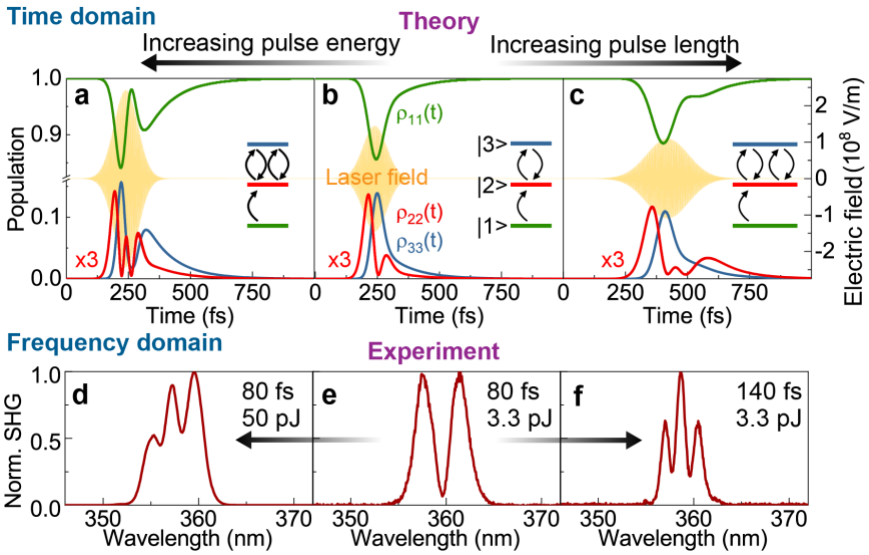

Figure 1 | Correspondence between Rabi flopping in the excited-state population and bifurcation in the SHG spectrum of monolayer WSe_2. a-c, Simulated density-matrix dynamics for different pulse lengths and energies in a ladder-type three-level system. The laser field drives the transitions $|1\rangle \leftrightarrow |2\rangle$ and $|2\rangle \leftrightarrow |3\rangle$, so that quantum interference occurs between transition pathways $|1\rangle \rightarrow |2\rangle$ and $|1\rangle \rightarrow |2\rangle \rightarrow |3\rangle \rightarrow |2\rangle$. Rabi flopping between states $|2\rangle$ and $|3\rangle$ is resolved in the populations $\rho_{22}(t)$ and $\rho_{33}(t)$. The number of Rabi flops during the laser pulse (yellow) determines the number of dips in the experimental SHG spectra (d-f).

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Quantum Emitters in 2D Materials

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For atomically thin 2D materials, several approaches have been explored to trap excitons including using local strain, environmental dielectric contrast and the site-selective generation of luminescent point defects. In this talk, we will present our recent results on tailoring quantum emitters in transition metal dichalcogenides.
First, we discuss how dipolar interlayer excitons (IX) can be trapped within a nanoscale confinement potential induced by placing a MoSe2-WSe2 hetero-bilayer onto an array of nanopillars [1]. We control the mean occupation of the IX trap via the optical excitation level and observe discrete sharp-line emission from different configurations of localized IXs. By their power dependencies these features are identified as single and multiple localized IX which allows to deduce the hierarchy of dipolar and exchange interactions.
Second, we will present the generation of single photon emitters in hBN encapsulated MoS2 using local He-ion irradiation [2,3]. These emitters are detuned by ~195 meV from the MoS2 exciton emission and exhibit dominant emission into the zero-phonon line and narrow linewidth at low temperatures.

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Predicting Interactions in Correlated Low Dimensional Quantum Systems

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Quantum systems host spectacular excited-state effects, but many of these phenomena remain challenging to control and, consequently, technologically under-explored. My research, therefore, focuses on how quantum systems behave, particularly away from equilibrium, and how we can harness these effects[1]. By creating predictive approaches to study dynamics, decoherence and photo-induced correlations in molecules and matter, our work could enable technologies that are inherently more powerful than their classical counterparts. In this talk, I will present examples from my research group on describing 2D materials for quantum technologies from first principles. We explicitly incorporate the microscopic dynamics, decoherence and optically-excited collective phenomena in matter at finite temperature to quantitatively link predictions with atomic-scale imaging, quantum spectroscopy, and macroscopic behavior. Capturing these dynamics poses unique theoretical and computational challenges. The simultaneous contribution of processes that occur on many time and length-scales have remained elusive for state-of-the-art calculations and model Hamiltonian approaches alike, necessitating the development of new (and in our case GPU-accelerated) methods in computational physics[2–4]. I will show selected examples of our approach in *ab initio* design of active defects in quantum materials[5–7], and control of collective phenomena to link these active defects[8]. Building on this, I will present promising physical mechanisms and device architectures for coupling to other qubit platforms *via* dipole-, phonon-, and magnon-mediated interactions. Finally, I will present an outlook on driving these systems far out-of-equilibrium to control the coupled electronic and vibrational degrees-of-freedom.

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Energy and charge transfer in hybrid transition metal dichalcogenides/2D perovskite heterostructures (MX_2/$(PEA)_2PbI_4$)

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Van der Waals heterostructures are currently the focus of intense investigation, this is essentially due to the unprecedented flexibility offered by the total relaxation of lattice matching requirements, and their new and exotic properties compared to the individual layers. I will present the results of the experimental and theoretical studies of the novel hybrid transition metal dichalcogenide/2D perovskite heterostructures. I will discuss the first DFT calculations of a WS_2/PEA_2PbI_4 heterostructure ensemble, which reveal a novel band alignment, where direct electron transfer is blocked by the organic spacer of the 2D perovskite. In contrast, the valence band forms a cascade from WS_2 through the PEA to the PbI_4 layer allowing hole transfer. These predictions are supported by optical spectroscopy studies, which provide compelling evidence for both charge transfer, and non-radiative transfer of the excitation (energy transfer) between the layers. Next, I will demonstrate a long lived interlayer exciton formed in $MoSe_2$/PEA_2PbI_4 system. Our results show that TMD/2D perovskite heterostructures provide a flexible and convenient way to engineer the band alignment. WS_2/PEA_2PbI_4.

Investigation of polariton-polariton interactions in monolayer $MoSe_2$

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Owing to their giant binding energy and versatile excitonic transitions, lamellar semiconductor materials such as hexagonal boron nitride or transition metal dichalcogenides (TMDC) are technologically appealing potential building blocks for photon-based quantum circuits. It was recently shown that they can exhibit quantum dot like behavior and they could thus be used to manipulate light down to the quantum level. Another approach to do so is to harness the two-body interaction between excitons propagating freely in the plane and exploit it within an optical cavity. Provided the interaction is strong enough, the light can be manipulated at the quantum level without the need for quantum dot like confinement. Proof of principle demonstration in Arsenide based materials have shown the feasibility of this approach [1] but in this case the small binding energy forbids room temperature applications. We have thus started to explore this strategy, known as polariton quantum blockade, using monolayer of TMDC [2]. We study a single layer of $MoSe_2$ in the strong-coupling regime with the photonic resonance of an optical microcavity. We characterize quantitatively the magnitude of the two-body interaction between exciton-polaritons by optical micro-transmission spectroscopy. Upon increasing the optical excitation power, we observe a strongly non-linear behavior as a result of the interactions. Eventually, the polariton gap closes at maximum power. This indicates that, in addition to Coulomb interactions, the saturation of the electron-hole density of states plays an important role. We find that its magnitude is largely enhanced compared to hydrogenic excitons and we also observe an unusual spin anisotropy of the interaction. These results are significantly different from semiconductor materials better known in this context, such as Arsenides or Tellurides and open up new perspectives for the manipulation of light using excitons in TMDC.

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Strain-engineered single photon sources with atomically thin crystals

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Monolayers of transition metal dichalcogenides (TMDs) have emerged as a modern material platform to study manybody effects and quantum phenomena via optical spectroscopy.
The high stability and large oscillator strength of quasi-particle excitations emerging in TMD monolayers enables the direct observation of excitons, trions, and more complex manybody states via standard spectroscopy. In the presence of strain, and at cryogenic temperatures, one intriguing feature, which is particularly well- pronounced in WSe_2 thin sheets, is the emergence of tightly localized excitons, acting as single photon sources. The formation of these sources can be manipulated by surface strain, and their proximity to the surface can be harnessed for coupling to surface resonances, e.g. in metallic nanoparticles or dielectric grating cavities. I will address recent developments exploiting those two features, including first implementations of cavity-quantum electrodynamics experiments based on such localized excitons in WSe_2 quantum emitters [1,2] as well as the implementation of highly strain-tuneable single photon sources based on WSe2 monolayers integrated with piezoelectric actuators [3].

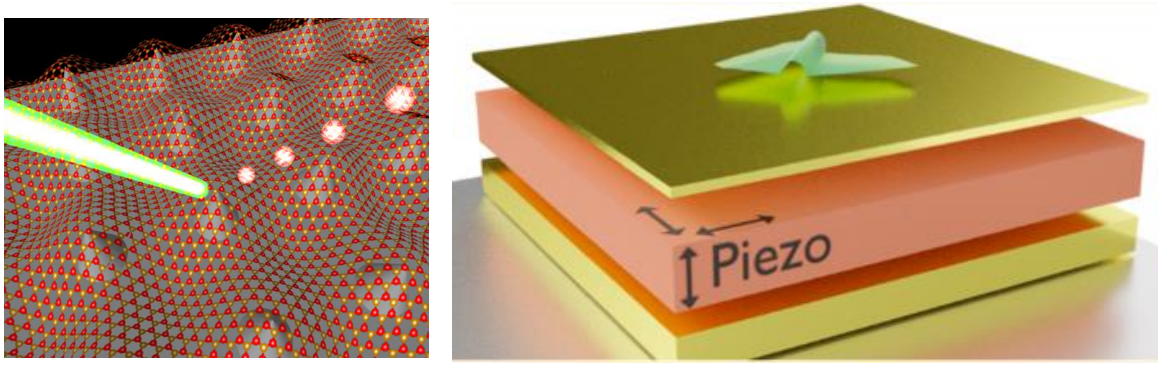

Figure: Left: Artistic Illustration of a strain engineered WSe_2 single photon source; Right: Illustration of a strain-tuneable WSe_2 single photon source

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Tunable van der Waals nano-photonics

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Recently, transition metal dichalcogenides (TMDs) emerged as promising materials for nano-photonic resonators due to their large refractive index and low absorption within a large portion of the visible spectrum as well as compatibility with a wide variety of substrates. Recent reports have realised WS_2 nano-disks, where strong light-matter coupling [1] and second harmonic generation (SHG) enhancement [2] were observed. However, further uses for this material family within nano-photonics have been in short supply. In our studies, we fabricate and numerically simulate nano-antennas made from TMDs and other dielectric and semiconducting layered materials in a variety of geometries including single and coupled nano-pillars with circular, hexagonal and square cross-sections, the latter two with potentially atomically sharp edges and vertices. By varying nano-antenna parameters, we demonstrate the tuning of their photonic modes, probed in the light scattering and SHG experiments. Our simulations for hotspots surrounding the edges of fabricated dimer nano-antennas yield enhancements of the confined electric field intensity of more than 10^3 corresponding to Purcell factors exceeding 150 for an emitter positioned at the hotspot, with a route for tuning of these values by varying the gap and relative rotations of the nano-pillars. To emphasize the feasibility of this approach, we demonstrate reposition of pillars in a dimer nano-antenna in a post-fabrication step using the tip of an atomic force microscope, which allows us to reduce the dimer gap to a simulated value of 10 nm. This, in addition to potential for Purcell-enhanced operation of single photon emitters can be utilised in optical trapping [3] with applications in life-sciences, as we also demonstrate in our calculations.

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Engineering optical transitions in 2D nanostructures

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This talk is devoted to 2 material systems. In the first part, we will discuss how to engineer light emission from WSe_2 monolayers. We introduce a novel approach to dynamic strain control at cryogenic temperature. These experiments allow changing the bandgap by 20 % and give new insights into the role of nominally dark excitons for low energy emission under strain [1], which is also important for single photon emitters.

When WSe_2 monolayers are coupled to photonic or plasmonic nano-structures, it is difficult to disentangle the role of strain and local electric field amplification. Here we shed light on the different contributions. We can distinguish the role of strain compared to that of optical Mie-resonances by investigating WSe_2 monolayers coupled to planarized (no strain) and non-planarized (strained) nano-resonator samples, respectively [2].

In the second part, we discuss engineering of optical transitions by combining monolayers to form multilayers. We examine the correlation between the stacking order and the interlayer coupling of valence states in MoS_2 homobilayer samples. We aim to combine the strong light-matter interaction of excitons in monolayers with high tunabilty of interlayer excitons in external electric fields in our experiments based on the quantum confined Stark effect [3]. Based on the strong, tunable interlayer exciton absorption we show tunable non-linear optical properties in second harmonic generation spectroscopy [4].

These results are based on fruitful collaborations of the LPCNO Toulouse with University of Basel, FSU Jena, CEMES & LAAS Toulouse, Harvard University and NIMS Tsukuba.

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Why are we still talking about diversity in STEM?

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When I was studying aerospace engineering, we were just 10% female students, and strangely, I considered that normal. Years after, while working in industry, I was the only woman in a room full of white men, and I also considered that was the normal situation in a big aeronautical and defense industry.

Forward some more years, until when I returned to academia, and I saw many female students in physics. Well, this is not bad, I thought. But it is bad indeed, as from all those students, only a few will continue to PhD, and even fewer will stay and pursue a career in academia. And that is why it is so difficult to find female speakers for physics conferences. They just don't exist. It is not like in other fields such as in biology, where the ratio is more favorable for women. In those fields, the 50/50 ratio is real. Despite this, we still read articles such as "Women Are Invited to Give Fewer Talks Than Men at Top U.S. Universities" or "Women not getting a fair say at academic conferences, research reveals".

Where is the problem?

With this talk I would like to raise the awareness, and share experiences, which you might have encountered but never really thought about.

Furthermore, I would like to share some initiatives to promote diversity in physics, and specially in quantum, around the world.

I do not want this talk to be only a summary of statistics, I want you to understand the situation of gender diversity in physics, to have a dialogue with you, and to invite you to think about it.

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Quantum devices at THz frequencies exploiting 2D materials

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Bi-dimensional nano-materials and related heterostructures are establishing themselves as intriguing material systems for the development of electronic, photonic and plasmonic quantum devices with properties that can be engineered "from scratch". Their peculiar band-structure and electron transport characteristics, which can be easily manipulated via layer thickness control, indeed suggest they could also form the basis for a new generation of high-performance devices operating in the Terahertz frequency range (1-10 THz) of the electromagnetic spectrum.

This talk will review our latest achievements in the developments of active and passive THz quantum devices exploiting 2D nano-materials and hybrid semiconductor/2D material systems, with a focus on high-speed photodetectors, THz frequency combs, THz modulators and THz near field nanoscopy and will discuss future perspectives for quantum technologies of this rapidly developing research field.

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Degenerate many-body states and multi-valley physics of excitons in vdW hetero-bilayers

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Increasing the interaction strength between quasiparticles can cause strong correlations, collective phenomena and transition to emergent quantum phases. VdW heterobilayers are ideal systems for the realization of exciton condensation because of large exciton binding energies [1], long lifetimes [2] and a permanent dipole allowing for the manipulation of the exciton ensembles via electric fields [3]. Light emission and electron energy-loss spectroscopy showed first evidence of excitonic many-body states in such two-dimensional materials [4,5]. Pure optical studies, the most obvious way to access the phase diagram of photogenerated excitons have been elusive. We demonstrate electric field control of layer index, orbital character, lifetime, and emission energy of indirect excitons in MoS_2 - WS_2 heterobilayers due to valley selective hybridization [3,6]. In contrast, in photogenerated exciton ensembles hosted in $MoSe_2$–WSe_2 hetero-bilayers, we observe several criticalities with respect to photoluminescence intensity, linewidth, and temporal coherence pointing towards the transition to a coherent many-body quantum state [7]. The phenomena survive above 10 Kelvin consistent with the predicted critical degeneracy temperature.

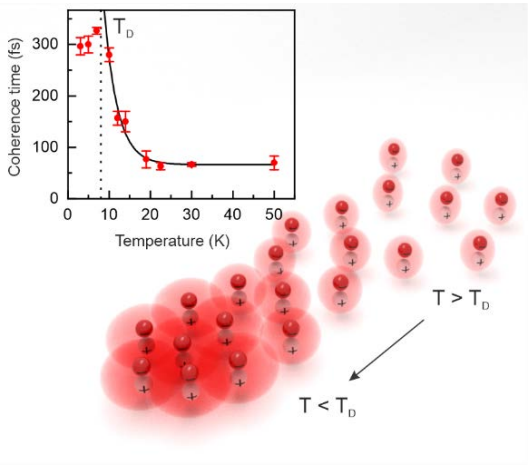

Figure 1: Below the degeneracy temperature T_D, a many-body state emanates of interacting excitons, giving rise to enhanced coherence time [7].

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Abstracts of Posters

(in alphabetical order)

Graphene Plasmons in Optically Forged Structures

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Graphene plasmonic devices have been under rigorous research in the past years, due to their wide range of applications. Optical forging is a method that enables the creation of 3D patterns on 2D materials via ultra-short laser pulse introduced strain. The material tries to overcome the strain by bending, stretching bonds and creating point defects, which eventually form a curved circular structure.[1]-[2] The circles include sub-wavelength features that could in theory be used to overcome the wave vector mismatch between the incident light and graphene plasmons.[3] Overlapping optically forged structures enables creation of larger 3D structures such as pyramids. In this study, larger scale structures such as graphene nanoribbon resembling lines and blister matrices were created and tested for plasmonic resonances. The possible plasmons were expected to be in the far infrared or terahertz (THz) range. However, no change in absorption was detected. The plasmons could still be further in the THz region and thus not visible in the measurements or the measurement signal could have been insufficient for any plasmonic response to be detectable. Aside from creating graphene structures that could support plasmons, optical forging could be utilized to introduce strain to 2D materials, which is an integral step in the creation of scalable quantum light sources.[4]

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Modifying optical properties of monolayer molybdenum dichalcogenides by ultra-low energy ion implantation

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Semiconducting transition metal dichalcogenides (TMDCs) in two-dimensional monolayer (ML) limit with their strong Coulomb interactions, have been shown to be very attractive for quantum optical active devices. Technological success of bulk semiconductors relies on an ability to tune their properties locally using deterministic and reliable methods, such as doping. Similar technologies are needed to realize the potential of ML semiconductors for applications.
Here, implantation with low energy ions is explored as a method to introduce dopant atoms into TMDC MLs. First, data are shown for the prototypical system of Se-implanted MoS_2, where isoelectronic substitution of Se for S in the MoS_2 converts the material into $MoSe_{2x}S_{2(1-x)}$ without introducing free carriers. Different implantation conditions including post-implantation annealing were investigated for the optimal compromise between Se and defect incorporation. Structural and electronic effects of ion implantation on MLs were investigated using Raman and photoluminescence (PL) spectroscopies. Implantation levels much higher than required for doping, up to 20%, could be achieved, but PL was determined by strain introduced by the doping. Results of implantation of Cr for the substitution of Mo in $MoSe_2$ ML is also presented and the nature of defect-related lines observed in PL below neutral exciton energy are discussed.

Coupling 2D single-photon emitters and nano-beam cavities

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In order to make fully operational quantum photonic integrated circuits, it is of great importance to develop a platform capable of supplying an efficient coupling between single-photon emitters and photonic circuitry, being this last the responsible for performing the on-chip manipulation of single photons. Single-photon emitters hosted in 2D materials are a new emerging technology and in order to efficiently couple the light from these emitters into the photonic circuitry and characterized the 2D emitters, cavities are employed. Integrating the emitters with a cavity is advantageous due to the Purcell effect, which results in an increment of the spontaneous emission rate of the emitter. Furthermore, the coupling efficiency between the emitter and a waveguide is also increased because the cavity, which is coupled to the waveguide, redirects the light coming from the emitter into the waveguide. In this work 1D photonic crystal cavities, were simulated for the purpose of later integration with 2D emitters. These photonic crystal cavities can be coupled with waveguides and they possess high-quality factors and small mode volumes which results in large Purcell factors. The cavities are designed using with fundamental resonant modes at 646 nm and 890 nm.

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Unconventional Photon Blockade – Single Photons from Weak Nonlinearities

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The Unconventional Photon Blockade (UPB) [1] is a quantum interference process that uses weak nonlinearities (down to 1/1000 of the cavity linewidth) to turn the Poissonian photon number distribution of a laser field into a number squeezed state close to a single-photon Fock state.

A convenient system to demonstrate this effect without any discrete emitters are zero dimensional microcavity polaritons. Our system consists of a cavity with epitaxially grown AlGaAs DBR mirrors and a thin film of InGaAs embedded in the antinode of a 1λ-cavity. The excitons in this film strongly couple to the cavity light field and the resulting polaritons show the desired weak Kerr nonlinearity, mainly due to exchange interactions of the their excitonic part [2].

This nonlinearity was subject to debate for years and a recent work on conventional Kerr Blockade showed a measured value in excellent agreement to the theory [3], as well as an experiment on UPB in the higher photon number regime [4].

In [1] it was shown that by using input/output mixing in the UPB one can relax the constraints on the parameters of the coupled nonlinear system, and also achieve antibunching that lasts up to five times the lifetime of a strongly coupled system. This brings the theory into a regime where it can be demonstrated using state of the art polaritonic micropillars and fast superconducting nanowire detectors for photon counting and autocorrelation measurements.

In our contribution we will show how we realized a transmission spectroscopy setup in order to observe this effect. Also we will present some preliminary measurements that demonstrate that it should be feasible in our experiment do observe the UPB. Supported by simulations based on our experimental parameters we will discuss possibilities and limitations and give an insight into future prospects for the UPB. In the context of this seminar we will discuss how our experiment could be used to gain further insights into the exciton-exciton interactions of various systems, including 2D materials, using such interferometric measurements.

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2D Materials Coating on Exposed-Core Fibers: A New Approach for Nonlinear Integrated Waveguides

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Two-dimensional (2D) transition-metal dichalcogenides (2D TMDs) are particularly appealing for photonics due to their photophysical effects and strong light-matter-interaction per unit length [1]. However, their total optical response in transmission experiments cases is often limited by the sub-nanometer interaction length imposed by their minuscule thickness. Moreover, there is, up to now, no scalable method for the integration of 2D-materials with waveguides, apart from mechanical transfer. Here, we present a solution to this problem by growing 2D TMDs directly on the guiding core of all-silica exposed-core optical fibers. The direct growth is facilitated with a high-temperature chemical vapor deposition process [2], which can be tuned to yield films of few-layer MoS_2, as well as regions of interspersed single crystals of MoS_2 over length of centimeters. Due to the specific geometry of the fibers, 2D materials are deposited in direct physical contact with the guiding core of the optical fiber, such that there is a considerable overlap of the optical mode with the TMDs, yielding a drastic enhancement of the interaction length.

We will show data regarding transmission of light through these fibers and explore the excitation of photoluminescence in the fiber modes as well as perpendicular to the fiber, both of which may lead to new experiments in exciton dynamics. We will further demonstrate, how the 2D-materials influence the nonlinear behavior of the optical fibers and how it leads to enhanced generation of third-harmonic light by a strong modification of the nonlinear polarization field, yielding a novel mode-matching mechanism to high order modes.

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Ultra-stable open micro-cavity platform for closed cycle cryostats

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We present a fully 3D-scannable, yet highly stable micro-cavity setup, which features a stability on the sub-pm scale under ambient conditions and unprecedented stability inside closed-cycle cryostats. An optimized mechanical geometry, custom built stiff micro-positioning, vibration isolation and fast active locking enables quantum optics experiments even in the strongly vibrating environment of closed-cycle cryostats.
High-finesse, open-access, mechanical tunable, optical micro-cavities [1] offer a compelling system to enhance light matter interaction in numerous systems, e.g. for quantum repeaters, single-photon sources, quantum computation and spectroscopy of nanoscale solid-state systems. Combining a scannable microscopic fiber-based mirror and a macroscopic planar mirror creates a versatile experimental platform. A large variety of solid-state quantum systems can be brought onto the planar mirror, analyzed, addressed individually, and (strongly) coupled to the cavity by moving the microscopic mirror [2,3]. With simple mechanical tuning of the cavity length, the resonance frequency can be adapted to the specific quantum system of interest. However, the flexibility of the mechanical degrees of freedom bears also downsides. Inside close-cycle cryostats, fluctuations of the cavity length on the picometer scale are often enough to prevent the use of high-finesse cavities desired in quantum optics experiments. Through its high stability, our system enables the use of a flexible high-finesse micro-cavity system for quantum applications even in this adversarial environment.

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Lanthanide complexes: Luminescence properties and morphological characterizations

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Lanthanide (Ln) ions are unique for applications in lighting, sensing, and display technologies. Depending on the Ln(III) ion, the emission wavelength varies from visible to near-infrared region of the electromagnetic spectrum. In our approach, we investigate the potential of using Ln(III) complexes as attractive luminescent materials due to its characteristics of narrow emission bands and wide emission spectrum.

Two different types of Nd(III) complexes are investigated: Nd complexes with phosphonate ligands with varying aromatic residues and complexes where the Nd ion is incorporated in a POSS (polyoctahedral silsesquioxane) cage. Both are rigid structures that should suppress vibrational relaxation of excited states at the coordination metal, and hence increase the emission intensity of the transition.

Optical properties of Nd complexes are determined by photoluminescence (PL) spectroscopy, which reveals three emission bands of Nd(III) ions in the NIR region. The complexes are excited with a laser wavelength of 750 nm and 800 nm, respectively. To achieve a low-density molecular distribution on the sample surface, the complexes are dissolved in dichloromethane and drop-casted on a flat surface.

For light enhancement, single molecules will be immobilized on photonic crystal cavities (PhCs). The fabrication of PhCs by electron-beam lithography, inductively coupled plasma reactive ion etching and selective wet etching techniques is discussed. Optical properties of fabricated structures are determined by micro-PL measurements.

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Synthesis of laterally interfaced homo- and heterobilayers of transition metal dichalcogenide semiconductors

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Stacks of two-dimensional semiconductor transition metal dichalcogenides in van der Waals heterostructures have emerged as a novel material platform for quantum simulation and novel computing technologies [1,2]. Despite substantial progress achieved with standard exfoliation stacking techniques, the fabrication of large-scale vertical heterostructures remains challenging. It is even less obvious how to obtain lateral heterojunctions of homo- and heterobilayers from exfoliation stacking. We demonstrate that direct synthesis of such heterojunctions with spatial dimensions of several microns can be obtained with chemical vapor deposition. Within a single-step synthesis process, we realize homobilayer islands of MoSe2 laterally interfaced with MoSe2-MoS2 heterobilayer regions. We performed basic optical characteristics of the vertical van der Waals heterostructures embedded in hexagonal boron nitride and identified spectrally narrow monolayer exciton resonances as well as interlayer exciton transitions consistent with type-II band-alignment heterostructures [3,4]. Our synthesis technique promises deterministic progress in the scaling of van der Waals heterostructures along lateral and vertical dimensions.

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Fabrication of Single-Crystal Diamond Membranes for Quantum Photonics

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Due to its exceptional physical and chemical characteristics, single-crystal diamond (SCD) in a form of thin membranes is a particularly promising material for the fabrication of high-quality photonic devices. Especially, for envisioned applications in quantum information technologies (QITs), such as quantum memories and quantum communication, SCD membranes gained as a host material an ever-increasing scientific interest based on remarkable properties of different optically active point defects in its crystal lattice, the so-called color centers, serving as single-photon emitters.

Here, we report on the fabrication process of µm-thin SCD membranes, with various diameters, exhibiting a low surface roughness down to 0.4 nm on a small area scale (4 x 4 µm), by means of inductively coupled plasma reactive ion etching (ICP RIE). A diamond bulk mask was utilized as an etch mask, featuring distinct hole diameters with angled sidewalls to avoid trenches and cracks at edges of the membrane. A significant reduction of micromasking leading to formation of pits and of polishing damages was accomplished by the application of alternating $Ar/Cl_2 + O_2$ dry etching steps. By a variation of etching parameters regarding the Ar/Cl_2 step, an enhanced planarization of the surface was obtained, in particular, for surfaces with a higher initial surface roughness of several nanometers. Such smooth SCD membranes can be successfully bonded via van der Waals forces on a cavity mirror and when incorporated with NV or SiV color centers can serve as an efficient, coherent spin-photon interface.

Ion beam based direct writing of single photon sources

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The on-chip integration and utilization of the quantum properties of light constitutes the next revolution in information technology. Non-classical light is generated by single-photon sources (SPS). However, the fabrication of SPS is still non-deterministic and, for this reason, non-integrable in the process chain. Direct writing of solid state emitters, especially in the 2D material hexagonal boron nitride (hBN), may be one promising approach. Being a large band-gap semiconductor that is robust to harsh environmental conditions, hBN can contain defect states deep in the band gap that enable stable single photon emission at room temperature [1]. The deterministic creation and the dynamical stabilization of such defects may be realized by focused ion beam manufacturing using He ions [2,3], possibly combined with appropriate functionalization of the created defects. Helium ion microscopy (HIM) relies on a gas field ion source that provides spot sizes of 3 Å while maintaining an ion current that is appropriate for imaging and high precision patterning, thanks to its super-high brightness combined with a low energy spread (< 1 eV) [4]. Using active charge compensation by low energy electron irradiation, the microscope can be used on insulating samples without the need for conducting sample coating. The 16-bit scan generator enables the fabrication of delicate sub-10 nanometer structures with a maximum degree of flexibility and reproducibility.

We currently perform test experiments on exfoliated hBN flakes suspended on a SiN membrane provided from the group of K. Bolotin. Using a python tool for pattern creation, we are able to realize dot and line arrays covering six orders of magnitude in He ion dose. The search for SPS in manufactured hBN samples of varying thickness and with different post-treatments is currently under progress.

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Mechanically isolated quantum emitters in hexagonal Boron Nitride

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Single coherent photon sources are crucial building blocks for novel hybrid quantum system, which will allow for implementing quantum repeaters or other quantum network architectures. Quantum emitters in hexagonal boron nitride (hBN) revealed promising characteristics such as persisting Fourier limited linewidths from cryogenic [1] up to room temperatures [2]. This observation was attributed to decoupling from in-plane phonon modes. Here, we present our recent results towards identifying the origin of this mechanical decoupling, which could be caused by out-of-plane emitters [3]. Our measurements contribute to a better understanding of single quantum emitters in hBN, thus paving the way for implementation of novel hybrid quantum systems and quantum optics experiments at room temperature.

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nanostructured MoS2 as optical metasurface

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Two-dimensional (2D) materials have emerged as promising candidates for miniaturized optoelectronic devices , due to their strong inelastic interactions with light and unique properties of 2d materials family. it's promising in wide range of optical and optoelectronics applications Range from plasmonics and THZ application to nanograting and lensing[1]. however, a miniaturized optical system also requires strong elastic light-matter interactions to control the flow of light. And that were done before in many ways by adding another layers including using noble metals plasmonics , metasufaces or photonics crystals[2].

Managing Deposit of nanostructures MoS2 with controllable positions and sizes for photonics applications can be new way to control flow of light and reduce need for other layers , as results control reflection or absorption can be done directly by control sizes of nanostructures and lateral distance between them.

Two structures were deposited to show this idea. first, nanosizes vertical sheets show new peaks in reflection and percentage of reflection can be tuned by sizes of sheets and distance between them and can reach 100%. Second, growth nano-pyramids can make reflection spectrum flat around all visible range of light. both structures deposited by one step MOCVD and that can much reduce cost and complexity of fabrications devices..

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Tunable exciton-polaritons emerging from WS_2 monolayer excitons in a photonic lattice at room temperature

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The engineering of exciton-polaritons in optical lattices has emerged as a powerful platform for the simulation of Hamiltonians and complex coupled systems. Exciton-polaritons have also revealed its potential to probe non-trivial topology phenomena.

In this work, we present an experiment conducted at room temperature in an open optical cavity of high quality, with an implemented one-dimensional photonic lattice (see Fig. 1a). Such optical microstructure has been utilized recently in experiments addressing Bloch-mode condensates using fluorescent proteins [1]. In our present work, however, we integrate an atomically thin layer of WS_2 to form room temperature Bloch-band exciton-polaritons [2]. Benefiting from the tunability and versatility of our optical platform, we investigate the strong-to-weak coupling crossover, and highlight the emergence of a lattice-band-structure in the tight-binding configuration at room temperature (Fig. 1b).

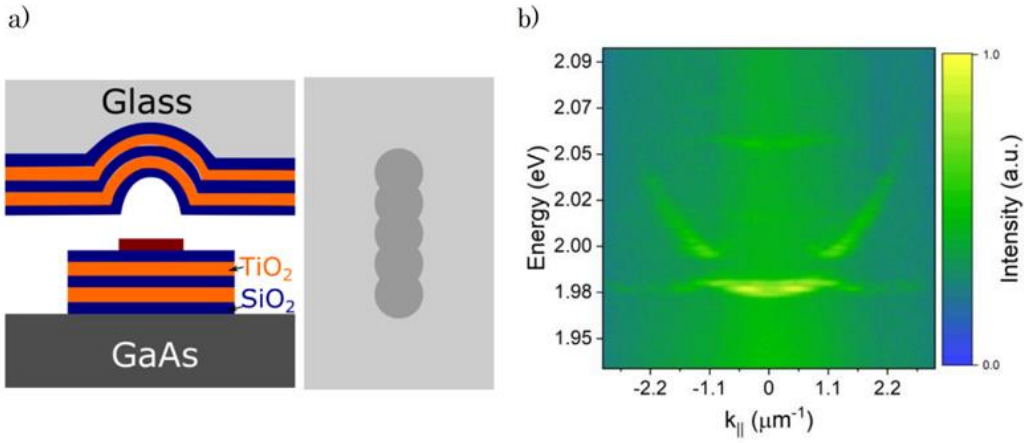

Figure 1: a) Schematic presentation of the open cavity system shown in a vertical cut. The bottom and top mirrors are composed by 10 Bragg pairs of SiO2/TiO2. The top mirror is deposited on a pre-structured glass substrate (see a sketch of the one-dimensional photonic lattice). b) Dispersion relation of WS_2 polaritons in the one-dimensional chain showing a typical Bloch-band structure.

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Integration of TMD-based vdW heterostructure with a nanobeam cavity

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Scalable quantum photonic systems are crucial for the implementation of quantum technologies. A major goal in creating such systems is to achieve an efficient integration of single-photon emitters with control of the rate of radiative recombination via Purcell enhancement in a scalable platform [1]. Moiré-trapped excitons (IXs) in van der Waals (vdW) two-dimensional (2D) heterostructures offer a unique platform of quantum emitter arrays, whose properties can be tailored through the stacking angle [2]. In particular, transition metal dichalcogenides (TMD) are appealing materials for such heterostructures, for their strong Coloumb interaction and spin-orbit coupling, valley-selective optical selection rules and high tunability through the application of electric and magnetic fields [3].

In order to explore the potential of moiré-trapped IXs and their integration with photonic platforms, we propose the design, fabrication and characterisation of a single-layered $MoSe_2$/WSe2 vdW heterostructure on top of a photonic circuit formed by etched one-dimensional nanobeams, integrated in Si_3N_4 waveguides. This design is a promising first step towards the possibility of integrating moiré-trapped IXs excitons with a nanophotonic platform that allows Purcell enhancement of highly tunable emitters.

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Exploring TMDC nanophotonics

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Transition metal dichalcogenides (TMDs) have attracted significant attention as a unique excitonic platform for advanced optical and electronic functionalities. However, in spite of intense research efforts, it has not been widely appreciated that, in addition to displaying rich exciton physics, bulk TMDs also possess a very high refractive index [1-4]. This opens a possibility to utilize these materials for constructing resonant nanoantennas based on subwavelength geometrical modes [1-4]. First, we show that thick flakes of layered van der Waals TMDs can themselves serve as low quality resonators due to their high background permittivity. Optical modes of such "cavities" can in turn hybridize with excitons in the same material [2-4]. Second, we demonstrate pronounced optical Mie resonances in WS_2 nanodisks by nanopatterning the exfoliated multilayer TMD flakes. The fabricated nanodisks support not only optical Mie resonances, but also anapole states that are tunable over the visible and near-infrared spectral range by varying the nanodisks' size and aspect ratio. Moreover, we show that these Mie resonances hybridize with excitons in WS_2, leading to anapole-exciton polaritons [2]. Third, we discuss a facile and controllable anisotropic wet etching method that allows scalable fabrication of TMD metamaterials with atomic precision. We show that TMDs can be etched along certain crystallographic axes, such that the obtained edges are atomically sharp and exclusively zigzag-terminated [4]. This results in a few nanometer thin nanoribbons and nanojunctions. The method thus enables future studies of a broad range of TMD metamaterials with tailored functionality. Therefore, our results suggest that nanopatterned TMDs are promising materials for high-index nanophotonics.

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Beyond fluorescence: An ultra-senstive cavity absorption microscope for new insights into 2D materials

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We use a tunable high-finesse optical micro-cavity [1] as a versatile and powerful tool to measure absorption in transition metal dichalcogenides (TMDs) down to the parts-per-million level. Our scanning-cavity imaging technique [2,3], where a microscopic mirror is scanned across a larger mirror that hosts the sample, allows to collect absorption images of 2D materials with unprecedented sensitivity, spatially resolved with 1µm resolution and in real time. Our approach can be extended to allow for spectrally resolved measurements and reveals polarization-dependent absorption, implanted defects, crystal foldings, and bubbles. Furthermore, we present our progress to extend this absorption measurements to cryogenic temperatures.

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Electrically driven optical nano-antennas

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Plasmonic nano-antennas can be used to enhance the light outcoupling of nano-emitters to the farfield and shape the pattern of their radiation and thus are promising for the use in future photonic quantum technologies [1]. However in many cases the excitation of these nano-emitters is photon-based whereas an electrical excitation would be beneficial for applications. In our group we were able to show that the latter is possible by driving optical nano-antennas via inelastic electron tunneling [2]. This poster will give an overview on how we fabricate plasmonic nano-antennas in our lab and how they are electrically driven.

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Enhancing the spin-photon interface of color centers in diamond for a quantum network

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The Nitrogen-Vacancy (NV) center in diamond is an excellent node candidate, because of its long spin coherence and controllable local qubit registers. While coherent photon collection is inherently limited, integration into a cavity can drastically boost this value via the Purcell effect. However, poor optical coherence of near-surface NV centers has so far prevented their resonant optical control, as would be required for entanglement generation.[1,2]

Future quantum networks will allow for secure communication, networked quantum computing and tests of quantum theory at a large scale. To overcome this challenge, we embed a thin diamond membrane containing NV centers into an open, tunable Fabry-Perot cavity and show that this can preserve the optical coherence of near-surface NV centers in cavities.[3] This allows us to demonstrate resonant addressing of individual, fiber-cavity-coupled NV centers, and collection of their Purcell enhanced coherent photon emission. We extract Purcell factors of up to 4, consistent with a detailed theoretical model including collection efficiencies and cavity length fluctuations.

Based on our results and model, we project that with some near-term improvements present day networks can be sped up by at least a factor of 100. This could allow entanglement generation which outpaces decoherence even for distant NV centers, a crucial ingredient for large scale quantum networks. Furthermore, the open and tunable nature of Fabry-Perot microcavities makes them a promising platform for quantum applications with many different qubit host materials and defect centers beyond those that can easily be integrated into photonic nanostructures.

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Photon-pair generation mediated by coupling of emitters to nonlinear photonic nanostructures

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We theoretically investigate hybrid nonlinear systems of an atom-like emitter coupled to a nonlinear photonic nanostructure [1]. Using the spectral selectivity and the fermionic nature of the atom's transition together with the ability to shape the optical density of states (DOS) in nanostructures, we suppress the individual responses of the two constituents to achieve regimes where the response of the hybrid system is dominated by coupling-induced nonlinear effects. In particular, photonic nanostructures allow for spectral gaps with zero DOS, such that nonlinear effects, like spontaneous photon-pair generation, are prohibited, if the frequency of one of the generated photons is in a gap. Using a rigorous Green's function quantization method to model the hybrid source, we show that a coupled atom with a transition frequency in the gap of the photonic structure mediates the otherwise forbidden generation of exactly one photon pair, where the idler photon directly excites the emitter and the signal photon occupies an optical mode. This effect can serve as a sensitive indicator for the presence and excitation of single atoms. Furthermore, this scheme could be used to implement quantum memories or deterministic and tunable single-photon sources.

Emitters in 2D material are specifically suited for implementing this new branch of hybrid sources of quantum light. Firstly, they are stable and can work in room temperature. Furthermore, they can be positioned accurately on top of a photonic nanostructure, which is required in controlling the atom-mediated effect. Moreover, due to their atomic-size thickness, they can have a very strong overlap with the evanescent tail of optical modes, once there are positioned on top of a nanostructure. Finally, 2D materials such as hexagonal boron nitride offer a very wide bandgap, which could be important in this effect, in avoiding unwanted excitations of the emitter by the strong classical pump beam.

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Resonance fluorescence from waveguide-coupled strain-localized two-dimensional quantum emitters

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Efficient on-chip integration of single-photon emitters imposes a major bottleneck for applications of photonic integrated circuits in quantum technologies. Resonantly excited solid-state emitters are emerging as near-optimal quantum light sources, if not for the lack of scalability of current devices.

A promising scalable platform is based on two-dimensional (2D) semiconductors. However, resonant excitation and single-photon emission of waveguide-coupled 2D emitters have proven to be elusive. Here, we show a scalable approach using a silicon nitride photonic waveguide to simultaneously strain-localize single-photon emitters from a tungsten diselenide WSe_2 monolayer [1,2] and to couple them into a waveguide mode [3]. We demonstrate the guiding of single photons in the photonic circuit by measuring second-order autocorrelation of $g^{(2)}(0)=0.150\pm0.093$ and perform on-chip resonant excitation yielding a $g^{(2)}(0)=0.377\pm0.081$ [4]. These results open up the way towards coherent control of 2D quantum emitters and more elaborate two-dimensional emitter based on-chip quantum photonic circuits.

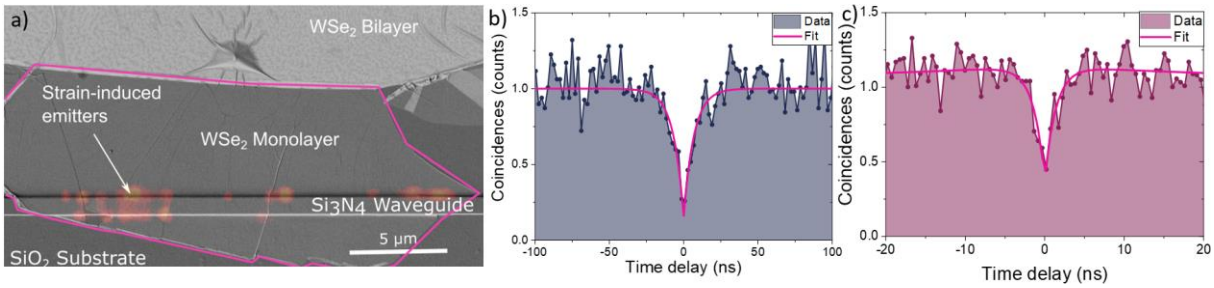

Figure 1: a) SEM picture of the WSe_2 monolayer on top of a SiN waveguide, Second-order correlation measurement b) detected through the waveguide under nonresonant excitation, c) under resonant excitation through the waveguide.

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Site-controlled and energy-tuneable single photon emitters in WSe2 monolayers

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Localized excitons in transition metal dichalcogenides (TMDs) are attracting considerable interest for their capability to generate single photons with high brightness [1, 2]. While the origin of these quantum emitters is still under debate, several works have demonstrated that their appearance is tightly connected to spatial strain gradients that usually arise from wrinkles or buckles [3]. Achieving dynamic control of strain fields in 2D materials is thus fundamental to understand the properties of TMDs and to exploit their full potential for quantum technologies. In this work, we show how strain fields provided by ordered arrays of micro-pillars made from piezoelectric material can be used to control the nucleation site of quantum emitters as well as to modify dynamically their emission properties [3,4]. Specifically, we demonstrate that the energy of localized excitons in TMD monolayers can be precisely tuned across a spectral range as large as tens of meV with no change in the multi-photon emission probability [4]. Our hybrid 2D-semiconductor-piezoelectric platform thus provides a simple method to fabricate ordered arrays of single photon sources with tuneable energy – an important requirement for the exploitation of 2D materials in quantum advanced quantum optics protocols involving remote quantum emitters.

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Open-cavity in closed-cycle cryostat as quantum optics platform

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The introduction of an optical resonator can enable efficient and precise interaction between a photon and a solid-state emitter. It facilitates the study of strong light-matter interaction, polaritonic physics and presents a powerful interface for quantum communication and computing. A pivotal aspect in the progress of light-matter interaction with solid-state systems is the challenge of combining the requirements of cryogenic temperature and high mechanical stability against vibrations while maintaining sufficient degrees of freedom for in-situ tunability. Here, we present a fiber-based open Fabry-Perot cavity in a closed-cycle cryostat exhibiting ultrahigh mechanical stability while providing wide-range tunability in all three spatial directions. We show the design of the cavity setup and the measurement scheme to characterize the stability of the system and demonstrate the operation with the root-mean-square stability of less than 90 pm at temperature of 6.5 K and integration bandwidth of 100 kHz. Finally, we benchmark the cavity performance by demonstrating the strong-coupling formation of exciton-polaritons in monolayer WSe_2 with a cooperativity of 1.6. This set of results manifests the open-cavity in a closed-cycle cryostat as a versatile and powerful platform for low temperature cavity QED experiments.

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Bright single photon emitters in a two-dimensional semiconductor coupled with dielectric nano-antennas

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Single photon emitters (SPEs) in two-dimensional (2D) semiconductor WSe_2 can be deterministically positioned using localized strain induced by underlying nano-structures [1, 2], potentially opening a route for SPE integration with nano-photonic structures and devices. Here, we couple SPEs in monolayer WSe_2 to broadband optical cavities formed by high-refractive-index gallium phosphide (GaP) dielectric nano-antennas [3] also providing the monolayer deformation [4] required for creating the SPEs. We find that in comparison with WSe_2 SPEs formed on SiO_2 pillars, devoid of any photonic action, SPEs on GaP nano-antennas show 10^2 to 10^4 times brighter photoluminescence (PL) accompanied by low PL saturation pulse energy densities < 30 nJ/cm^2 and PL lifetimes from 2 to 200 ns. We show that the key to these observations is the increased quantum efficiency (QE) in SPEs on the GaP nano-antennas, reaching 86%, with an average of 21% compared to 4% in SPEs on SiO_2. The bright PL and high QE enables us to explore the SPE PL dynamics at ultra-low laser powers. From the power-dependent PL rise times, we reveal the ns-scale lifetimes of dark exciton reservoir in the 2D WSe_2 feeding the SPEs, as well as its population decay due to Auger processes at higher powers, providing insight into the PL saturation phenomenon in WSe_2 SPEs. We further measure the coherence time of a high QE SPE, and show that its PL linewidth is limited by intrinsic dephasing processes. Our work establishes dielectric nano-antennas as a platform for high-efficiency quantum light generation in monolayer semiconductors.

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Capacitively-coupled and inductively-coupled excitons in bilayer MoS_2

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Transition metal dichalcogenide (TMD) bilayers provide a promising platform to study interaction-driven physics. In particular, optical spectroscopy of bilayer TMD structures unveils excitonic coupling effects similar to semiconducting coupled quantum wells (CQWs). Excitons in bilayer TMDs can be sorted into two categories: Intralayer and interlayer excitons. For intralayer excitons, the Coulomb-bound electron-hole pair resides in the same layer while for interlayer excitons the electron and hole reside in different layers. The interaction of intralayer and interlayer excitons is studied in a two-dimensional semiconductor, homobilayer MoS_2. The excitonic interaction is well-described by a model of two coupled optical dipoles with different oscillator strength driven by a light field. Applying the model to the excitonic absorption reveals the sign of the excitonic coupling, positive or negative. Comparatively, in an electrical system, the sign of the coupling indicates either a capacitive (positive) or an inductive (negative) coupling. While the interlayer excitons interact inductively with the A-excitons, they interact capacitively with the B-excitons. Our model also predicts constructive interference in one eigenmode ("bright"), destructive interference in the other eigenmode ("dark"), near the energetic crossing of the bare states. We argue that this is a general feature of coupled excitons.

Spectroscopy of single Defect Centers in hBN

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Single photon emitters play a central role in the rapidly developing field of quantum technologies. Therefor new single photon sources are highly sought after. Understanding their properties is essential for their applications in integrated quantum technology.
Defect centers in hexagonal boron nitride (hBN) have become prominent candidates as single photon sources during the last years due to their highly favorable properties, like bright emission, narrow linewidth, and high photostability at even at room-temperature.
Several recent studies have shown a spectral dependency on the excitation wavelength of fluorescence behavior of these emitters [1, 2]. In general, both the intensity and second order autocorrelation function, as well as the emission spectrum, vary with the excitation wavelength.
By tuning the excitation over a broad range inside the visible spectrum and performing measurements regarding the quantum nature as well as the spectral decomposition of the emission light, we gain further insight to the characteristic properties and energy level schemes of these defect centers.

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Deterministic optical modification of monolayer MoS_2

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Transition metal dichalcogenide monolayers have demonstrated exquisite optical and electrical properties [1]. Being able to tune these properties would improve their feasibility for different applications. It has been demonstrated that by using high power laser pulses in a nitrogen environment, one can create three-dimensional structures on graphene [2]. Here, we demonstrate that this method can also be used for CVD grown monolayer MoS_2. In addition, we also show that the high-power laser pulses can also be used to locally modify the optical properties of MoS_2. These results indicate a deterministic modification method for tuning of physical properties of monolayer MoS_2 [3].

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Temperature-dependent Spectral Emission of Hexagonal Boron Nitride Quantum Emitters on Conductive and Dielectric Substrates

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We report a reduction in the linewidth and suppression of spectral diffusion of quantum emitters in hexagonal boron nitride supported on a conductive substrate. We observe a temperature-dependent reduction in the spectral emission linewidth for CVD-grown and exfoliated crystals on conductive ITO relative to those seen on silicon dioxide (SiO2) substrates. We show that the inhomogeneous linewidth can be suppressed by 45% as a result of using a conductive substrate. We investigate the zero-phonon line profile at temperatures ranging from 4 to 300 K and decompose the effects of thermal broadening and spectral diffusion at each temperature by Voigt fitting. The temperature dependence of homogeneous and inhomogeneous components of the broadening is discussed.

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Quantum advantage in interferometry using single photons emitted from 2D hexagonal boron nitride

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Quantum theory is the foundation of modern physics. Some of its basic principles, such as Born's rule, however, are based on postulates which require experimental testing. Any deviation from Born's rule would result in higher-order interference and can thus be tested in an experiment [1, 2]. Here, we report on such a test with a quantum light source based on a color center in hexagonal boron nitride (hBN) coupled to a microcavity. Our room-temperature photon source features a narrow-linewidth, high-efficiency, high-purity, and on-demand single-photon generation [3]. With the single-photon source we can increase the interferometric sensitivity of our three-path interferometer compared to conventional laser-based coherent light sources by fully suppressing the detector nonlinearity [4]. Moreover, our light source is not shot-noise limited, which further reduces systematic errors that could mask as deviations from standard quantum theory. We thereby obtain a tight bound on the third-order interference term of $3.96(523) \times 10^{-4}$. We also measure an interference visibility of 98.58% for our single photons emitted from hBN at room temperature, which provides a promising route for using the hBN platform as light source for phase-encoding schemes in quantum key distribution.

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Cryogenic photoluminescence spectroscopy of interlayer excitons in TMD heterostructures

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The emerging field of van der Waals heterostructures provides the unique opportunity to rationally tailor the properties of solids. Within this innovative framework, heterostructures of atomically thin semiconductors with strong exciton transitionsplay a key role. The possibility to tune the excitonic response of heterobilayers by interlayer twist or doping effects provides novel opportunities for both basic and applied research in optics and optoelectronics. The design degrees of freedom are particularly rich in semiconductor heterobilayers, where the optical properties are intimately tied to layer-separated yet Coulomb-bound electrons and holes of interlayer excitons. Here, we report the results of cryogenic photoluminescence studies of MoSe2-WSe2 and MoS2-WSe2 heterobilayers for further progress towards developments of semiconductor van der Waals heterostructures with tailored optical and optoelectronic functionalities.