Summer School

Polaritons and spectroscopic methods

June 30 to July 2, 2025

Berlin

Book of Abstracts

Poster Session A: 01 – 12

Poster Session B: 13 – 23

Poster	Presenter	Title
1	Felix Ehring	Acousto-optic characterization of van der Waals systems
2	Ke Xiao	Self-intercalation of Fe atoms in MBE grown Fe_3GeTe_2 thin films
3	Maximilian Scharpey	Nanoscale mapping of hBN color centers: Tip-enhanced and tip-assisted photoluminescence
4	Lina Jäckering	Tailoring hyperbolic phonon polaritons in van der Waals materials with the phase-change material In_3SbTe_2
5	Khairi Elyas	Optimizing Helium Ion Beam Milling to Minimize Beam Damage in the Patterning of Suspended hBN
6	Zamin Mamiyev	Surface-Enhanced Raman Spectroscopy of Epitaxial Graphene via Plasmonic Sn Nanoantennas
7	Shachi Machchhar	Cathodoluminescence Imaging of Localized and Delocalized Exciton Complexes in Transition Metal Dichalcogenide Monolayers
8	Bhabani Sankar Sahoo	Unveiling Interlayer Exciton Dynamics of HBL and HTL Heterostructure on Chirped DBR Substrate
9	Güven Budak Julian Hirschmann	Exciton-Polaritons and Magnons in the 2D Antiferromagnet CrSBr
10	Pablo Galan Vazquez	Electronic proximity effects in 2D materials integrated with ultrahigh-k dielectric oxide membranes
11	Ali Mermoul	Numerical Simulations of Electromagnetic Radiation Scattering of Free Monolayer Dielectric Microspheres
12	Priyanka Thawany	Global mapping of heterogeneities in two-dimensional materials
13	Minushree Rout	Transport of exciton complexes in the presence of Fermi sea of free carriers in monolayer semiconductors
14	Lara Blinov	Signatures of efficient intervalley scattering by acoustic phonons in $WSe_2/MoSe_2$ heterostructures
15	Hsin-Mei Ho	Ab initio study of anthracene-MoS_2 heterostructures: effects of interfaces on optical properties
16	Mikołaj Metelski	Gate-tunable Bose-Fermi mixture in a strongly correlated moiré bilayer electron system
17	Bent van Wingerden	Time-resolved Momentum Microscopy: A Methodological Overview
18	Sai Shradha	Excitonic Properties of Tailored CVD-Grown TMDs
19	Moritz Knaak	Towards proximity-control in Graphene/MOF-Heterostructures
20	Pavel Trofimov	Directed light emission in molecular monolayers on 2D materials via optical interferences
21	Ilias Oikonomou	Defect-Driven Magnetism and Emergent Phenomena in $PtSe_2$/graphene Heterostructures
22	Raghav Dhingra	Strain Engineering Moiré Excitons in 2D Heterostructures
23	Tfyeche Tounsi	Inelastic tunneling into multipolaronic bound states in single-layer molybdenum disulfide

Acousto-optic characterization of van der Waals systems

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Abstract
With wavelengths in the micrometer range at GHz frequencies, surface acoustic waves (SAWs) are a versatile tool for radio frequency control and probing of charge carrier dynamics in novel semiconductor nanostructures. They are generated on a piezoelectric chip and routed over long distances to couple either mechanically or electrically with almost any nanosystem [1]. In our experiments, we fabricated hybrid lithium niobate SAW-devices including SAW delay lines with design frequencies of 150-250MHz, on which different mechanically exfoliated transition metal dichalcogenide (TMDC) 2D materials can be placed. The dynamic strain and electric field of the SAW induce a band modulation in the TMDC structure. The focus of the experiments was the investigation of MoSe2-WSe2 heterostructures and their interlayer excitons. For the characterization, the influence of the SAW fields on the recombination time and energy was investigated. Since interlayer excitons provide a much longer lifetime than intralayer excitons, transport along the propagation direction of the wave should be possible and will be part of future experiments.

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Self-intercalation of Fe atoms in MBE grown Fe_3GeTe_2 thin films

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Abstract

Unlike conventional ultrathin magnetic heterostructure, such as Ta/CoFeB/MgO systems grown on Si substrates, 2D magnets feature naturally layered structures, a high degree of crystallinity, and a much weaker substrate dependence. The vdW gap between adjacent layers in 2D magnets offers a unique site for the intercalation of magnetic or non-magnetic atoms during film or crystal growth [1-2]. In this work, we have successfully employed molecular beam epitaxy (MBE) to grow FGT films in the thickness range between 1 quintuple layer (QL) and 20 nm and then investigate the thickness-dependent structural, optical and transport properties on these thin films. We observed an unsaturated magnetization of FGT in both reflective magnetic circular dichroism (RMCD) and Hall measurements, which we attributed to the self-intercalation of Fe atoms in the vdW gap between Fe_3GeTe_2 layers, leading to the breakdown of carrier density estimation in FGT films by decoupling the anomalous Hall effect (AHE) and ordinary Hall effect (OHE) based on conventional Hall measurements.

Figures

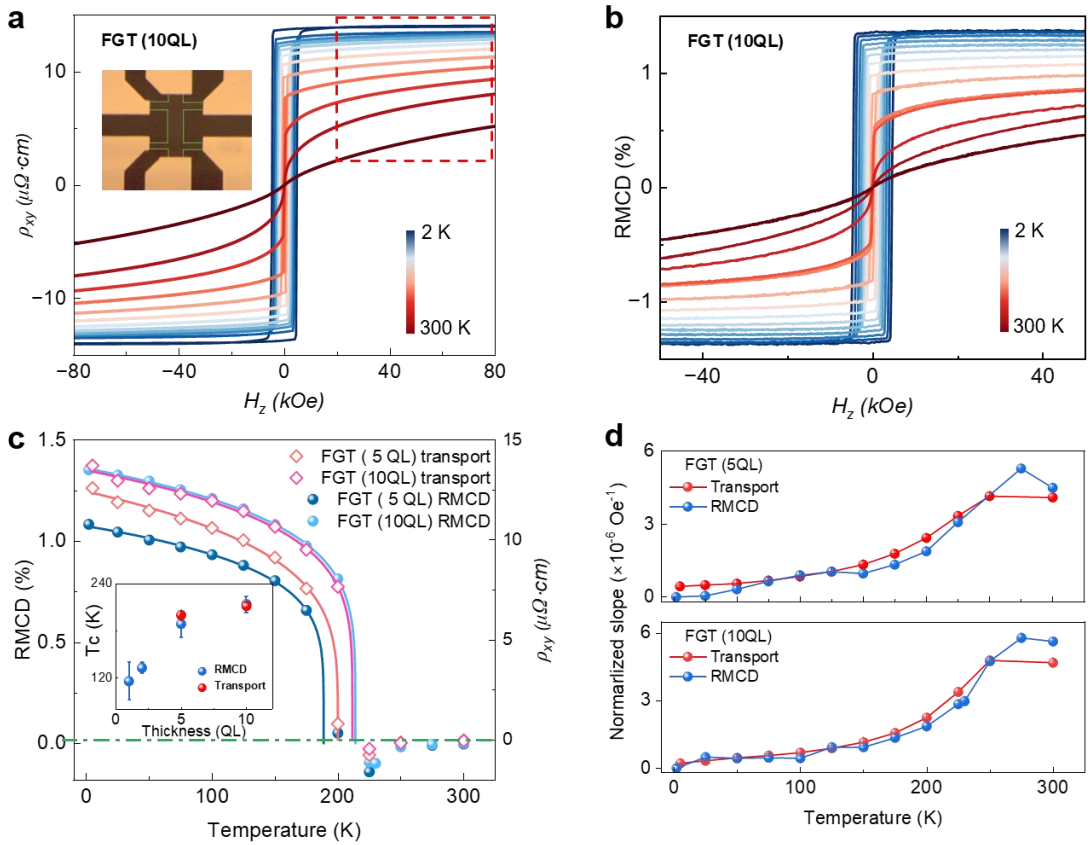

Figure 1: (a) Hall measurement and (b) RMCD on FGT with thickness (10QL) as a function of external magnetic field at different temperature ranging from 2K to 300K. The left inset in b

shows the device for transport measurement. The right inset shows a zoom-in of the Hall resistivity at high magnetic region. (c) The anomalous Hall resistance (red (5QL) and pink (10QL) hollow diamonds) and remnant RMCD (cyan (5QL) and blue (10QL) balls) as a function of temperature. Solid lines: fitting curves of the critical power-law form $(1 - T/T_c)^{\beta}$ using β and T_c as two simultaneous fitting parameters. Inset: the value of T_c obtained are plotted versus thickness. As thickness decrease, the T_c decrease correspondingly. (d) The comparison of normalized slopes between RMCD and transport measurements at high field region (25 kOe-50 kOe).

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Nanoscale mapping of hBN color centers: Tip-enhanced and tip-assisted photoluminescence

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Abstract

Hexagonal boron nitride (hBN) features optically active color centers (CCs), which are promising candidates for quantum light sources in a variety of future applications due to their bright single-photon emission in the visible regime at room temperature. Utilizing a scattering-type scanning near-field optical microscope reaching resolutions far beyond the diffraction limit, studies of the photoluminescence (PL) emission characteristics are executed of such CCs in metalorganic vapor phase epitaxy grown hBN [1]. To do so, a laser beam is focused onto the sharp metallic tip of an atomic force microscope (AFM) resulting in the formation of a concentrated near-field at the tip apex known as the nanofocus. Unlike the diffraction limited spot with elliptical shape observed in conventional far-field PL maps, near-field PL maps of the CCs reveal two distinct features: a dot and an arc surrounding the dot (see Fig. 1). The dot is traced back to the direct near-field interaction of the CC with the nanofocus and corresponds to the previously established tip-enhanced PL (TEPL). The bright arc surrounding the dot can be identified as a far-field contribution resulting from the interference between the direct beams to/from the CC and those scattered from the AFM tip. This effect is called tip-assisted photoluminescence (TAPL) and allows us to determine the dipole orientation of the CCs.

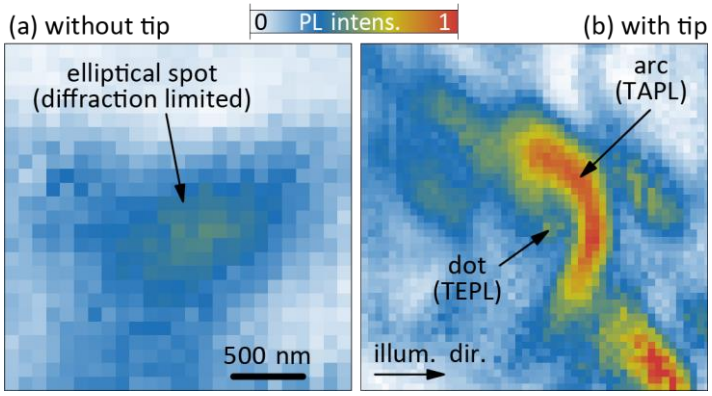

Fig. 1: Comparison of PL maps of a CC without AFM tip (a) and with AFM tip (b) illustrating the features of TEPL and TAPL as well as the powerful resolution enhancement of near-field techniques [1].

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Tailoring hyperbolic phonon polaritons in van der Waals materials with the phase-change material In_3SbTe_2

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Abstract
Polaritons in van der Waals materials (vdWM) stand out due to their high confinement and tailoring options. Confining and tailoring of polaritons - key to advances in nanophotonics- can be achieved by optical structures, such as resonators, launching structures and lenses, which are conventionally fabricated by etching or lithography. While optical structures fabricated by these conventional multi-process techniques used to be static, phase change materials (PCMs) offer fast and reconfigurable programming of optical structures. PCMs can reversibly be switched between two stable phases with distinct permittivities by local heating, e.g., by optical laser pulses.[1] The well-known dielectric PCM GeSbTe-alloys feature a change between two dielectric phases with positive permittivities.[1] This permittivity change has been exploited to confine and tailor polaritons for example in the bulk materials quartz [2] and the vdWM hexagonal boron nitride (hBN) [3]. In contrast, the plasmonic PCM In_3SbTe_2 can be switched between a dielectric and metallic phase. This makes In_3SbTe_2 promising for programming metallic polariton launching structures.[4–6] These optically programmed crystalline In_3SbTe_2 launching structures have been exploited to confine and tailor polaritons in bulk materials such as SiC.[5] Here, we demonstrate direct optical programming and thereby rapid prototyping of optical launching structures in In_3SbTe_2 to tailor and confine polaritons in vdWM. We combine the vdWM hBN with In_3SbTe_2 and optically program circular resonators for hBN's phonon polaritons through hBN into In_3SbTe_2. We investigate the polariton resonators with near-field optical microscopy (SNOM). Demonstrating the reconfigurability, we decrease the resonator diameter to increase the polariton confinement. Furthermore, we fabricate focusing structures for hBN's phonon polaritons whose focal point is changed in a second post-processing step.[7] We envision our approach can easily be transferred to other vdWM such as α-MoO_3 or β-Ga_2O_3. As the thin vdWM flakes are highly transparent in the visible, we can optically program structures through the vdWM into the In_3SbTe_2 below. Thereby, we shrink down the fabrication process of optical structures to two steps: the exfoliation of the vdWM flake onto In_3SbTe_2 and the subsequent optical programming of the desired structure. We promote In_3SbTe_2 as a versatile platform for rapid prototyping of reconfigurable polariton optics in vdWM.

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Optimizing Helium Ion Beam Milling to Minimize Beam Damage in the Patterning of Suspended hBN

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Polaritons in two-dimensional (2D) materials can lead to a significantly enhanced light-matter interaction [1] making them interesting for highly-confined and low-loss light transport. A polariton is defined as a quasiparticle that couples a photon to a dipole-carrying excitation in matter, with this process being strongly dependent on the material type and geometry. Hexagonal boron nitride (hBN) is a non-metallic insulator that has been shown to support phonon polaritons, resulting from strong coupling between infrared photons and lattice vibrations (phonons). Tailoring the geometry of hBN structures is critical to advanced photonic quantum applications, which e.g. rely on enhanced radiative emission of defect-based single-photon emitters [2]. Due to its extreme spatial resolution, helium (He) ion beam patterning is well-suited for structuring 2D materials at the nanoscale [3, 4]. In order to preserve the unique properties of these crystalline materials, it is crucial to minimise beam-induced damage in such 2D materials.

Samples were produced by dry transfer using polydimethylsiloxane (PDMS) and poly(propylene) carbonate (PPC) films due to their favorable viscoelastic and thermoplastic properties. By cutting through suspended layers of hBN with focused He ion beams, we manipulate the geometry to modify and study the arising polaritons.

Optimizing the He ion beam patterning involves fine-tuning both, the geometrical pattern routine itself and the beam parameters that affect the ion beam profile. Variations in parameters such as beam current, spot control, acceleration voltage and beam scanning velocity result in distinct beam profiles and local sputter/damage distributions, each exerting different effects on the final structure.

In the aim of systematically optimizing He ion-induced patterning of hBN, a study of line cuts for optimized beam profiles at varying beam velocities for different hBN thicknesses was performed to obtain information from damage profiling [5]. This is based on low-dose diffraction line scans. Line scans are performed along the direction perpendicular to the cuts to obtain the microstructural information from the diffraction patterns in correlation with the real-space detector signal indicating the crystallinity, defectivity or degree of amorphization of material. The resulting diffraction line scans data shows a clear beam velocity dependent behaviour in both defect creation and amorphization.

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Surface-Enhanced Raman Spectroscopy of Epitaxial Graphene via Plasmonic Sn Nanoantennas

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Surface-enhanced Raman spectroscopy (SERS) is a powerful tool for amplifying inelastic light scattering from phononic excitations in low-dimensional materials. Graphene, due to its chemical inertness, stable and tunable electronic properties, and Raman-active phonons, provides a unique platform for investigating underlying mechanisms and advancing applications. In this work, we present a novel SERS system based on plasmonic Sn nanoantennas, enabling more than a 100-fold enhancement of graphene Raman signatures. We compare the SERS response of Sn nanoantennas placed atop Sn-intercalated, charge-neutral quasi-free-standing monolayer graphene (QFMLG) and intrinsically doped epitaxial monolayer graphene (MLG) on SiC(0001) [1,2]. The results reveal that the localized surface plasmon resonances (LSPRs) of the Sn nanoantennas drive the observed signal amplification. The SERS effect is accompanied by Raman shifts indicative of hot carrier-induced doping in graphene. Moreover, the strong plasmonic coupling and associated electromagnetic field gradients activate otherwise Raman-inactive phonon bands in graphene. Quantitative analysis shows that this interaction is tunable via the intrinsic carrier concentration of graphene [3]. The present study establishes a tunable and effective SERS platform, offering a promising alternative to conventional noble metal-based substrates.

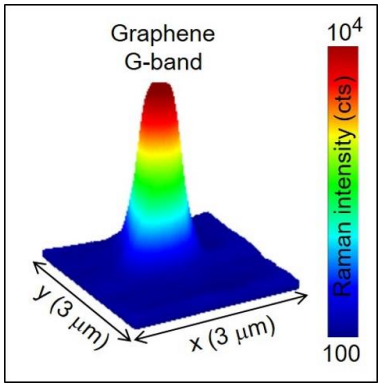

Figure 1: 3D representation of the SERS signal obtained for Sn nanoantenna on QFMLG/Sn at λ=532 nm, showing enhanced intensity of the graphene G-band with the maxima on the Sn nanoisland.

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Cathodoluminescence Imaging of Localized and Delocalized Exciton Complexes in Transition Metal Dichalcogenide Monolayers

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Abstract

The development of on-demand sources of single photons with high indistinguishability represents a crucial step in the creation of photonic quantum systems, such as those required for the construction of large-scale quantum networks for the secure transfer of data. One potential avenue for the realization of such sources in a scalable and cost-effective manner is the exploitation of defect centres in transition metal dichalcogenides (TMDCs) as single-photon emitters. [1] The fabrication of these defect centres in TMDC monolayers (MLs) can be achieved through the introduction of strain, ion implantation, and the structuring or patterning of the substrate. In this study, we pattern hBN with the help of electron beam lithography and deposit a WSe_2 ML on the top to induce strain, which facilitates the generation of single-photon emitters with distinct quantum optical properties. We then perform cathodoluminescence imaging [2] on the fabricated structure to determine the localised and delocalised excitonic states in the ML. We optically characterise the said states and furthermore, demonstrate the single-photon nature of these quantum emitters through second-order autocorrelation measurements.

Figures

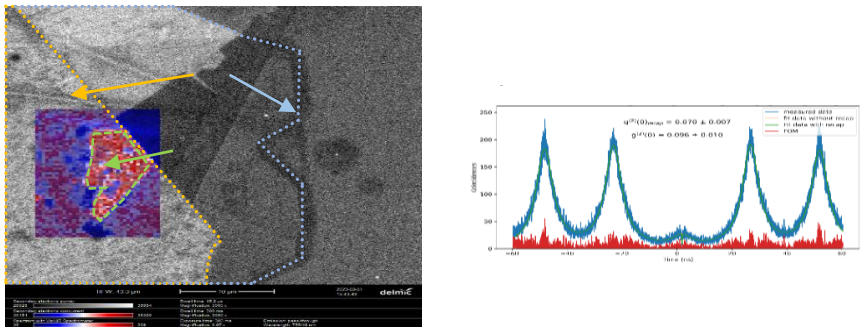

Figure 1: a.) Room temperature (RT) CL imaging of an encapsulated ML of WSe_2. b.) Second-order autocorrelation measurement under non-resonant (660 nm) excitation with $g^{(2)}(0) = (9.6 \pm 1)\%$ (orange) $g^{(2)}(0) = (7.0 \pm 0.7)\%$ with recapture (green).

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Unveiling Interlayer Exciton Dynamics of HBL and HTL Heterostructure on Chirped DBR Substrate

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Abstract

Interlayer excitons (IX) of transition metal dichalcogenide (TMDC) van der Waals heterostructures (HS) exhibits low photoluminescence (PL) yield above cryogenic temperatures, posing a significant bottleneck for their application in optoelectronic devices. To enhance the IX emission, we utilize chirped distributed Bragg reflectors (cDBRs) centered at 950 nm as a substrate and backside mirror. This cDBRs consist of 15 mirror pairs designed for 950 nm wavelength and 3 mirror pairs for other wavelengths, resulting in a uniform 600 nm wide reflection across the IX emission range [1]. To further boost the IX density, we introduce a WSe_2 monolayer on top of the $WSe_2/MoSe_2$ heterobilayer (HBL) to form a novel heterotrilayer (HTL). The top WSe_2 layer provides additional radiative pathways and improves interlayer coupling which amplifies the IX emission [2].

In the present work, we fabricate a HTL using H-type stacking with twist angle of 55^0 and 50^0 for the $MoSe_2/WSe_2$ and WSe_2/WSe_2 HS, respectively. PL emission at 4 K shows that the HTL exhibits more than 10-fold higher intensity compared to HBL, and a redshift of the HTL peak confirms hybridization in the WSe_2 layers. Additionally, with increasing the temperature, the HBL displays two distinct peaks with varying intensities. Both HS show PL emission from 4 K to room temperature due to the presence of the cDBR, which reflects a significant portion of incident light in the IX emission range. The temperature-dependent radiative lifetime further provides insights into the different decay processes in both HS.

Figures

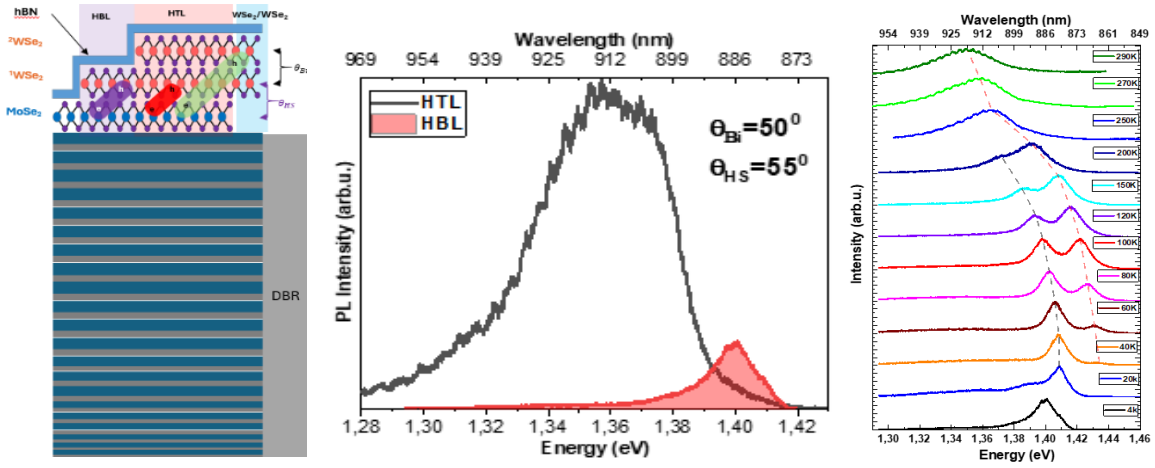

Figure 1: (a) Schematic of a HTL on cDBR, (b) Comparison PL plot of HBL and HTL, (c) Temperature dependent PL spectra of HBL.

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Exciton-Polaritons and Magnons in the 2D Antiferromagnet CrSBr

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Featuring strong and robust magnetic excitons, the van der Waals antiferromagnet CrSBr offers exceptional opportunities to study collective magnetic phenomena in the regime of strong light-matter coupling. In this contribution, we introduce two major directions of our new research group at TU Munich:

In the first, we focus on optical detection and control of magnons, which can propagate coherently over tens of microns in nanoseconds in CrSBr and couple to excitons [1]. We plan to coherently drive the magnons by microwaves and to optically detect their dynamics by monitoring changes in the transient reflectance. Our first step in this direction is to maximize the photonic response to coherent magnons by optimizing layer thicknesses and substrate materials; a challenging task, especially when multiple layers of different materials are involved.

The second project builds on recent demonstrations of exciton-polariton condensates in CrSBr microcavities [2, 3]. A key challenge now is to identify resonator structures that support stable condensates with magnetic tunability and allow for ultrafast modulation of the condensate's coherent emission by magnons. Ultimately, the goal is to realize the first polariton laser with magnetic memory functionality.

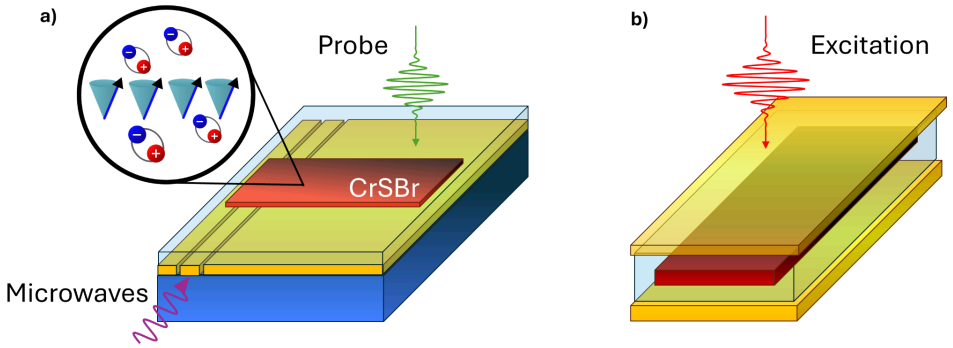

Figure 1: a) Transient reflectance measurements for magnon-exciton coupling. b) Fabry-Perot Cavity structure to realize Exciton-Polariton condensation

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Electronic proximity effects in 2D materials integrated with ultra-high-k dielectric oxide membranes

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Abstract
The sensitivity of excitons in 2D materials to their environment introduces the possibility to **modulate the excitonic bandgap** by patterning their surrounding dielectrics [1]. In environments with extreme values for the ratio of **static to dynamic dielectric constant**, this determines the direction of the shift in the optical bandgap [2].
The growth and manipulation of **freestanding membranes** of complex oxides [3] allows to integrate such materials with extreme values for dielectric constants, such as $SrTiO_3$ [4,5], into **van der Waals 2D heterostructures**, as well as to pattern them via **He-ion beam milling**, a technique that can achieve pitch and feature sizes in the nanometer scale [6].
Combining both provides a **top-down approach** to introduce excitonic confinement on transition metal dichalcogenides (TMDs) via **proximity effect**, where a patterned $SrTiO_3$ membrane is used as a neighboring layer for the excitonic-hosting TMD.

Figures

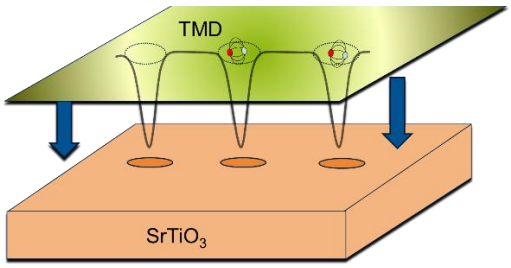

Figure 1: Proximity effect confinement scheme of excitons in a TMD.

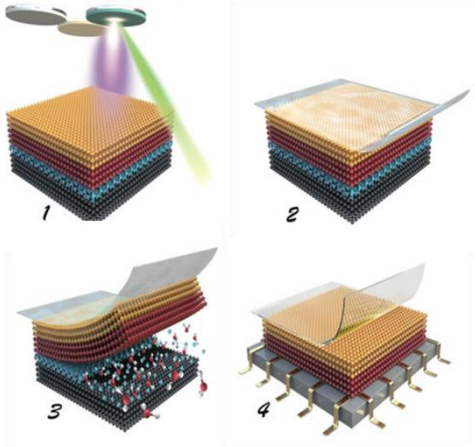

Figure 2: PLD growth of freestanding $SrTiO_3$ membranes. Image taken from [3]

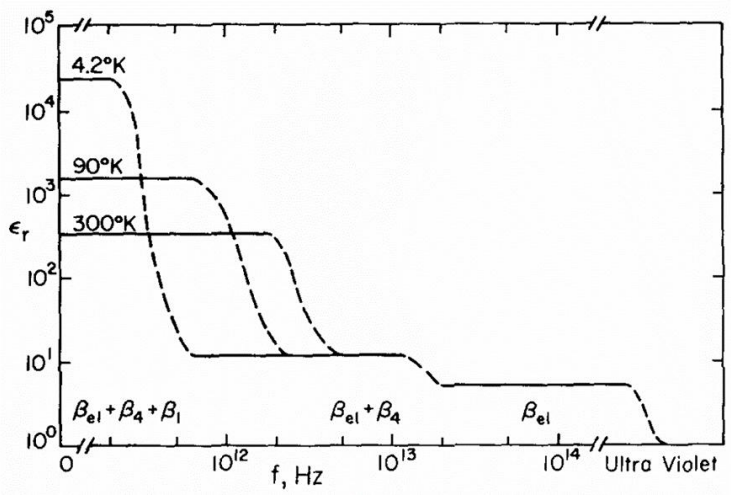

Figure 3: Temperature and frequency dependence of the dielectric constant of $SrTiO_3$. Image taken from [4].

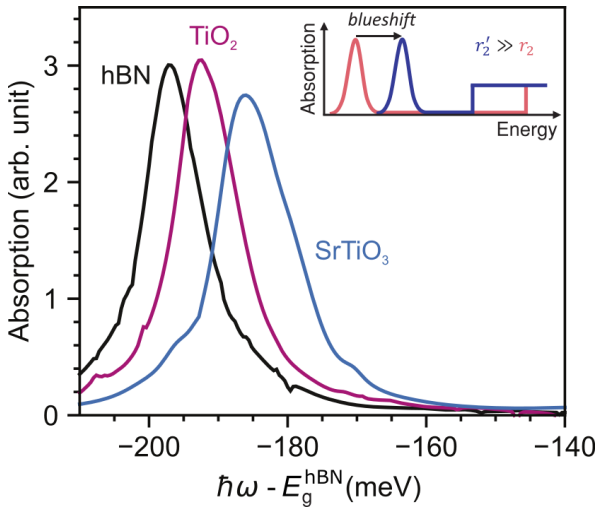

Figure 4: Blueshift in the X^0 absorption spectrum in WSe_2 due to an increased dielectric constant of the substrate. Image taken from [2].

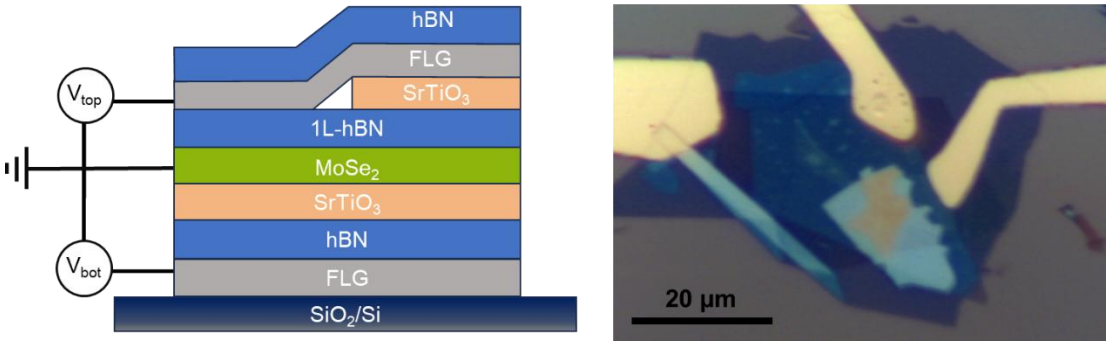

Figure 5: Double gated heterostructure with $SrTiO_3$ membranes encapsulating $MoSe_2$. Left: Schematic of the heterostructure. Right: Optical image of the transferred heterostructure with evaporated Au contacts.

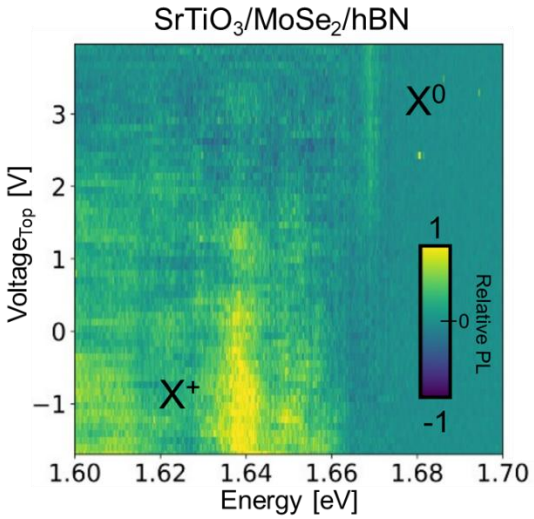

Figure 6: Photoluminescence signal of $SrTiO_3$ supported $MoSe_2$. The emission from X^0 and X^+ is blueshifted by 12 meV with respect to hBN encapsulated $MoSe_2$.

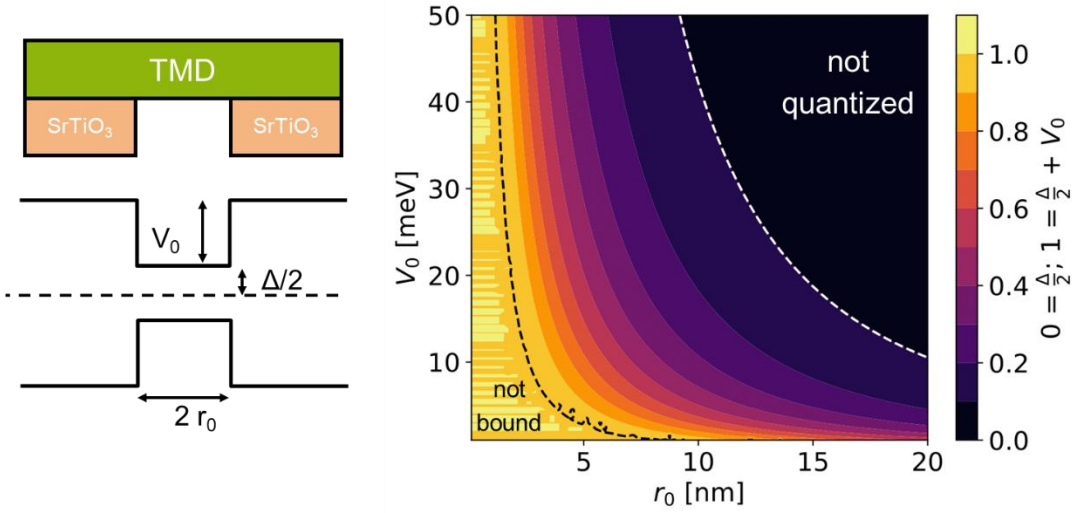

Figure 7: Quantized bound states for electrons and holes in $MoSe_2$ in a square well potential as a function of the confinement potential and the trap size.

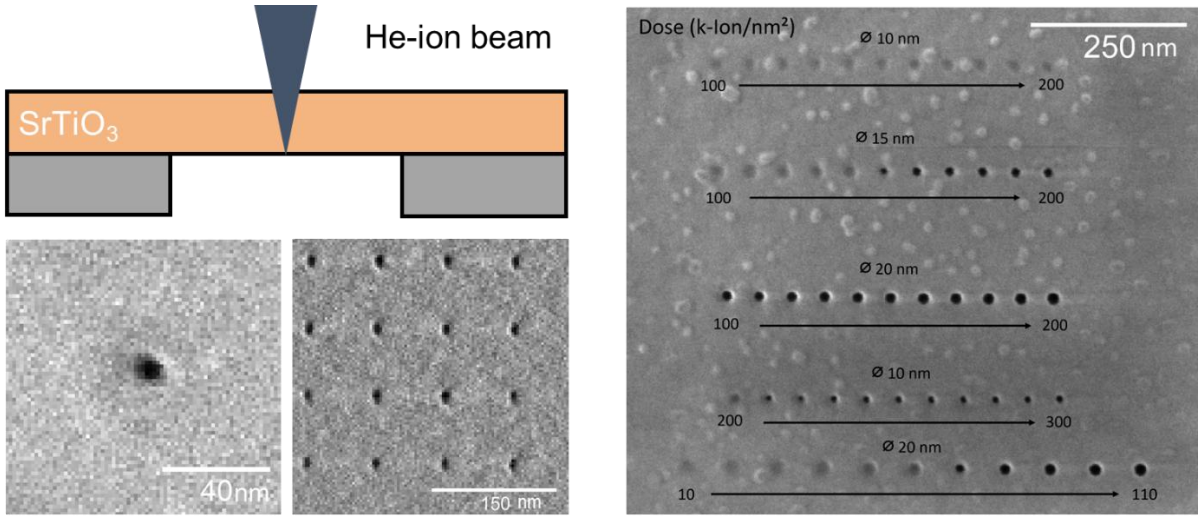

Figure 8: Nanopatterning of suspended $SrTiO_3$ membranes. Right: Etching dose test for different diameter holes. Left: Single 10 nm diameter hole and array of 15 nm diameter holes with 80 nm spacing.

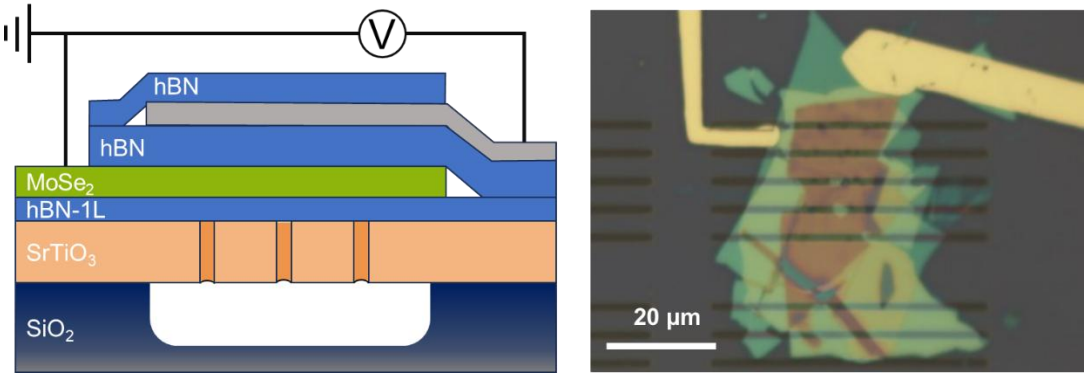

Figure 9: Gated $MoSe_2$ heterostructure on suspended nanopatterned $SrTiO_3$ membranes. Left: Schematic of the heterostructure. Right: Optical image of the heterostructure with evaporated Au contacts.

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Numerical Simulations of Electromagnetic Radiation Scattering of Free Monolayer Dielectric Microspheres

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Abstract

Light scattering from dielectric microspheres has attracted considerable attention because of their unique characteristics, attributes, and great potential [1-4]. Herein, the results of numerical simulations of the near-field electromagnetic wave (EMW) distribution arising from dielectric microspheres are presented. While previous research focused on the EMW distribution intensity [4]; here, phase and vectorial representations alongside the intensity of the electric field are reported. This investigation aims to provide a comprehensive understanding of light behavior when interacting with dielectric microspheres in order to be used effectively as probes for spectroscopic investigation of few-atoms-thick 2D films [5].

Figures

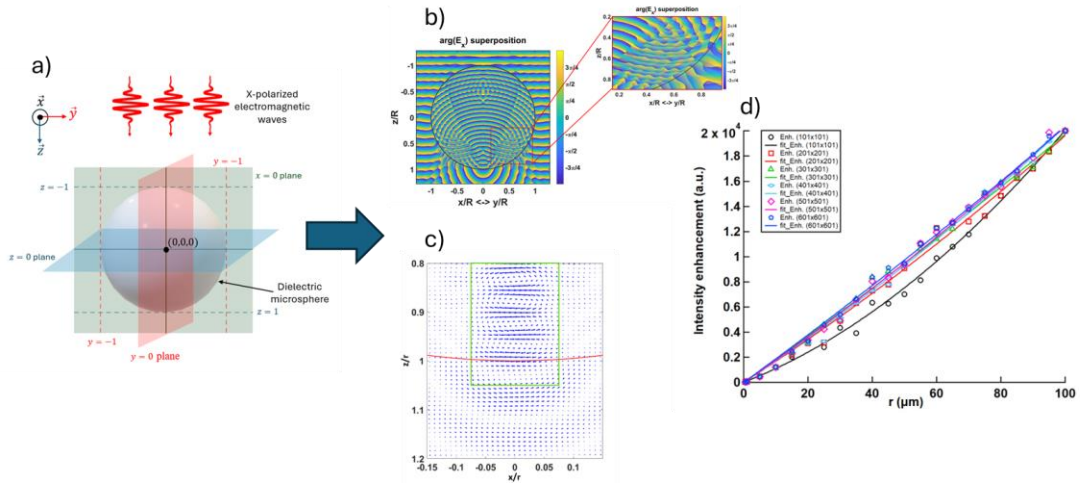

Figure 1: a) Schematic illustration of incident light on a free microsphere, b) phase plots of the electric field x, y components and their superposition, c) vectorial representation of photonic nanojet, d) photonic nanojet maximum enhancement versus microsphere radius.

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"Polaritons and spectroscopic methods"
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Global mapping of heterogeneities in two-dimensional materials

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Abstract

Structural heterogeneities in 2D materials and interfaces are strongly correlated to material properties (e.g. electrical and optical) and as a detriment to future technological development for the lack of sophisticated characterization at large scale [1]. Addressing this crucial challenge, we present a multi-modal approach combining imaging surface plasmon resonance (iSPR), Raman spectroscopy, and AFM for 'global mapping' of heterogeneities in substrate-transferred MoS_2 stacks. The iSPR provides high-resolution mapping of local dielectric variations with sensitivity to layer thickness, interlayer coupling, and defects. Raman mapping reveals vibrational signatures correlating with electronic properties and strain [2]. AFM provides topographical context, distinguishing thickness variations from morphological features like wrinkles or artifacts due to substrate transfer.

A systematic correlation analysis identifies four heterogeneity types: (1) atomic layer dependency of distinct optical signatures, (2) stacking variations modulating interlayer coupling, (3) substrate-induced strain affecting vibrational modes and plasmonic response, and (4) localized defects showing anomalous optical behavior. SPR contrast variations strongly correlate to specific Raman peak shifts and intensity ratios, enabling rapid heterogeneity assessment. This approach provides spatial insight into MoS_2 structural and optical properties, with implications for charge transport, optical response, and device uniformity. The methodology extends to other 2D materials and offers a toolkit for TMD device quality assessment.

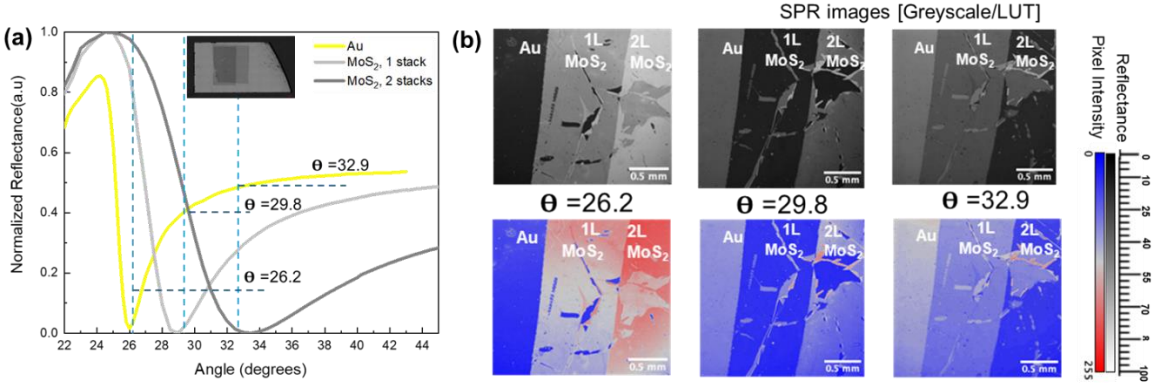

Figure SPR Point-to-Imaging measurements in MoS_2 Stacks. (a) average/standard SPR angle-scan point measurements, and (b) iSPR map revealing heterogeneities masked by averaging.

References

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Transport of exciton complexes in the presence of Fermi sea of free carriers in monolayer semiconductors

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Abstract

Exciton-carrier interactions in doped monolayer semiconductors present an interesting and technologically relevant scenario in solid-state physics. Among the consequences is the formation of trions—three-particle system formed when excitons bind with free charge carriers with distinct transport properties due to their large mass and strong coupling with phonons [1]. In this study, we aim to explore how trion-phonon and exciton-carrier interactions influence excitonic quasiparticle diffusion using transient microscopy. Theoretical results predict that trions have reduced mobility at low carrier densities due to strong phonon coupling and increased mass. Interestingly, at higher carrier densities, effective trion diffusion should increase significantly due to the Fermi pressure effect [2]. Previous experimental studies already revealed that exciton diffusion shows a non-monotonic dependence on carrier density, transitioning from elastic scattering regime to the formation of bound quasiparticle states like trions and Fermi-polarons [3]. This work aims to uncover the fundamental mechanisms governing the transport of light-emitting quasiparticles in the presence Fermi-Bose mixtures in two-dimensional semiconductors and experimentally test the prediction of the Fermi-pressure effect.

Figures

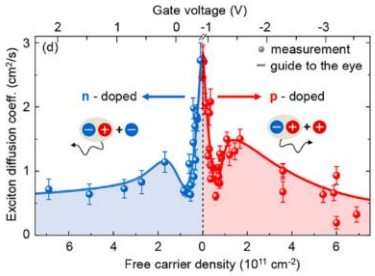

Figure 1: Exciton diffusion coefficients as a function of gate voltage and free charge carrier density.[3]

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Signatures of efficient intervalley scattering by acoustic phonons in $WSe_2/MoSe_2$ heterostructures

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Abstract

Research on interlayer excitons in TMDC bilayers demonstrates their potential for forming a degenerate electron gas due to their longer lifetime compared to intralayer excitons [1,2]. This thermalization process is influenced by exciton-phonon interactions, with ongoing interest in the dominant phonon types involved [3]. Phonons also facilitate interlayer charge transfer in heterobilayers via layer-hybridized orbitals. We employ resonant Raman scattering at cryogenic temperatures to study exciton-phonon coupling in $WSe_2/MoSe_2$ heterostructures and WSe_2 monolayers. In resonance with the WSe_2 intralayer exciton, we observe complex Raman spectra with multiple activated phonon modes. Already for the WSe_2 monolayer, the resonance profile around the exciton energy shows two asymmetric peaks, indicating a higher-order Raman process involving acoustic M or K point phonons. This suggests strong electron-phonon coupling and efficient intervalley scattering. In the $WSe_2/MoSe_2$ heterostructure, the resonance profile is significantly affected, indicating additional scattering channels and demonstrating the role of exciton-phonon interactions in these systems.

Figures

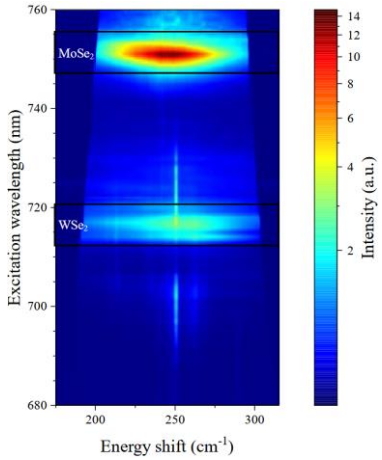

Figure 1: False color representation of resonant Raman spectra of $WSe_2/MoSe_2$ heterobilayer at <500 mK. Resonances with $MoSe_2$ and WSe_2 1s exciton energies are marked by black boxes.

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Ab initio study of anthracene-MoS_2 heterostructures: effects of interfaces on optical properties

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Transition metal dichalcogenides (TMDs) have revolutionized fundamental and applied sciences. While preserving advantages of individual building blocks, combinations of atomically thin layers yield promising properties for optoelectronic devices. In this study, we consider organic-inorganic hybrid systems of anthracene molecules adsorbed on monolayer MoS_2 through van der Waals (vdW) interactions. As oligoacene molecules are known for ordered structures when grown on substrates,[1, 2] less is known about the electronic properties at different adsorption geometry and molecular coverage. Our *ab initio* calculations demonstrate that anthracene/MoS_2 heterostructures show type-II level alignment in agreement with previous studies on oligoacene-TMDs systems.[3, 4] Specifically, anthracene molecules in horizontal and vertical orientations (Figure 1) give rise to band dispersions, consequently shifting the frontier energy levels and causing charge transfer to different extents. The absorption spectra further illustrate the small transition dipole moment across the anthracene/MoS_2 interface for both orientations, which is primarily due to the vdW gap between anthracene and MoS_2. This study provides detailed insights regarding the fundamental understanding of organic-inorganic layers for both theoretical and experimental perspectives.

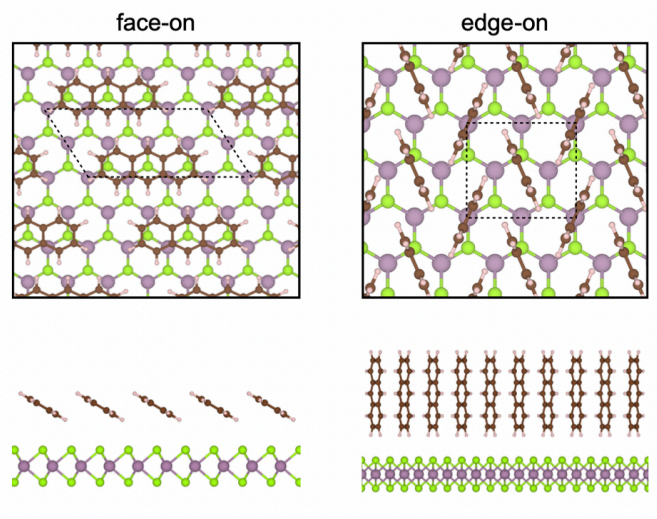

Figure 1: Top views and side views of anthracene-MoS_2 heterostructures in the face-on and edge-on configurations

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Gate-tunable Bose-Fermi mixture in a strongly correlated moiré bilayer electron system

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Abstract

Quantum gases with mixes quantum statistics, such as Bose-Fermi mixtures, may behave vastly different from their unmixed constituents. The experimental investigation of such systems can help answer questions about quantum many-body phenomena such as mediated interactions and unconventional pairing. Here [1], we realize an equilibrium Bose-Fermi mixture in a bilayer electron system implemented in a WS_2/WSe_2 moiré heterobilayer with strong Coulomb coupling to a nearby moiré-free WSe_2 monolayer. Without the fermionic component, the underlying bosonic phase is a dipolar excitonic insulator. We show that the bosonic phase forms a stable mixture with added excess electrons but abruptly collapses upon hole doping. We develop a microscopic model to explain this asymmetry. We demonstrate gate tunability over a wide volume in the boson/fermion density phase space, in agreement with theoretical calculations. Our results demonstrate potential of phases stabilized in moiré bilayer electron systems for exploring the exotic properties of equilibrium Bose-Fermi mixtures.

Figures

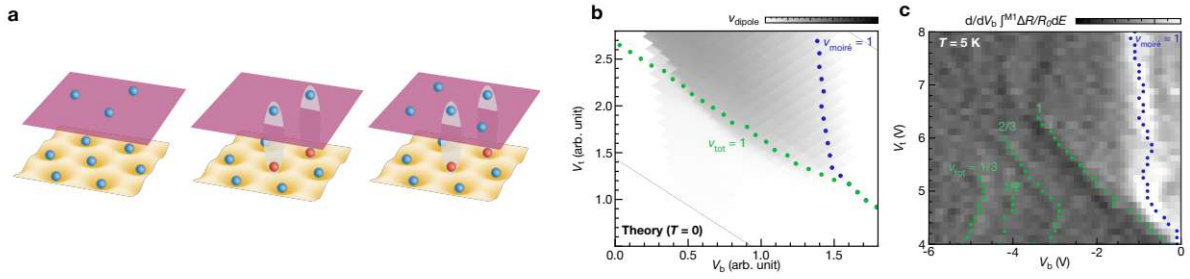

Figure 1: a) The schematic of the structure: WSe_2 monolayer (pink) coupled a WS_2/WSe_2 bilayer close to unit filling. b) Theoretical calculation of dipolar exciton density as a function of applied gate voltages. c) Experimental moiré exciton intensity versus gate voltages, overlaid with identified integer and fractional fillings of the composite bilayer system and moiré unit filling.

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Time-resolved Momentum Microscopy: A Methodological Overview

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Abstract
Time-resolved photoemission spectroscopy is well established as an excellent tool for the investigation of the electronic structure in condensed matter systems [1]. Recently, we and others [2, 3, 4] have achieved unprecedented access to the ultrafast dynamics in the energy- and 2D momentum-resolved photoemission spectrum by integration of momentum microscopy (MM) and pump-probe-schemes, made feasible by advances in tabletop high-repetition-rate high harmonic generation [5]. Here, we present a selection of contributions to this field from the time-resolved MM setup in Göttingen, including dark-field microscopy, electrostatic gating and orbital tomography.
Dark-field momentum microscopy combines the real- and momentum-space imaging capabilities of the MM, where contrast and field apertures enable precise selection of regions of interest. Successively selecting a specific momentum signature and imaging real space, allows to examine inhomogeneities in physical properties, such as quasiparticle lifetime, which can further be correlated with other physical quantities [6].

To investigate the non-equilibrium quasiparticle dynamics of in-operando devices, we implemented an electrically contacted sample holder, where the charge carrier density in 2D materials can be tuned via the electric field effect. We will show our first time-resolved photoemission data of a WSe_2 bilayer with simultaneous gating induced charge carrier doping.

Finally, the capability of the MM to measure 2D momentum distributions, covering the full Brillouin zone or more, facilitates the method of orbital tomography to reconstruct the orbitals of adsorbed molecules and the electronic components of excitonic wave functions [7, 8]. By varying the incident probe photon energy, we extend this method to achieve a full three-dimensional reconstruction of molecular orbitals with sub-angstrom resolution, opening new avenues for the study of quantum materials and nanostructures under non-equilibrium conditions [9].

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"Polaritons and spectroscopic methods"
Berlin, June 30 to July 02, 2025

Excitonic Properties of Tailored CVD-Grown TMDs

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Abstract

Transition metal dichalcogenides (TMDs) such as $MoSe_2$ and WSe_2, exhibit properties such as strong light matter interactions and host excitons that can be tuned in various ways including optically and via electric fields. Bottom-up fabrication techniques, such as chemical vapor deposition (CVD), facilitate the tailoring of standard TMD to create lateral heterostructures [1] and Janus-TMDs [2]. These materials display noteworthy properties such as the presence of charge transfer [3] and dipolar excitons, anisotropic Rashba-spin splitting [4] and exciton collimation [5]. This work explores the excitonic properties via optical and magneto-optic studies of such materials.

Figures

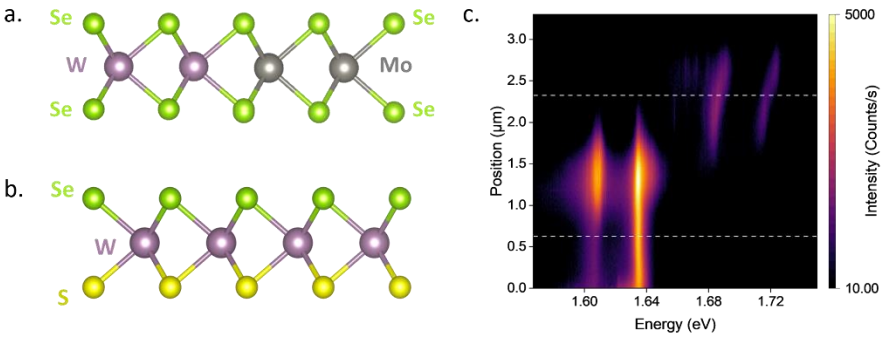

Figure 1: Side-view of a. a single layer of $MoSe_2$-WSe_2 LH, and b. Janus SeWS. c. Line scan of the photoluminescence emission across the interface of a $MoSe_2$-WSe_2 LH.

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Towards proximity-control in Graphene/MOF-Heterostructures

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The material class of Metal-organic Frameworks (MOFs) offers a wide-variety of properties, such as intrinsic porosity, electrical conductivity as well as tailorable band gaps, stemming from the interchangeability of the used linkers and metal-nodes in the synthesis. [1]
Especially the two-dimensional (2D) variants of MOFs are of great interest, as they offer the possibility of incorporation in the well-established work frame of Van-der-Waals materials.
While certain MOFs are predicted to have a high conductivity [1], in electrical transport measurements this can often not be reproduced, due to the polycrystalline nature of MOFs. [2][3]
The polycrystallinity is accompanied by domain walls, which dominate the charge transport across the MOF. [4]
Therefore, rather than focusing on the properties of MOFs on their own, in this work the influence of monolayer MOFs on the properties of graphene in a MOF/graphene-heterostructure (HS) are investigated. By exchanging the metal-nodes and the linkers the magnetic coupling, magnetic ordering and spin-orbit coupling are suspected to be tunable.
To study this, magneto-transport measurements in dual-gated hexagonal boron nitride encapsulated MOF/graphene devices are conducted down to sub-Kelvin temperatures using different MOFs.
The used devices are fabricated utilizing the established methods for Van-der-Waals devices, e.g. exfoliation, a dry-transfer method, reactive ion etching and electron-beam lithography.

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Directed light emission in molecular monolayers on 2D materials via optical interferences

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Abstract
Two-dimensional materials provide a rich platform to explore phenomena such as emerging electronic and excitonic states, strong light-matter coupling and new optoelectronic device concepts. The optical response of monolayers is entangled with the substrate on which they are grown or deposited on, often a two-dimensional material itself. Here we employ angle-resolved reflectivity and photoluminescence spectroscopy on highly ordered molecular monolayers on hexagonal boron nitride (hBN) to systematically investigate the angle-dependent optical response as a function of the thickness of the hBN flake. We observe that light reflection and emission occur in a strongly directed fashion and that the direction of light reflection and emission is dictated by the hBN flake thickness. Transfer matrix simulations reproduce the experimental data and show that optical interference effects in hBN are at the origin of the angle-dependent optical properties. Our findings demonstrate the importance of careful substrate parameters choice for a given experimental geometry but also highlight opportunities in applications such as lighting technology where the direction of light emission can be controlled via substrate thickness.

Figures

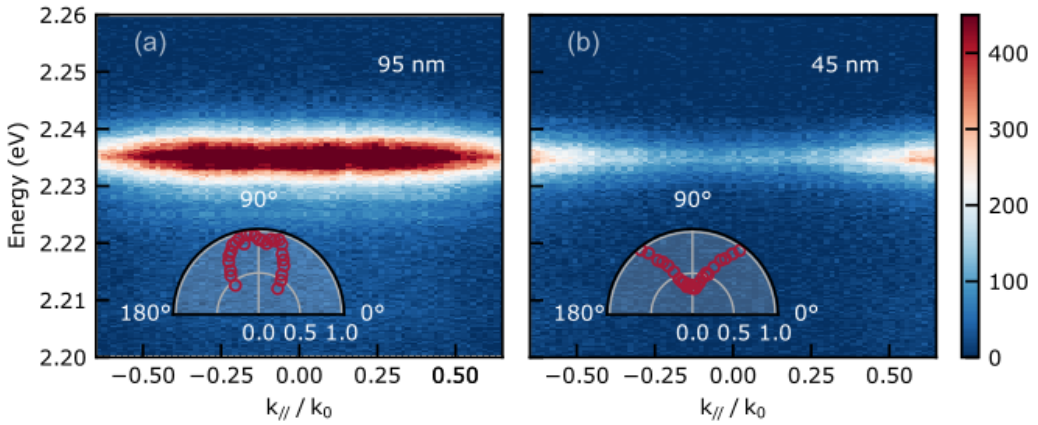

Figure 1: (a) Angle-resolved photoluminescence spectra from the MePTCDI structure with (a) 95 nm and (b) 45 nm thick hBN. The insets show a polar plot of the energy cross-section of the angle-resolved spectra taken at the exciton peak position.

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Defect-Driven Magnetism and Emergent Phenomena in $PtSe_2$/graphene Heterostructures

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Abstract
Two-dimensional (2D) materials and their heterostructures (HS) offer a fertile platform for exploring emergent quantum phenomena and engineering next-generation nanoelectronics and spintronic devices [1]. Monolayer $PtSe_2$ is a characteristic example of a defect-engineered system, where Pt vacancy induces localized magnetic moments in the neighboring Se atoms [2,3]. In this work, we investigate the role of atomic-scale defects in shaping the electronic and magnetic behavior of $PtSe_2$/graphene HS using density functional theory (DFT) calculations. Low-voltage aberration-corrected STEM was first utilized to precisely resolve and characterize realistic defect structures in layered $PtSe_2$. Incorporating these defect motifs into DFT simulations of $PtSe_2$/graphene HS, we reveal the maintenance of localized magnetic moments accompanied by a band gap opening in graphene—highlighting a defect-driven route to modulate spin and charge transport at the interface. The computed binding energies also suggest thermodynamically favorable HS formation. To complement our theoretical findings, we employ an alternative fabrication protocol based on liquid-phase exfoliation to prepare $PtSe_2$/graphene hybrid nanosheets. The resulting 2D ink exhibits high electrical conductivity and long-term stability over a year. STEM-EDX elemental mapping confirms uniform nanosheet morphology, while Raman spectroscopy provides insights into vibrational modes and interlayer interactions. This integrated approach bridges first-principles modeling and scalable synthesis, offering a promising path toward defect-engineered 2D quantum materials for future device applications.

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Strain Engineering Moiré Excitons in 2D Heterostructures

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Abstract
Tunable-moiré superlattices hold potential for programmable quantum emitters, exotic quantum phases and resonant-hybridization of excitonic states. In this poster, I will discuss our results on strain-tuning interlayer and intralayer moiré excitons in 2D Transition Metal Dichalcogenides (TMDCs). Employing electrostatic actuation [1], we apply upto 1% controllable, tensile strain to suspended heterobilayers at 5K. Photoluminescence and reflectivity measurements reveal the excitonic energies to be red-shifting with different strain gauges on the order of tens of meV/%, thus enabling fingerprinting of valley-character for moiré excitons [2]. We also exhibit control over many-body interactions showing i) energetic resonance between inter- and intralayer moire species, and ii) strain-tunable dipolar interactions between interlayer excitons.

Figures

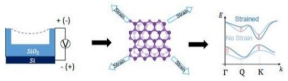

Figure 1: Platform for applying tunable strain at cryogenic temperatures. Suspended heterostructure is strained biaxially by electrostatic actuation. Different valleys in the momentum-space shift according to their orbital character enabling fingerprinting and tuning.

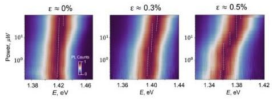

Figure 2: Strain-tunable interlayer exciton (IX) states. Changing moiré period with strain (ε) leads to higher quasi-equilibrium population for all localized-IX stated

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Inelastic tunneling into multipolaronic bound states in single-layer molybdenum disulfide

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Abstract

A polaron is a quasiparticle that forms when an excess of electrons or holes interacts with the vibrations of the surrounding atomic lattice. This interaction causes the nearby ions to displace from their equilibrium positions, creating a localized trap for charges. When the Coulomb interaction is suppressed, a strong electron-phonon coupling takes place. As a result, the individual polarons couple to each other giving rise to multipolarons.

In this work, we investigate the role of electron-phonon coupling and its link to multipolarons in single layer (SL) MoS_2 on graphene (Gr) on Ir (111) substrate. We use scanning tunneling microscopy and spectroscopy to measure the inelastic excitations of polaronic bound states emerging from the coupling of non-polar zone-boundary phonons to Bloch electrons in n-doped metallic SL MoS_2. Tunneling into the vibrationally coupled polaronic states leads to a series of evenly spaced peaks in the dI/dV spectra on either side of the Fermi level as shown in figure (1.c). Combining density functional (perturbation) theory with a recently developed *ab initio* electron-lattice downfolding technique, we show that the energy spacing stems from the longitudinal-acoustic phonon mode that flattens at the Brillouin zone edge and is responsible for the formation of stable multipolarons in metallic MoS_2 [1].

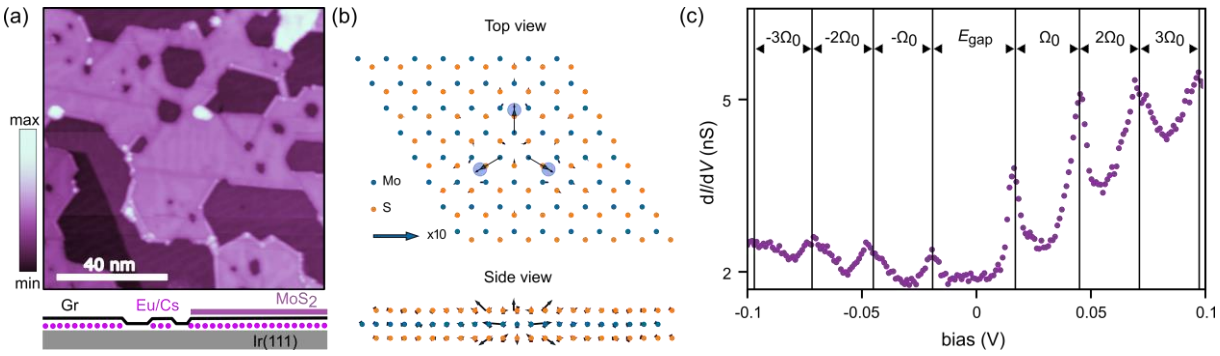

Figure 1: (a) STM image of MoS2 on Eu intercalated Gr on Ir(111). Below STM topograph is a cross-sectional schematic view of the system. (b) Relaxed crystal structure based on *ab initio* model calculations on an 18 × 18 supercell. (c) Low-bias STM dI/dV spectrum of metallic SL MoS_2, revealing peak-dip features and a gap at the Fermi level.

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