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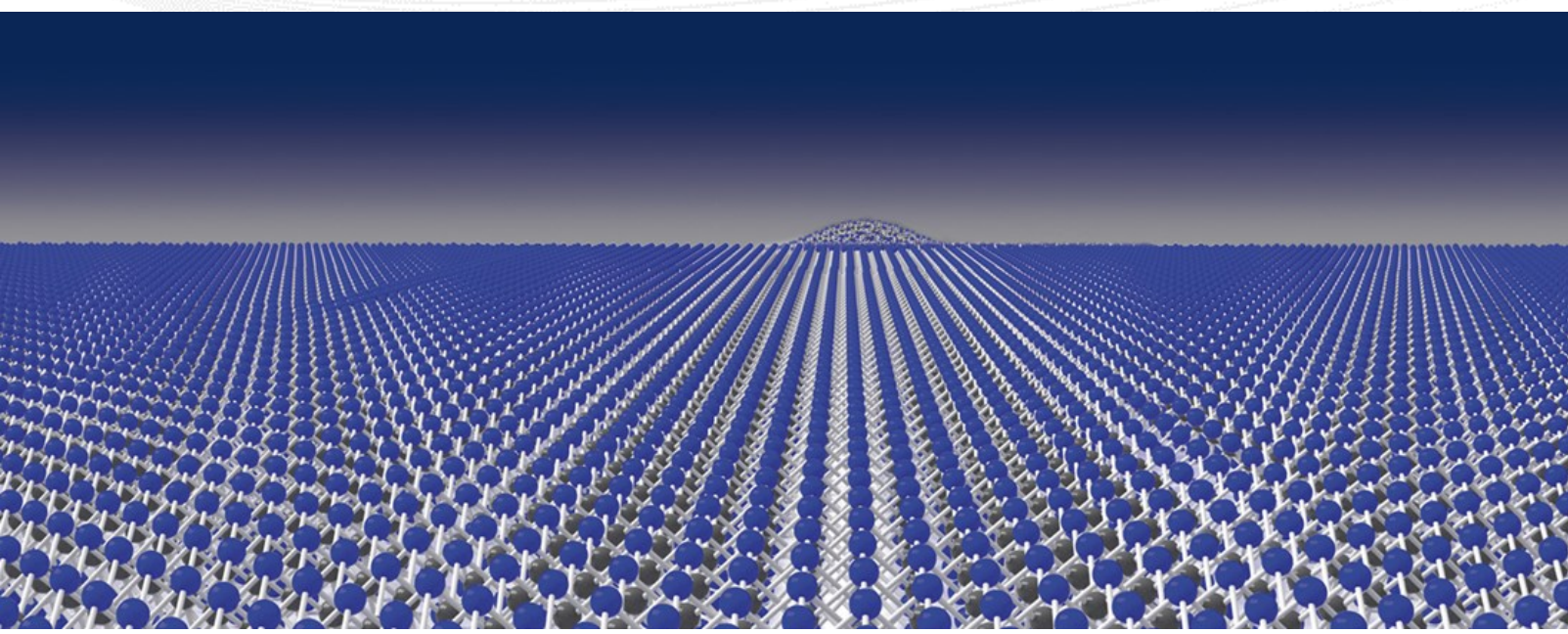
2D Materials Conference

Munich, June 3 – 8, 2024



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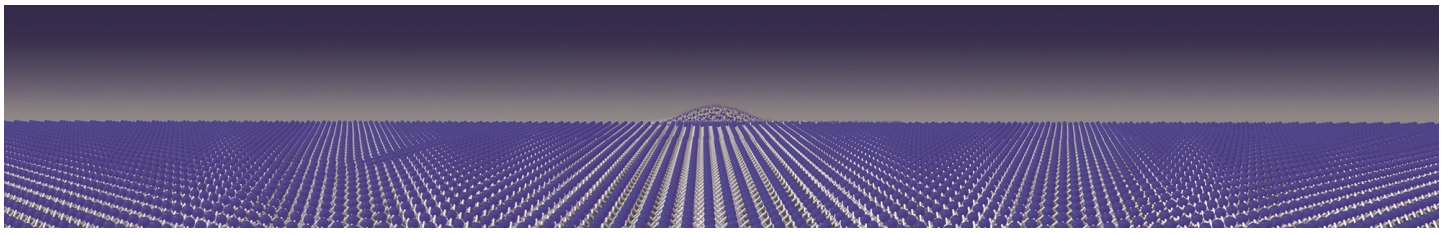

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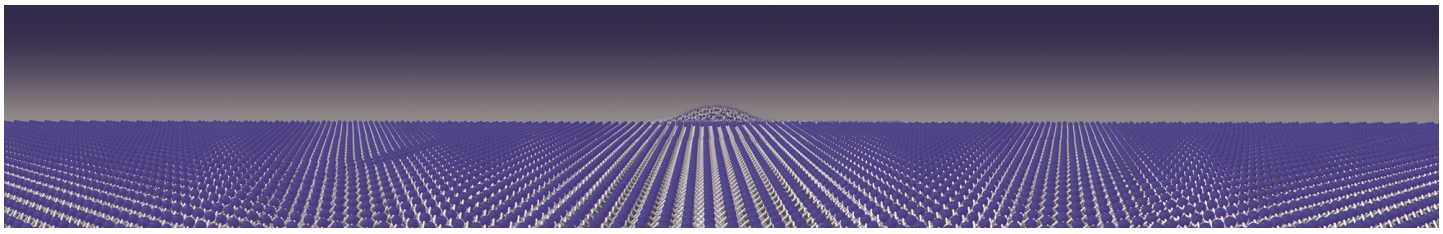

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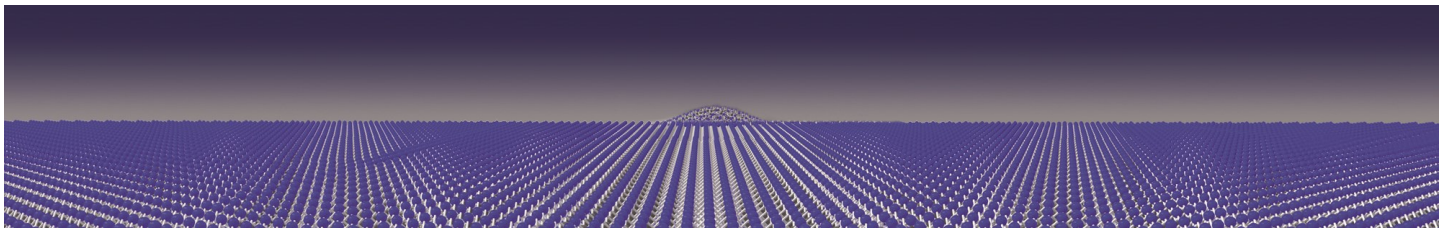

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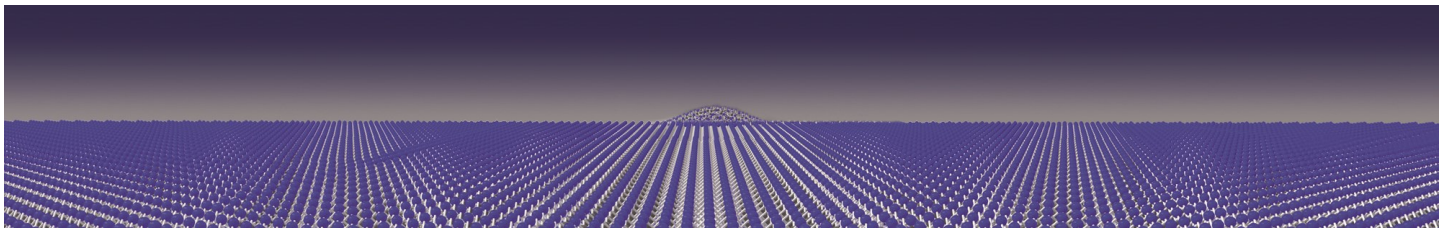

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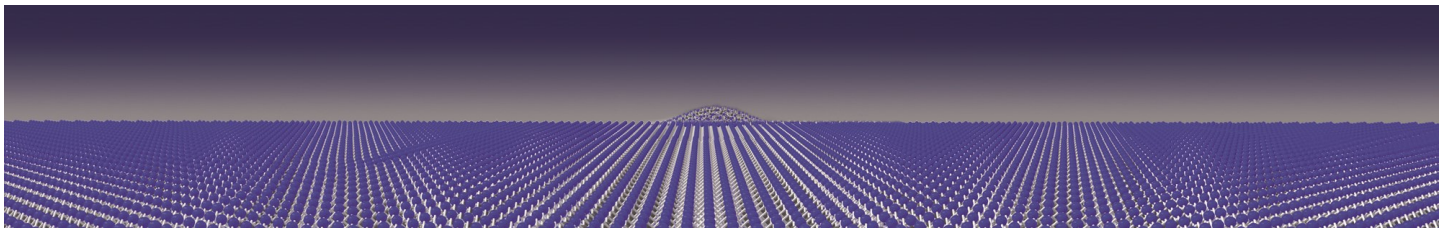

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Monday | June 3, 2024

Tutorials

Introduction to s-SNOM. Basic concept, Instrumentation, mechanisms, and applications in 2D materials research

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Optical measurements of 2D Materials

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Probing functional properties with AFM

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Plenary Talk: Electron fractionalization under zero magnetic field

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Electron fractionalization is of significant interest to both fundamental physics and topological quantum computing. The emergence of two-dimensional moiré materials provides a platform to explore the physics of electron fractionalization under zero magnetic field. In this talk, I will discuss two examples of zero-field electron fractionalization in moiré semiconductors: 1) the fractional Chern insulator that spontaneously breaks the time reversal symmetry, and 2) the time reversal symmetric fractional quantum spin Hall insulator.

News from the Quantum Twisting Microscope

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In this talk I will present the latest results from Quantum Twisting Microscope (QTM) experiments performed at cryogenic temperatures. The QTM is a novel scanning probe microscope that enables the creation of pristine two-dimensional interfaces between two van-der-Waals layers – one on its tip, and another on a flat substrate. Upon application of a voltage bias between the two layers, an electron tunnels across the interface at many locations at once, and the quantum interference between these tunneling events results in momentum-conserving tunneling. With its continuous control over the twist angle between the layers, the QTM can scan through momentum space and map the energy bands of quantum materials. I will describe recent inelastic momentum-resolved tunneling experiments, revealing an intriguingly strong electron-phason coupling in twisted bilayer graphene, as well as using the QTM as an ultra-high-resolution single electron transistor to image the electrostatic potential landscape within moiré lattices.

Plasmonic Twistronics: Discovery of Plasmonic Skyrmion Bags

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Plasmonic skyrmion lattices are created by the interference of surface plasmon polariton waves. Superimposing two plasmonic skyrmion lattices with a relative twist creates a moiré skyrmion superlattice. Their vector fields are calculated numerically and measured using time-resolved PEEM vector microscopy, demonstrating that the topology contains skyrmion bags of controllable size for certain magic angles.

Twistronics are studied intensively in 2D-materials, especially in twisted bilayer graphene, following the discovery of flat electronic bands. This has led to groundbreaking findings, such as unconventional superconductivity and correlated insulator states. In these systems, the moiré lattice is created by introducing a relative twist between the upper and lower layer of the material by a twist angle ϕ as illustrated in Figure 1 (a).

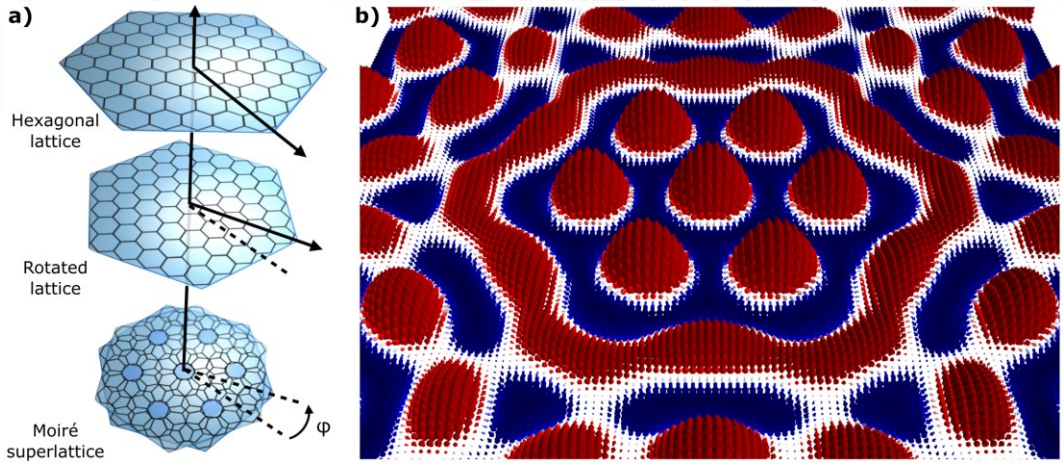

Figure 1: (a) Two superimposed hexagonal lattices with a relative twist create a moiré superlattice. (b) Vector field of a surface plasmon polariton skyrmion bag when twisting about a magic angle.

We combine the concepts of twistronics with plasmonic topological excitations and demonstrate that the topology of moiré skyrmion lattices contains skyrmion bags as complex topological quasiparticles that so far have been demonstrated only in liquid crystals, and whose formation has been predicted in chiral

ferromagnets [3]. The size of plasmonic skyrmion bags can be controlled by the twist angle and its center of rotation. The resulting electric field distribution of a skyrmion bag can be derived numerically (see Figure 1 (b)) and verified experimentally using time-resolved two-photon photoemission electron microscopy (PEEM) vector microscopy [2].

The ability to control topological properties of light has great potential for applications such as spin-optics, imaging, structured illumination microscopy, non-dipolar light-matter-interaction, as well as topological and quantum technologies.

References

[1] S. Tsesses, E. Ostrovsky, K. Cohen, B. Gjonaj, N. H. Lindner, G. Bartal, Optical skyrmion lattice in evanescent electromagnetic fields. *Science,* **361**, 993–996 (2018).
[2] T. J. Davis, D. Janoschka, P. Dreher, B. Frank, F. J. Meyer zu Heringdorf, H. Giessen, Ultrafast vector imaging of plasmonic skyrmion dynamics with deep subwavelength resolution. *Science*, **368**, eaba6415 (2020).
[3] D. Foster, C. Kind, P. J. Ackerman, J. S. B. Tai, M. R. Dennis, I. I. Smalyukh, Two-dimensional skyrmion bags in liquid crystals and ferromagnets. *Nat Phys.* **15**, 655–659 (2019).

Thermodynamic measurements of correlated states in MATBG

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Beyond Moiré in twisted 2D magnets: tailoring the magnetization switching in 2D CrSBr by an orthogonal-twist

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The advent of twist engineering in two-dimensional (2D) crystals enables the design of van der Waals heterostructures with emergent properties.[1] In the case of magnets, this approach can afford artificial antiferromagnets with tailored spin arrangements.[2] Here,[3] we fabricate an orthogonally-twisted bilayer by twisting two CrSBr ferromagnetic monolayers with an easy-axis in-plane spin anisotropy by 90 degrees. CrSBr is a metamagnetic layered semiconductor formed by antiferromagnetically-coupled ferromagnetic layers (Tc∼150 K) that can be exfoliated down to the single-layer limit. The ferromagnetic monolayer exhibits a marked low-dimensional character, with short-range correlations above Tc and an Ising-type in-plane anisotropy, being the spins spontaneously aligned along the easy axis (b) below Tc. By applying moderate magnetic fields along the b axis, a spin-flip of the layers take place whereas, for the intermediate and hard magnetic axis (a and c axes, respectively), a spin-reorientation occurs. In

multilayers, a spin-valve behaviour is observed, characterized by negative magnetoresistance.[4] Thus, taking advantage of the in-plane Ising magnetic anisotropy of this 2D magnet, twisting by 90 degrees two monolayers yields to an intriguing spin scenario where several terms compete with an applied magnetic field such as the Zeeman split energy, the interlayer magnetic interactions (which favours an antiparallel orientation between the layers) and the local spin anisotropy in each CrSBr layer (which are perpendicular in the twisted configuration). This case is different from the common Moiré patterns in twisted bilayers, where a modification of the band structure is reached by twisting by small angles.[1] In particular, the magneto-transport properties of the orthogonally-twisted bilayer reveal a multistep magnetization switching with a magnetic hysteresis opening, which is absent in the pristine case.[4] By tuning the magnetic field, we modulate the remanent state and coercivity and select between hysteretic and non-hysteretic magnetoresistance scenarios. This complexity pinpoints spin anisotropy as a key aspect in twisted magnetic superlattices. Our results highlight control over the magnetic properties in van der Waals heterostructures, leading to a variety of field-induced phenomena and opening a fruitful playground for creating desired magnetic symmetries and manipulating non-collinear magnetic configurations.

References

[1]: Cao et al., Nature, 556 (2018) 80
[2]: Wang, Nature Materials, (2023) DOI: 10.1038/s41563-023-01762-3
[3]: Boix-Constant et al., Nature Materials, (2024) DOI: 10.1038/s41563-023-01735-6

Imaging quantum oscillations in strongly correlated moiré systems

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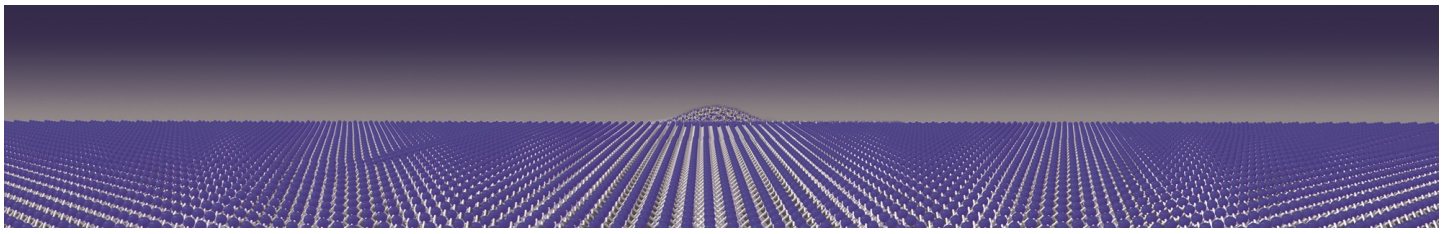
De Haas-van Alphen quantum oscillations in magnetization have traditionally served as the prime tool for determining the band structure of metals and semiconductors. Utilizing a scanning SQUID-on-tip, we image thermodynamic quantum oscillations with nanoscale spatial resolution and at very low magnetic fields, which allows reconstruction of the local band structure with high energy resolution. In Bernal-stacked trilayer graphene with dual gates, we reconstruct the band structure and its controllable evolution with the displacement field with unprecedented precision, and map the naturally occurring strain-induced pseudomagnetic fields as low as 1 mT, corresponding to graphene twisting by 1 millidegree over 1 µm distance [1]. In Bernal bilayer graphene aligned to hBN, we reveal complex band structure with narrow moiré bands and multiple overlapping Fermi surfaces separated by very small momentum gaps. In addition to conventional oscillations obeying Onsager quantization, pronounced quantum oscillations are found to arise from particle-hole superposition states induced by coherent magnetic breakdown [2]. In twisted trilayer graphene, we observe renormalization of the single-particle band structure by Coulomb interactions, greatly increasing the bandwidth of the flat bands and leading to symmetry breaking at half filling. On approaching charge neutrality, we find the ground state to be a

nematic semimetal in which the flat-band Dirac cones migrate towards the mini-Brillouin zone center, spontaneously breaking the C_3 rotational symmetry.

References

[1] H. Zhou, N. Auerbach, M. Uzan, Y. Zhou, N. Banu, W. Zhi, M. E. Huber, K. Watanabe, T. Taniguchi, Y. Myasoedov, B. Yan, and E. Zeldov, "Imaging quantum oscillations and millitesla pseudomagnetic fields in graphene", Nature 624, 275 (2023).

[2] M. Bocarsly, M. Uzan, I. Roy, S. Grover, J. Xiao, Z. Dong, M. Labendik, A. Uri, M. E. Huber, Y. Myasoedov, K. Watanabe, T. Taniguchi, B. Yan, L. S. Levitov, and E. Zeldov, "De Haas–van Alphen spectroscopy and magnetic breakdown in moiré graphene", Science 383, 42 (2024).



Tuesday | June 4, 2024

Session 2: Topological 2D Materials

Interaction, magnetism, and topology in a fractional Chern insulator

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Twisted $MoTe_2$ bilayer is an emergent fractional Chern insulator with spontaneous time reversal breaking. As semiconducting transition metal dichalcogenides famously exhibit spin-valley locking and circularly polarized valley-optical selection rules, a natural question arises as to how the interaction induced ferromagnetism couples to the optical response. Here, we demonstrate that the degree of circular polarization (DOCP) in the trion photoluminescence at zero magnetic field reaches near unity in the anomalous Hall metal phase, with the helicity controlled by the magnetization direction. Spin-valley Hall response is shown to tune the emission helicity, establishing the electric current as an additional control of the PL helicity. We further show that the PL DOCP is a sensitive probe of the integer and fractional quantum anomalous Hall effects, the putative zero-field composite fermi liquid state, as well as their electric field-driven topological phase transitions. The unprecedented optical properties of this system promise to have profound implications for spintronics, valleytronics, and topological-optoelectronic devices.

2D Quantum Material Josephson Junctions

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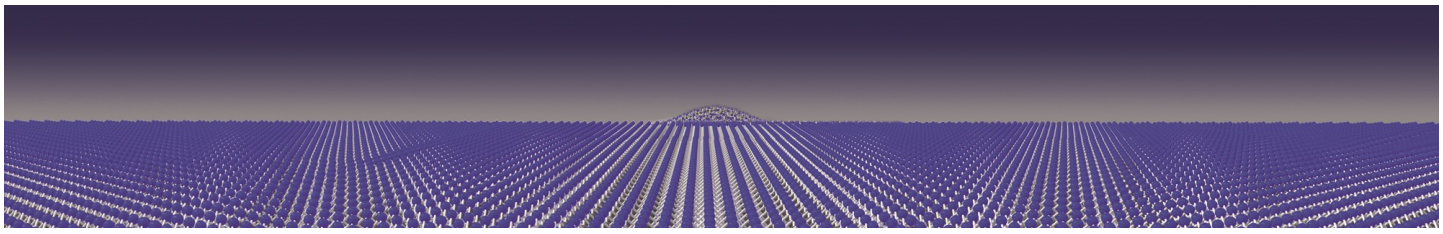
Josephson junctions are an important scientific and technological devices where two superconductors are coupled together by a non-superconducting barrier, resulting in a sandwich-like heterostructure with superconducting properties which can modulated by the barrier or magnetic field through the barrier. Recently, great progress has been made in incorporating 2D quantum materials into these structures where their inherent properties can affect the tunneling superconductivity in novel ways. In this presentation we will discuss some of these results with particular focus on the creation of non-reciprocal superconductivity (i.e. one directional), how it is realized, and the route to its technological use.



Half-integer quantized Hall conductivity in magnetic topological insulator heterostructure

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A three-dimensional topological insulator hosts a two-dimensional surface state with a single linear-dispersive Dirac cone. Breaking of time-reversal symmetry opens an energy gap at the charge neutrality point of the Dirac cone, and the Hall conductivity of the surface state is predicted to be quantized to half of the quantum conductance e^2/h. This can be regarded as a manifestation of parity anomaly in quantum field theory. However, the half-integer quantization of the surface Hall conductivity has been elusive because the Dirac cones always appear in pairs, and the contributions from the even number of Dirac cones are measured simultaneously. In this presentation, we report the direct observation of the half-integer quantized surface Hall conductivity in a synthetic heterostructure of magnetic topological insulators, where only one surface is gapped by magnetic doping and the opposite one remains non-magnetic and gapless. We observed half of the quantized Faraday and Kerr rotations with terahertz magneto-optical spectroscopy and half-integer quantized Hall conductivity in charge transport measurement [1].

References

[1] M. Mogi, MK *et al*., "Experimental signature of parity anomaly in a semi-magnetic topological insulator", Nature Phys. **18**, 390 (2022).

Strong interactions and isospin symmetry breaking in a supermoiré lattice

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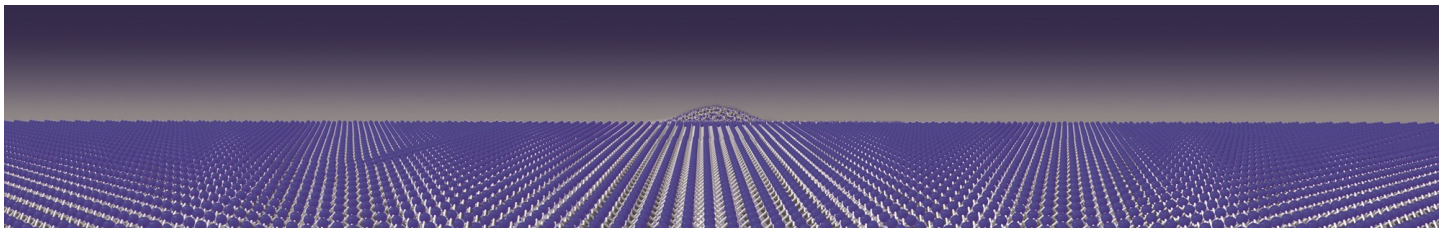
In multilayer moiré heterostructures, the interference of multiple twist angles ubiquitously leads to tunable ultra-long-wavelength patterns known as supermoiré lattices. However, their impact on the system's many-body electronic phase diagram remains largely unexplored. We present local compressibility measurements revealing numerous incompressible states resulting from supermoiré-lattice-scale isospin symmetry breaking driven by strong interactions. By using the supermoiré lattice occupancy as a probe of isospin symmetry, we observe an unexpected doubling of the miniband filling near $\nu=-2$, possibly indicating a hidden phase transition or normal-state pairing proximal to the superconducting phase. Our work establishes supermoiré lattices as a tunable parameter for designing novel quantum phases and an effective tool for unraveling correlated phenomena in moiré materials.



Tuesday | June 4, 2024

Session 3: 2D Magnets – Part I

Plenary Talk: Chiral spin textures on the racetrack

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The simplest chiral spin texture is a one-dimensional Néel magnetic domain wall that separates two magnetic regions that are magnetized in opposite directions. Under the influence of spin orbit torques, that are derived from spin currents that carry angular momentum, these walls can be driven at high speeds exceeding 1 km/sec along magnetic nano-wires that, thereby, form “magnetic racetracks”. This is the basic principle of the magnetic racetrack memory that stores digital data in the form of the presence or absence of such chiral domain walls.

We discuss recent developments including the scaling of racetrack to sub-100 nm widths and the first 3D racetrack memory devices. Chiral domain walls are, however, just one member of an ever-expanding family of chiral spin textures that are of great interest from both a fundamental as well as a technological perspective. Recently a zoology of complex 2D and 3D spin textures stabilized by volume or interface Dzyaloshinskii-Moriya vector exchange interactions have been discovered including, in our work, anti-skyrmions, elliptical Bloch skyrmion, two-dimensional Néel skyrmions and fractional antiskyrmions. Such nano-objects are potential candidates as magnetic storage bits on the racetrack.

Incommensurate spin crystal phases in ultra-thin ferromagnetic and ferroelectric oxide layers

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Ferroics can form complex topological spin structures such as vortices and skyrmions, when subjected to particular boundary conditions. Especially in ferromagnets these whirling magnetic structures are chiral, generating abnormal behaviour such as topological Hall effect (THE) in ferromagnets. They are caused by local symmetry breaking induced for example by interface Dzyaloshinskii–Moriya interaction (DMi). We reveal that a PbTiO3 ferroelectric layer can break the surface inversion symmetry in a contiguous SrRuO3 layer generating a periodic chiral domain. Instead of skyrmions, the domains that emerge are an incommensurate (I-C) spin crystal which is seen to coincide with a significant topological-like Hall effect. [1]

One the other we observe in single PbTiO3 epitaxial layer sandwiched between SrRuO3 electrodes a domain structure analogue of the double-$\vec{Q}$ magnetic spin crystal phase. The periodic clockwise and anti-clockwise ferroelectric vortices are modulated by a second cycloidal ordering along their toroidal core. [2]

The presence of such a double-$\vec{Q}$ structure, mediated by incommensurate interactions, is a direct hint of the electric Dzyaloshinskii–Moriya interaction as the counterpart of the magnetic DMi.

References

[1] S. D. Seddon, et al., Nature Communications 12:2007 (2021).
[2] D. Rusu, et al., Nature 602, 240 (2022).

Magnetic-electronic coupling in the van der Waals metal-phosphor tri-chalcogenides

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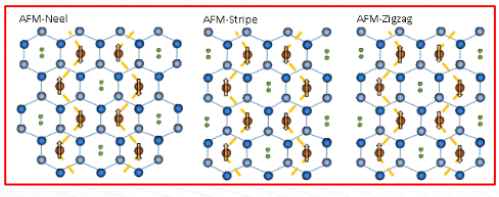
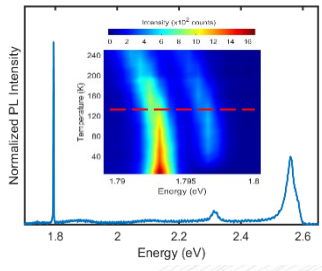
Magnetism is a topic of wide interest since the discoveries of motors/generators, through magneto-resistance and up to modern times, where low dimensional materials offer support for new magnetic phenomena. The talk will focus on the influence of magnetic moments and magnetism on the magneto-optical properties of semiconductors in an ultimate two-dimensional limit found in van der Waals transition metal phosphor tri-chalcogenides. A few types of magnetic effects will be discussed: The long-range magnetic order (e.g., ferromagnetism, anti-ferromagnetism [AFM]); A Rashba spin-orbit effect; Hyperfine interaction, and cyclotron resonance; all gaining special stabilization by the size confinement and shape anisotropy, being of special interest in emerging technologies of spin-electronics and quantum computation.

The Metal phosphor tri-chalcogenides with the general chemical formula MPX_3 (M=metal, X=chalcogenide) closely resemble the metal di-chalcogenides, but the metals are paramagnetic elements, while one-third of them are replaced by phosphor pairs. The metal ions within a single layer have a honeycomb arrangement (Neel, stripe, or zigzag [see the attached scheme]) mainly producing an anti-ferromagnetic structure, endowing those materials with unique magnetic and magneto-optical properties. Most recent magneto-optical measurements will be reported, exposing the dual relation between magnetism and electronic properties. The study tackled a few scientific questions: (1) What mechanism sustains the long-range AFM, and whether the type of magnetic arrangement can be manipulated? Previous work proposed a dominancy of spin-exchange coupling among next metal neighbors. To validate this assumption, we examined the magnetic and magneto-optical properties of a benchmark compound, $MnPS_3$, embedded with different diamagnetic cations (e.g., Zn^{2+}). The results designated a sustain of AFM, however, with a reduction of the Neel temperature with the increase of the dopant concentration, followed by a switch of a

magnetic arrangement from Neel to Zigzag in layers at Mn: Zn ratio of 1:1, and a complete loss of AFM arrangement with the dominancy of Zn ions. The gradual transitions with the increase of Zn content were reflected in shifts and polarization of the magneto-PL spectrum, exposing a solid magnetic-optical correlation. (2) Do other moments (e.g., spin-orbit) dictate spin arrangement? To address this question comparison of magneto-optical properties among a few different compounds ($MnPS_3$, $FePS_3$) has been explored. The study designated a unique behavior in $FePS_3$ compared to the two others, exposing new magnetic phenomena that have not been demonstrated before, supposedly related to a strong spin-orbit effect and to an inversion of symmetry breaking. A full description of observations and their analysis will be given at the meeting (a representative emission spectrum of $FePS_3$ is attached here). The experimental observations were corroboration by considering the electronic properties in the framework of DFT+U studies.





Quantum sensing of 2D magnets using single-spin microscopy

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Quantum two-level systems can be harnessed as highly sensitive, quantitative magnetometers for magnetic imaging at the nanoscale. Over the past two decades, this concept [1] has evolved from the proof of concept [2] to a mature quantum technology [3], with a broad field of demonstrated applications in physics, materials engineering, life sciences, and beyond.

This talk will cover the foundational principles and key applications of nanoscale quantum sensing, specifically focusing on the emerging class of magnetically ordered, two-dimensional van der Waals (vdW) materials [4]. Specifically, I will outline our experimental strategy using all-diamond scanning probes and highlight our recent advancements in their performance and functionality [3]. After revisiting our earlier investigations of the ferromagnet CrI_3, where we quantitatively imaged nanoscale magnetization distributions and spin textures [5], I will focus on our recent findings on the novel vdW magnet CrSBr. This material stands out with its remarkable structural stability, exceptionally high ordering temperature ~140 K [6], a fascinating interplay between its magnetic and optical properties [4], and a rich magnetic phase diagram [7]. Using direct imaging by single-spin magnetometry, we unveiled an intriguing

coexistence of ferro- and antiferromagnetically ordered phases near the spin-flip transition in bilayer CrSBr. The resolution of our approach enabled us to reveal intriguing morphologies of the phase boundary between these regions, suggesting spin-textures with nontrivial topology that offer valuable insights into domain wall energetics in few-layer CrSBr.
I will conclude with a perspective on upcoming advancements in single-spin microscopy for vdW magnetism, emphasizing real-space explorations of dynamic phenomena [8] like spin waves and their propagation as the next frontier.

References

[1] B. Chernobrod and G. Berman, J. of Applied Physics 97, 014903
[2] G. Balasubmaranian et al., Nature 455, 644; J. Maze et al., Nature 455, 644
[3] N. Hedrich et al. P.R. Appl., 14, 64007; P. Appel et al., Rev. Sci. Instr. 87, 63703; Qnami.com
[4] C. Gong and X. Zhang, Science 363, 706; M. Gibertini et al., Nature Nano. 14, 408
[5] L. Thiel et al., Science 364, 973
[6] E. J. Telford et al., Adv. Mat. 32, 2003240
[7] F. Tabataba-Vakili et al., 2312.11041; F. Dirnberger et al., Nature 620, 533
[8] S. Chatterchee et al., PRB 99, 104425

Quantum sensing with spin defects in hexagonal boron nitride

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Quantum sensors based on optically-active spin defects in semiconductors have found a broad variety of applications, in both basic and applied science, due to their unprecedented combination of sensitivity, spatial resolution and ability to operate under a wide range of experimental conditions. While the most prominent example is undoubtedly the nitrogen-vacancy (NV) center in diamond, the exploration of alternative spin defects and host materials remains an active field of research worldwide. In this context, the negatively-charged boron vacancy (VB) center in hexagonal boron nitride (hBN) is currently attracting a growing interest for the development of quantum sensing and imaging technologies on a two-dimensional (2D) material platform. This point defect, which can be readily created by various irradiation methods, has a spin triplet ground level whose electron spin resonance frequencies can be measured optically under ambient conditions and strongly depends on external perturbations. In this talk, I will describe our recent research work aimed at developing quantum sensing foils based on VB centers in hBN.

Optics with 2D Quantum Materials

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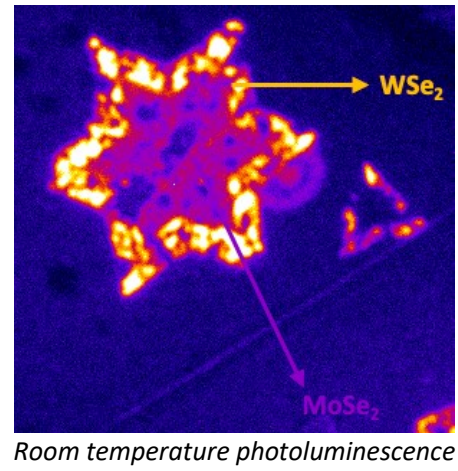
This work is a collaboration between TU Darmstadt (Germany), Friedrich Schiller University, Jena,(Germany), Philipps-Universität Marburg (Germany), CEMES and LPCNO Toulouse (France) and NIMS, Tsukuba (Japan).

Atomically thin semiconductors like $MoSe_2$ and WSe_2 have intruiging optical proporties in monolayer form. New dynamics and collective effects for charge carriers can be observed when these 2 materials are combined to form heterostructures. Through manual stacking *vertical* heterobilayers forming moiré superlattices can be obtained. *Lateral* heterostrucures can be achieved by CVD growth (chemical vapor deposition), where $MoSe_2$ and WSe_2 bond covaltently in the plane. In the first part of this talk we focus on the optical properties of these lateral heterostructures [1]. We report strategies to control exciton (Coulomb bound electron-hole pairs) flow [2] and we uncover fingerprints of charge-transfer excitons [3] at the junction between the two monolayer materials, with electron and holes residing in different materials. In the second part we discuss the optical properties of another promising system, namely Janus monolayers SeMoS, where the top and bottom chalcogen atoms are different, resulting in surprising linear and non-linaer optcial properties [4].



Room temperature photoluminescence imaging of lateral MoSe2-WSe2 monolayer heterostructure

References

[1] Beret, D., Paradisanos, I., Lamsaadi, H., Gan, Z., Najafidehaghani, E., George, A., Lehnert, T., Biskupek, J., Kaiser, U., Shree, S., Estrada-Real, A., Lagarde, D., Marie, X., Renucci, P., Watanabe, K., Taniguchi, T., Weber, S., Paillard, V., Lombez, L., Poumirol, J., Turchanin, A., Urbaszek, B., *Exciton spectroscopy and unidirectional transport in MoSe2-WSe2 lateral heterostructures encapsulated in hexagonal boron nitride*. npj 2D Mater Appl 6, 84 (2022).
[2] Hassan Lamsaadi, Dorian Beret, Ioannis Paradisanos, Pierre Renucci, Delphine Lagarde, Xavier Marie, Bernhard Urbaszek, Ziyang Gan, Antony George, Kenji Watanabe, Takashi Taniguchi, Andrey Turchanin, Laurent Lombez, Nicolas Combe, Vincent Paillard & Jean-Marie Poumirol, *Kapitza-resistance-like exciton dynamics in atomically flat MoSe2-WSe2 lateral heterojunction*, Nat Commun 14, 5881 (2023)
[3] Rosati, R., Paradisanos, I., Huang, L., Gan, Z., George, A., Watanabe, K., Taniguchi, T., Lombez, L., Renucci, P., Turchanin, A., Urbaszek, B., Malic, E., *Interface engineering of charge-transfer excitons in 2D lateral heterostructures*. Nat Commun 14, 2438 (2023).

[4] Ziyang Gan, Ioannis Paradisanos, Ana Estrada-Real, Julian Picker, Emad Najafidehaghani, Francis Davies, Christof Neumann, Cedric Robert, Peter Wiecha, Kenji Watanabe, Takashi Taniguchi, Xavier Marie, Johannes Biskupek, Manuel Mundszinger, Robert Leiter, Ute Kaiser, Arkady V Krasheninnikov, Bernhard Urbaszek, Antony George, Andrey Turchanin, *Chemical Vapor Deposition of High-Optical-Quality Large-Area Monolayer Janus Transition Metal Dichalcogenides*,Adv.Mater.2022,34,2205226

Optically Active Spin Defects in hBN

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Manipulating interactions in 2D-heterostructures using high-Q nanobeam cavities

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This talk will discuss 2D-heterostructures integrated into Si3N4 nanobeam optical cavities. These nanobeam optical resonators host high $Q > 10^4 - 10^5$ cavity modes and allow us to explore novel light-matter couplings and multimodal vibronic–phonon–photon couplings mediated by electronic excitations [1-6]. Figure 1 depicts schematically such nanobeam cavities, consisting of a non-perforated, fully hBN encapsulated 2D heterostructure placed onto a freestanding Si3N4 nanobeam that confines a single optical mode over wavelength lengthscales while efficiently coupling to the excitonic system of interest.

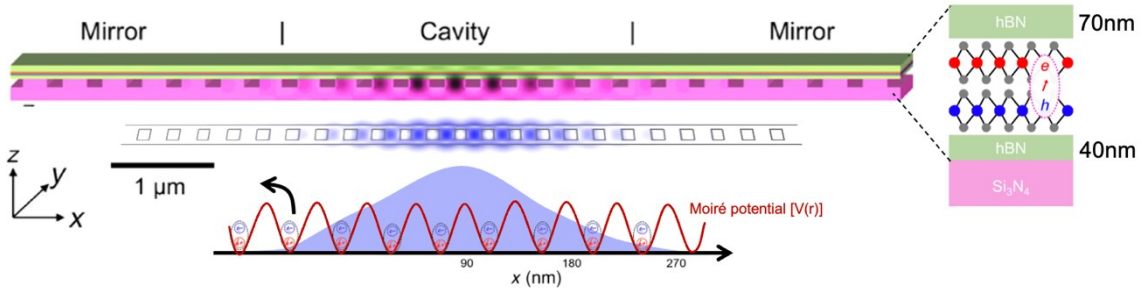

Figure 2 – Schematic representation of the Si3N4 nanobeam cavity onto which a fully hBN encapsulated 2D heterostructure is placed. The high-Q optical mode is confined over wavelength scale dimensions allow the study of the coupling of trapped moiré interlayer excitons magnetically tuned into resonance with the cavity mode.

Recently, we have used such nanobeam cavities to probe novel excitonic photo-physics in various 2D heterostructures. For example, in hBN encapsulated MoS_2 monolayers we observe a nonmonotonic temperature dependence of the cavity-trion interaction strength, a finding consistent with the spatial

extent of the centre-of-mass exciton wave function becoming comparable to the cavity photonic mode volume in space [1,2]. For R-type stacked $MoSe_2$-WSe_2 hetero-bilayers, we obtain evidence for the lasing of moiré trapped interlayer excitons (IX) as the cavity-IX detuning is controlled using a magnetic field. Here, threshold-like behaviour and line narrowing emerge in the pump-dependent cavity mode emission as the IX is magnetically tuned into resonance with the cavity mode [3]. Finally, cavity QED can be used to identify the zero-phonon line transition of the negatively charged Boron vacancy (V_B^-) center in hBN [5], an optically active spinful defect with intriguing properties at room temperature [6].

References

[1] C. Qian et al. Phys. Rev. Lett. 128, 237403 (2022) ,
[2] C. Qian et al. Phys. Rev. Lett. **130**, 126901 (2023)
[3] C. Qian et al. Science Adv. **10**, 2, (2024) DOI:10.1126/sciadv.adk635 ,
[4] C. Qian et al. Phys. Rev. Lett. **130**, 126901 (2023),
[5] C. Qian et al. Nano Lett, **22**, 13, 5137–5142, (2022), [6] R. Rizzato et al. Nat. Comm. **14**, 5089, (2023)

Many people in my group contributed to these works, including C. Qian, A. Stier, V. Villafane, P. Soubelet, N.P. Wilson, M. Petrić, P. Ji and M. Barbone and I gratefully acknowledge collaborations with the groups of A. W. Holleitner (TUM WSI-ZNN), D. Bucher (TUM), S. Höfling and S. Klembt (U. Würzburg) as well as M. Helm (Helmholtz-Zentrum Dresden-Rossendorf).

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Prolonged dephasing time of ensemble of moiré-trapped interlayer excitons in WSe_2-$MoSe_2$ heterobilayers

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Semiconducting transition metal dichalcogenides (TMDs) and their van der Waals heterostructures have been the subject of extensive research in the last decade. Although it has been demonstrated that the moiré superlattices of these heterostructures can induce a pronounced effect on the optical properties of interlayer excitons (IXs), their influence on temporal coherence has not yet been thoroughly investigated. Here, we demonstrate an extensive investigation of the coherence properties of both the ensemble of delocalized and the ensemble of moiré localized IXs of the hBN encapsulated WSe_2-$MoSe_2$ heterostructures. Using a home-built Michelson interferometer, we performed low-temperature first-order correlation measurements, resulting in prolonged dephasing time values up to T_2 = 730 fs from the ensemble of moiré localized IXs[1]. In comparison to the values we obtained from our delocalized IXs, our

results reveal an increase of two to almost five-fold, while it is more than two-fold prolonged compared to previously reported values of T_2 ~ 300 fs[2]. The prolonged dephasing times of the moiré-trapped IXs in comparison to the delocalized ones indicate that the presence of the moiré potentials within these heterostructures significantly suppresses the dephasing mechanisms (i.e., IX-low energy acoustic phonon and IX-IX scattering). Furthermore, the results of our power-dependent T_2 studies show that ultra-long dephasing times can be expected if the interferometric measurements are performed with the narrow photoluminescence emission line of a single moiré-trapped IX at a low pump power regime. The prolonged T_2 values of IXs would be crucial for future quantum information science applications and the development of two-dimensional material-based nanolasers[3].

References

1.Durmuş, M. A., Demiralay, K., Khan, M. M., Atalay, Ş. E. & Sarpkaya, I. Prolonged dephasing time of ensemble of moiré-trapped interlayer excitons in WSe2-MoSe2 heterobilayers. *Npj 2D Mater. Appl.* 7, 1–8 (2023).
2.Sigl, L. *et al.* Signatures of a degenerate many-body state of interlayer excitons in a van der Waals heterostack. *Phys. Rev. Res.* 2, 042044 (2020).
3.Qian, C. *et al.* Lasing of moiré trapped MoSe2/WSe2 interlayer excitons coupled to a nanocavity. *Sci. Adv.* 10, eadk6359 (2024).

Sulfur Vacancy Related Optical Transitions in Graded Alloys of $Mo_xW_{1-x}S_2$ Monolayers

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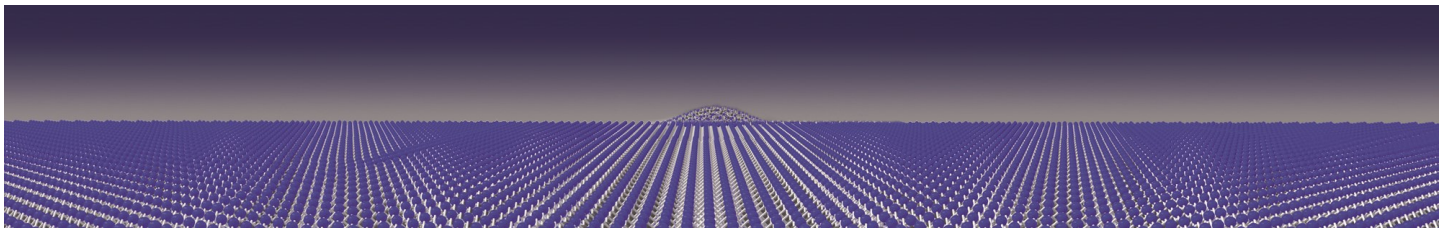
Transition metal dichalcogenides (TMDCs) provide a versatile platform for bandgap modulation through alloying, doping, and heterostructure formation. In this study, we explore graded $Mo_xW_{1-x}S_2$ monolayers, featuring a transition from a Mo-rich center to W-rich edges, and achieving a tunable bandgap of 1.85 to 1.95 eV from the center to the edge of the flake. Aberration-corrected high-angle annular dark-field scanning transmission electron microscopy reveals the presence of sulfur monovacancies (VS), whose concentration varies across the graded $Mo_xW_{1-x}S_2$ layer as a function of Mo content, with the highest value in the Mo-rich center region. Optical spectroscopy, supported by ab initio calculations, reveals a doublet electronic state of VS, split by spin-orbit interaction. The energy levels are positioned close to the conduction band or deep within the bandgap, depending on whether the vacancy is surrounded by W or Mo atoms. This unique electronic configuration of VS in the alloy facilitates four spin-allowed op5cal transitions between the VS levels and the valence bands.



Ultrafast electron dynamics in semiconducting thin films using subcycle terahertz nanoscopy

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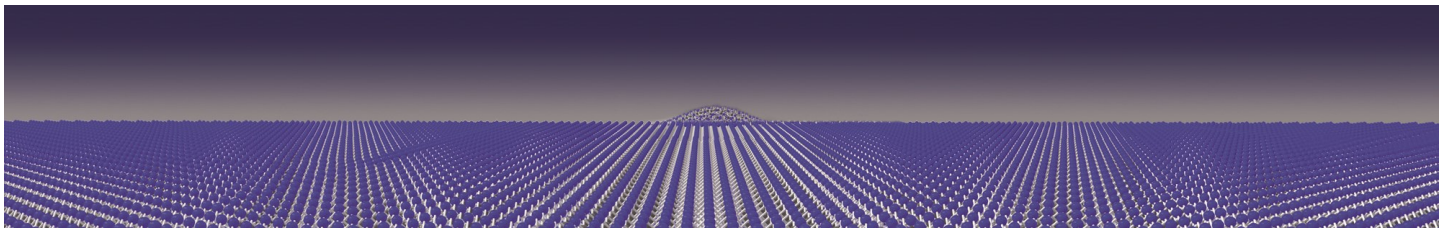
Advancing optical microscopy to increasingly shorter length- and timescales has been a key process to visualize the connection between nanoscopic elementary dynamics and macroscopic functionalities of matter. In this talk, I will show two recent breakthroughs tracing and understanding the ultrafast carrier dynamics in condensed matter systems on the nanoscale.
First, I will demonstrate how ultrafast terahertz nanoscopy unravels the interplay between structure, composition and carrier dynamics in individual grains of lead halide perovskite films [1] which are a promising class for future photovoltaic devices. Phonon fingerprinting is used to discern nano-grains of different crystallographic phase and chemical composition via their local dielectric function, directly extracted from our experimental data. Following the excitation with an optical pump pulse, we trace the photogenerated carrier dynamics with extreme temporal resolution. By accessing deep-subcycle shifts of the detected terahertz near-field waveforms, we introduce an approach to access the out-of-plane charge carrier diffusion, which constitutes a key quantity for solar cell performance. We find a surprising robustness of diffusion against structural and chemical variations on the nanoscale, possibly shedding light on the origin of the remarkable performance of perovskite-based devices. Our approach may help resolve further open questions, including the details of the charge collection process at the extraction layers or hot carrier effects.
Secondly, I will present a fundamentally new approach which brings all-optical microscopy to the atomic length scale while simultaneously retaining subcycle temporal resolution for the first time [2]. The technique utilizes the extreme nonlinearities within confined evanescent light fields to trace the path of electrons tunneling across a tip-sample junction combined with a purely optical detection mechanism. We demonstrate the capabilities of this new "Near-field Optical Tunnelling Emission" (NOTE) microscope by imaging packing defects on the surface of gold, alongside tracing the flow of electrons between the scanning tip and a semiconducting van der Waals trilayer in real-time. NOTE microscopy is inherently compatible with insulating samples, where no large-scale currents can flow, and allows for ultrafast spectroscopy with atomic spatial and subcycle temporal resolution. Hence, NOTE provides direct access to atomic scale quantum light-matter interaction and dynamics on their intrinsic length and timescales.

References

[1] M. Zizlsperger, S. Nerreter, Q. Yuan, K. B. Lohmann, F. Sandner, F. Schiegl, C. Meineke, Y. Gerasimenko, L.M. Herz, T. Siday, M. A. Huber, M. B. Johnston, and R. Huber, *In-situ nanoscopy of single-grain nano-morphology and ultrafast carrier dynamics in metal halide perovskites*, accepted in principle.
[2] T. Siday, J. Hayes, F. Schiegl, F. Sandner, P. Menden, V. Bergbauer, M. Zizlsperger, S. Nerreter, S. Lingl, J. Repp, J. Wilhelm, M. A. Huber, Y. A. Gerasimenko, and R. Huber, *All-optical subcycle microscopy on atomic length scales*, Nature **629,** 329–334 (2024).



Plenary Talk: van der Waals Interfaces

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Van der Waals (vdW) interfaces are emerging as a versatile platform to control and investigate electronic, magnetic and optical properties of quantum materials. I will discuss nano-optical studies of ambipolar charge transfer across an interface of vdW materials with different work functions. I will also discuss space-time metrology of tera-Hertz plasmon polaritons in graphene. This novel experimental approach allowed us to directly probe electronic interactions of the Dirac quasiparticles in graphene.

References:

1.Brian S. Y. Kim, Aaron J.Sternbach, Min Sup Choi, Zhiyuan Sun, Francesco L. Ruta, Yinming Shao, Alexander S. McLeod, Lin Xiong, Yinan Dong, Anjaly Rajendran, Song Liu, Ankur Nipane, Sang Hoon Chae, Amirali Zangiabadi, Xiaodong Xu, Andrew J. Millis, P. James Schuck, Cory. R. Dean, James C. Hone, and D.N. Basov, "Ambipolar charge-transfer graphene plasmonic cavities," Nature Materials 22, 838 (2023)

2.Suheng Xu, Yutao Li, Rocco A. Vitalone, Ran Jing, Aaron. J. Sternbach, Shuai Zhang, Julian Ingham, Milan Delor, James. W. McIver, Matthew Yankowitz, Raquel Queiroz, Andrew J. Millis, Michael M. Fogler, Cory R. Dean, James Hone, Mengkun Liu, D.N. Basov "Electronic interactions in Dirac fluids visualized by nano-terahertz spacetime mapping" (arXiv:2312.05444)

3.A. J. Sternbach, S. L. Moore, A. Rikhter, S. Zhang, R. Jing, Y. Shao, B. S. Y. Kim, S. Xu, S. Liu, J. H. Edgar, A. Rubio, C. Dean, J. Hone, M. M. Fogler, D. N. Basov "Negative refraction in hyperbolic hetero-bicrystals" Science 379, 555 (2023).

Optical interfaces from metasurface optics to low-symmetry phonon polaritons

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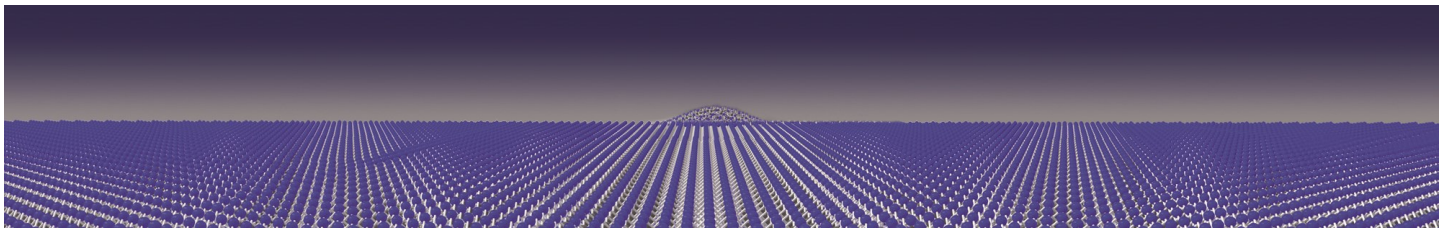
Fast progress in ultrathin and ultra-compact flat interface optics has been witnessed recently, including metasurface optics and hybrid metasurface-refractive optics. Many of those versatile flat-optics devices heavily rely on judiciously and artificially structured nanopatterns at the interface, and even the artificial intelligence is exploited to search for freeform and unexpected profiles of the structured meta-optics. Now it is about the time to sit back and look back – le voyage rétro – towards how we unlock the intrinsic power of natural materials. In this talk, I will show several breakthroughs in molding polaritons, hybrid excitations of matter and photons. We discover the photonic magic angle, the corresponding topological transition, ultra-large confinement and ultralong canalization, topological orbit angular momentum, and steerable unidirectional propagation of surface phonon polaritons in layered vdW materials. The grand challenges include the propagation loss of polariton waves and limited size of the exfoliated vdW materials. In this



regard, we showcase a peculiar type of ghost polariton with both propagation and evanescent natures inside a uniaxial crystal such as Calcite. The long-range (> 20um), directional and diffractionless propagation of polaritons are observed at room temperature. Such uniaxial crystals are lossless, large size and commercially available, and the properly slanted optic axis could facilitate wafer-scale on-chip polariton nanodevice with unprecedented nanolight control. We envision that such nature-based interface optics will spur new thoughts and directions, such as transformation and topological polaritonics, electron-polariton interactions, nano-imaging, energy transfer, on-chip circuitry, and quantum applications.

Cryogenic near-field spectroscopy from visible to midinfrared frequencies: exploring topological insulator nanostructures and 2D materials at the nanoscale

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In this talk, we present the near-field microscopy capabilities at Manchester, including cryogenic operation from visible to terahertz frequencies. We provide examples for different operations, including: surface chemical characterisation in InN nanostructures, sub-surface characterisation of water in graphene nanochannels; mapping polariton modes in 2D materials, and nanoscale spectroscopy of topological insulators. In particular, we focus on nanoscale characterisation of our 2D topological insulator thin films and nanostructures, demonstrating spectral features around ~1250cm^-1 in the topological insulator nanowires. We utilise multilayer modelling to establish the physical mechanism behind this resonance and discuss future work to utilise these materials for terahertz devices.

Nanooptics in flatlands

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Highly anisotropic crystals have recently attracted considerable attention due to their ability to support polaritons with unique properties, such as hyperbolic dispersion, negative phase velocity, or extreme confinement. In particular, the biaxial van der Waals semiconductor α-phase molybdenum trioxide (α-MoO3) has received much attention [1] due to its ability to support in-plane hyperbolic phonon polaritons (PhPs) —infrared (IR) light coupled to lattice vibrations in polar materials— with ultra-low losses, offering an unprecedented platform for controlling the flow of energy at the nanoscale.
In this talk, we will show experimental demonstrations of the unique behavior of PhPs in these crystals, including the visualization of anomalous cases of the fundamental optical phenomena of refraction [2] and

reflection [3], and the exotic phenomena of canalization and unidirectional ray propagation, in which PhPs propagate along a single direction with ultralow losses [4-7].

References
[1] W. Ma et al., Nature, 562, 557 (2018).
[2] J. Duan et al., Nature Communications, 12, 1, 1-8 (2021).
[3] G. Álvarez-Pérez et al., Science Advances 8, 29, (2022)
[4] J. Duan et al., Nature Materials, 22, 867-872 (2023).
[5] J. Duan et al., Nano Letters, 20 (7), 5323-5329 (2020).
[6] AI F. Tresguerres-Mata et al., Nature Communications 15 (1), 2696 (2024).
[7] J. Álvarez-Cuervo et al., arXiv.2403.18657 (2024).

Ultrafast nano-imaging: Probing quantum dynamics in space and time

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Understanding and ultimately controlling the properties of quantum materials and their coupled degrees of freedom will require counteracting the effects of dissipation and dephasing. This necessitates imaging the elementary excitations on their natural time and length scales. To achieve this goal, we developed scanning probe microscopies with ultrafast and shaped laser pulses for multiscale coherent spatio-temporal optical nano-imaging. In corresponding ultrafast movies, we resolve the fundamental quantum dynamics down to the few-femtosecond regime with nanometer spatial resolution. Specifically, in 2D materials and their heterostructures, the emergent electronic, spin, and other quantum properties are controlled by the underlying interlayer coupling and associated charge and energy transfer dynamics. These processes are sensitive to interlayer distance and crystallographic orientation, which are in turn affected by defects, grain boundaries, and other nanoscale heterogeneities. In this talk, I will present the use of adiabatic plasmonic nanofocused four-wave mixing (FWM) [1] to image the coherent electron dynamics in monolayer WSe_2 resolving nanoscale heterogeneities in dephasing ranging from $T_2 < 5$ fs to $T_2 > 60$ fs on length scales of 50-100 nm [2]. Further, in combination with Purcell-enhanced nano-cavity clock spectroscopy [3] in WSe_2/graphene heterostructures we identify interlayer energy transfer dynamics at times scales of 350 fs [4]. Beyond the fundamental understanding to the competition between intrinsic and extrinsic effects on excitation lifetimes and coherence, we discover a new regime of nonlinear nano-optics at the interplay of spatial coherence and disorder-induced scattering.

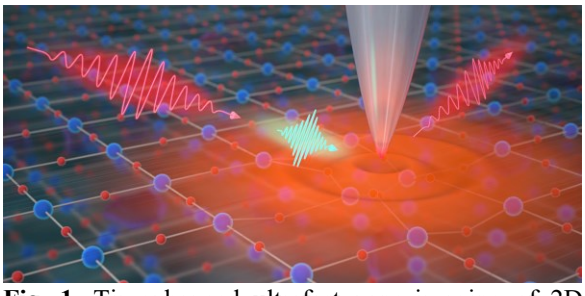

Fig. 1. Tip-enhanced ultrafast nano-imaging of 2D materials with simultaneous nanometer spatial and femtosecond temporal resolution resolving from few-fs coherent electron to ps interlayer dynamics.

References
[1] T. Jiang, et al., "Ultrafast coherent nonlinear nano-optics and nano-imaging of graphene", *Nature Nanotechnology* **14**, 838 (2019).
[2] W. Luo, et al., "Ultrafast nano-imaging of electronic coherence in monolayer WSe_2" *Nano Lett.* **23**, 1767 (2023).
[3] M. A. May, et al., "Nanocavity clock spectroscopy: resolving competing exciton dynamics in WSe_2/$MoSe_2$ heterobilayers", *Nano Lett.* **21**, 522 (2020).
[4] W. Luo, et al. "Nonlinear nano-imaging of interlayer coupling in 2D graphene-semiconductor heterostructures", *Small* 2307345 (2024).

Hyperspectral detectorless near-field nanoscopy at terahertz frequencies

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Quantum nano-optoelectronics of twisted 2D materials

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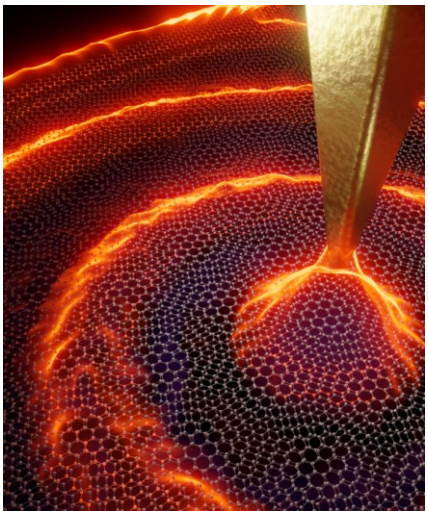
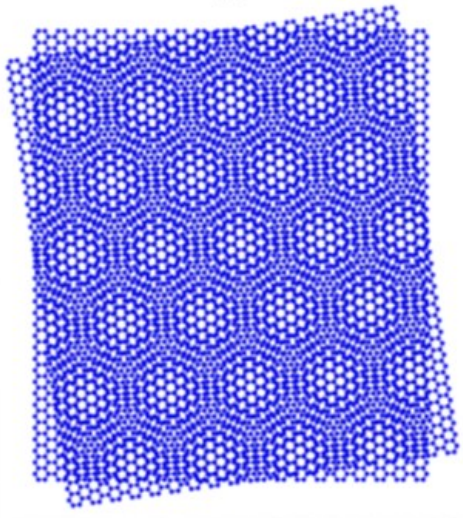
Two-dimensional (2D) materials have emerged as a fascinating platform for manipulating light and exploiting light-matter interactions at the atomic level. Twisted 2D materials, in particular, have represented a recent revolution in materials science as a tunable platform to tailor the periodic energy landscape for electrons at the nanoscale. This has led to the demonstration of tunable superconductivity, novel topological polaritons, tunable magnetism, etc.

We present innovative techniques to study the nano-optoelectronic properties and to develop novel quantum technologies. Our pioneering low-temperature near-field imaging techniques allow us to examine the electronic response to light with unprecedented nanometer-scale spatial resolution. One of our key interests is to unveil the interplay of topological and many-body phenomena in 2D-material heterostructures. Moreover, we present the discovery completely new functionalities, such as single-photon detection capabilities.





Quantum phases in flat-band van-der-Waals systems: making, controlling and measuring by quantum transport

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One exciting endeavor of condensed matter research is to understand how electrons in a solid interact with one another and the underlying atoms. Depending on this intricate interplay, the system can have drastically different properties, for example be either insulating or superconducting. Due to the many electrons and atoms involved, one can image that developing a general understanding of this interplay is very complex. In this sense, finding experimental systems that allow systematically control of e.g. charge carrier density and/ or their mutual interaction is highly desirable. The novel class of van-der-Waals materials offers such tunability.

This talk will focus on one specific van-der-Waals material, the naturally occurring Bernal bilayer graphene (BBG). It has shown to host electric-field tunable van-Hove singularities. Indeed, correlated states and even superconductivity was found close to these regions of diverging density of states. Here, I will show how we systematically identify and explore such phases by controlling not only the density of states, the charge carrier density but also the interaction between charge carriers. Most intriguingly we identified anomalous quantum Hall and Wigner crystal phases in BBG.

Enhanced Interactions of Interlayer Excitons in Free-standing Hetero-bilayers

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Low-frequency noise in the heterostructures of near-magic angle twisted bilayer graphene and transition metal dichalcogenide layers

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Twisted van der Waals heterostructures of two-dimensional (2D) materials introduces a new knob to engineer Coulomb interaction, structural symmetry breaking, electron-phonon interaction, among others

in a solid-state environment. The resulting phase space of physical phenomena is extremely rich that ranges from new correlated insulators to superconductors, ferromagnets, to Chern insulators and other broken symmetry states all embedded within the delicate interplay of moiré patterns resulting from layer misalignment. Partnering different genres of 2D materials, especially the transition metal dichalcogenides (TMDC), provides further flexibility in introducing spin-orbit interaction, topological properties etc [1,2]. While conventional electrical transport, surface-sensitive local microscopy or optical spectroscopic techniques have been frequently used to probe the electronic properties of the twisted heterostructures, a crucial technique that has not been used so far is the low-frequency 1/f noise [3], which is an extremely sensitive probe to the local screening properties and the time-dependent kinetics of disorder. In this talk [4] I shall present results of experimental measurements of 1/f noise in multiple twisted bilayer graphene devices at and close to the magic angle, both with and without partnering TMDC layers. A stochastic exchange of charge between the conducting channel (twisted bilayer graphene) and traps located in the encapsulating (hexagonal boron nitride) dielectric is found to be the dominant mechanism of the noise in these devices. At low temperature, the noise shows distinct minima at the commensurate filling factors inside the moiré band, which can be attributed to the singularities in the density of states, and thus enhanced screening of the charged trap states. Intriguingly, such states could be resolved with noise magnitude while the time averaged resistance remained largely featureless.

References

[1] S. Bhowmik et al. Nature Physics 18 (6), 639-643 (2022)
[2] B. Ghawri et al. Nature Communications 13 (1), 1522 (2022)
[3] P. Karnatak et al. Advances in Physics: X 2 (2), 428-449 (2017)
[4] P. Pal et al. (2024, submitted)

In-operando spectroscopy and microscopy on twisted 2D materials: from graphene to magnets

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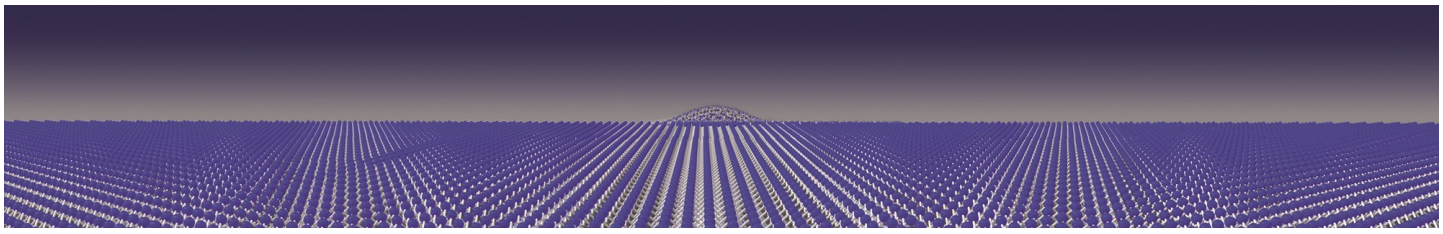
Two-dimensional materials offer unique opportunities to perform multimodal, “in-operando”, (nano)device-compatible measurements combining various surface science/optical microscopies and spectroscopies with electrical transport/gating, to gain a microscopic and deeper understanding of materials properties and device performance. In this talk, I will discuss examples of such multimodal measurements involving transport, optical Raman spectroscopy, magneto-optical-Kerr-effect (MOKE), micro angle resolved photoemission spectroscopy (ARPES), and scanning probe microscopies on 2D materials (ranging from graphene to 2D magnets) and their twisted/stacked heterostructures.



Quantum optical spectroscopy of 2D materials

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I will describe time-resolved nonlinear pump--probe measurements that reveal features of semiconductor moiré materials not accessible to linear spectroscopy. With an intense, red-detuned pump pulse, we generate a high density of virtual excitons or exciton--polarons in various moiré minibands. A broadband probe pulse in turn measures the response of all optical resonances induced by the pump-generated excitations. At charge neutrality, these measurements allow us to assess the spatial overlap between different optical excitations: in particular, we observe signatures of a bound biexciton state between two different moiré exciton modes.

Gate-tunable $NbSe_2/MoSe_2$ heterostructures

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Two dimensional (2D) materials and their heterostructures host rich physical phenomena. In this presentation, we will present results on metallic and superconducting bulk $NbSe_2$ and heterostructures of it with $MoSe_2$. Heterostructures of graphene and transition-metal dichalcogenides have shown significant quenching of photoluminescence emission through interlayer charge or energy transfer (ICT or IET) to the adjacent layer [1,2]. Here we explore the photoluminescence properties of gate-tunable gate-tunable $NbSe_2/MoSe_2$ heterostructures and observed a revival of the optical emission in $MoSe_2/NbSe_2$ under electrostatic gating.

In this investigation, we have carried out a comprehensive study of the optoelectronic characteristics exhibited by $MoSe_2/NbSe_2$ heterostructures under the influence of a vertical electric field. The results reveal notable increase of photoluminescence intensity, concerning the $MoSe_2$ excitons in the regions of the heterostructure with $NbSe_2$, approaching the levels observed in pristine monolayer $MoSe_2$. The degree of enhancement varies from sample to sample, with a maximum observed increase of tenfold. We attribute these phenomena to the establishment of a potential barrier, specially Schottky barrier, between $MoSe_2$ and $NbSe_2$, which effectively regulates charge separation dynamics and facilitates the transfer of charges between the two-dimensional material system depending upon the direction of the applied electric field. Our investigation provides a clear distinction between ICT and IET, a pertinent phenomenon observed in various 2D heterostructures.

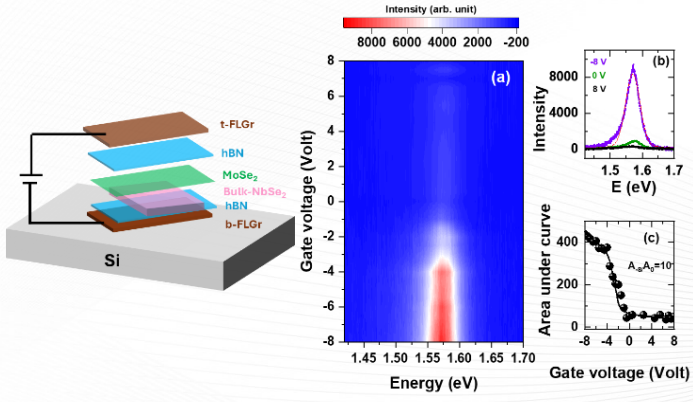

Figure: Schematic diagram of $NbSe_2/MoSe_2$, gated structure and PL enhancement under electric field.

References

[1] E. Lorchat et al., Nat. Nanotechnol. 15, 283 (2020).
[2] G Froehlicher et al., Phys. Rev. X 8, 011007 (2018).

Interband transitions in few-layer graphene and their coupling to phonon polaritons

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The crystallographic stacking order of few-layer graphene (FLG) greatly influences its electronic and optical properties, such as band structure and optical conductivity. The most common stacking in FLG is Bernal stacking (AB), which is the energetically favorable configuration, while rhombohedral stacking (ABC) is less common. For example, rhombohedral stacked trilayer graphene (TLG) exhibits superconductivity [1], absent in Bernal stacked TLG.
In the past, infrared s-SNOM contributed tremendously to the field of 2D materials by enabling the real-space imaging of plasmon- or phonon polaritons [2], e.g., in graphene and hexagonal Boron Nitride (hBN), respectively. Polariton imaging with s-SNOM has allowed for indirectly mapping (grain) boundaries and (stacking) defects in FLG via polariton reflection. While graphene polaritons are usually investigated with s-SNOM at energies below 0.2 eV, the stacking-specific interband transitions of FLG between 0.2 and 0.9 eV have been less explored with s-SNOM nanospectroscopy.
Here, we perform spectroscopic s-SNOM measurements with a broadly tunable OPO/OPA laser system [3] over the energy range from 0.3 to 0.54 eV to study the characteristic and stacking-dependent interband

transitions of bilayer graphene (BLG) [3], TLG and tetralayer graphene (4LG) [4]. We retrieve and reconstruct the complex optical conductivity resonances from the amplitude and phase of the scattered light, which e.g. allow for the unambiguous assignment of previously undetected ABCB domains in 4LG. [4] Our results establish near-field spectroscopy of interband transitions as a semi-quantitative tool, enabling the recognition of domains of previously unknown stacking orders and provide a basis for studying their physical properties.
For transport measurements, FLG is usually encapsulated in hBN because it increases the carrier mobility of graphene. However, this aggravates the domain identification with diffraction-limited optical techniques, such as far-field infrared- and Raman-spectroscopy. Furthermore, encapsulating FLG into hBN can alter the stacking order and induce defects within the FLG flake [5]. Recently, Liu et al. [6] visualized stacking domains in encapsulated 4LG using phonon-assisted near-field imaging. However, the underlying coupling mechanism and the visualization of subdiffractional defects remain elusive. Here, we use a hBN TLG heterostructure to proof that that such coupled polaritons are indeed hyperbolic phonon plasmon polaritons. We also explain how they allow for super-resolution imaging of subdiffraction-sized defects in graphene through the hBN cover layer via the so-called hyperlensing effect [7].
Our work paves the way for the characterization of FLG devices during fabrication, where the domains can be altered, and defects may form due to mechanical stress and strain during stacking, heating, and electric fields. Exploiting interband transitions, which are also characteristic for twisted FLG, and their coupling to Phonon Polaritons in hBN with our technique will open the door toward nanoscopic noncontact measurements of the electronic properties in complex hybrid 2D and van der Waals material systems.

References

[1] Zhou, H. et al. *Nature* 598, 434 (2021).
[2] Basov, D. N. et al., *Science* 354, aag1992 (2016).
[3] Wirth, K. G. et al., *ACS Photonics,* 8, 418 (2021).
[4] Wirth, K. G. et al., *ACS Nano* 16, 10, 16617 (2022).
[5] Geisenhof et al. *ACS Appl. Nano Mater*. 2, 6067 (2019)
[6] Liu et al., *Nature Nanotechnology* 19, 188 (2024).
[7] Li et al. *Nature Communications* 6, 7507 (2015).

Exploring Polaritons and Dielectric Behavior of Nanoconfined Water in Gypsum

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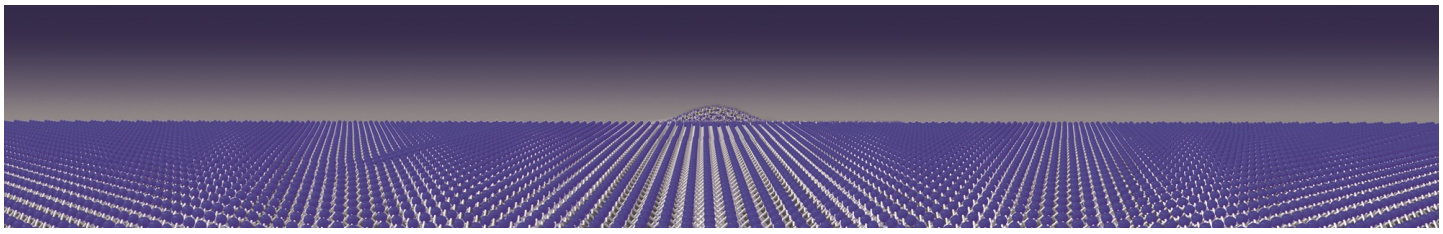
Gypsum, an exfoliable monoclinic crystal, offers unique opportunities for investigating both polaritonic response and hydrogen bonding. We employed scattering-type scanning near-field microscopy and nano-FTIR spectroscopy on exfoliated gypsum flakes to visualize, for the first time, a transition from shear hyperbolic to shear elliptical polaritons. This transition is accompanied by light canalization in a narrow mid-IR frequency range, expanding the potential applications of low-symmetry crystals in photonic devices

and enabling the fabrication of diverse heterostructures that could access novel optical phenomena at the nanoscale. Furthermore, we introduce a simple approach to conceptualize hydrogen bonds as elastic dipoles in an electric field, capturing a wide range of hydrogen bonding phenomena in water systems. By utilizing gypsum, with crystalline water embedded in a heterostructure, we determined the hydrogen bond strength through an externally applied electric field. Our approach quantifies not just the strength of hydrogen bonds, but also the dielectric behaviour in a wide range of systems directly from vibrational spectroscopy data.



Tunable phonon polaritons in oxide interfaces and nanomembranes

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Surface phonon-polaritons (SPhPs) - strongly coupled light-phonon modes bound to interfaces between two media, one of which is a polar material with negative permittivity - hold high promise in nano-photonics due to their capacity to squeeze the electromagnetic energy on ultra-subwavelength scales. While the SPhPs are extensively studied in conventional semiconductors (SiC, AlN) and van der Waals materials (hBN, MoS2), little is done in the vast family of complex perovskite oxides ABO_3. Using cryogenic scattering-type near-field optical microscopy (s-SNOM) in Geneva and synchrotron infrared nanospectroscopy (SINS) at the ALS (Berkeley), we explored SPhP modes in $LaAlO_3$(LAO)/$SrTiO_3$(STO) heterostructures [1] and 100 nm-thick transferable STO membranes [2]. The presence of conducting 2D electron gas (2DEG) at the LAO/STO interfaces strongly increases the temperature dependence of the PhP frequency, due to a coupling between the SPhPs in STO and the plasmon-polaritons in the 2DEG, and also allows for electrostatic tuning by applying voltage to a back gate [1]. In ultrathin membranes, we observe an even-odd SPhP mode splitting, where the low energy mode shows a propagating behavior with a strongly confined wavelength, while the high-energy mode (Berreman mode) shows the epsilon-near-zero (ENZ) behaviour with a huge enhancement of the electric field inside the sample. Our work shows great potential of oxides for infrared nano-photonics.

References

[1] Thermal and electrostatic tuning of surface phonon-polaritons in LaAlO3/SrTiO3 heterostructures, Y. Zhou, A.Waelchli, M. Boselli, I. Crassee, A. Bercher, W. Luo, J. Duan, J.l.m. van Mechelen, D. Van Der Marel, J. Teyssier,W. Rischau, L. Alexander Korosec, S. Gariglio, J.-M. Triscone, A. B. Kuzmenko, Nature Communications **14** , 7686 (2023).
[2] Highly confined epsilon-near-zero and surface-phonon polaritons in SrTiO3 membranes, R. Xu, I. Crassee, H.Bechtel , Y. Zhou , A. Bercher , L. Korosec , C.W. Rischau , J. Teyssier , K. Crust , Y. Lee , S. Gilbert Corder , J. Li, J. Dionne, H. Hwang, A. B. Kuzmenko, Y. Liu, Nature Communications (in press); arXiv:2312.14093.

Control of polaritons in low-dimensional nanomaterials

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Polaritons are well-established carriers of light, electrical signals, and even heat at the nanoscale. Achieving control over it is pivotal for the realization of nanoscale manipulation of light signals and even heat within on-chip devices. Our research explores efficient excitation of polaritons in one-dimensional to two-dimensional nanomaterials, leading to the discovery of polariton modes with ultra-high optical-field confinement and quality factors. Through the ingenious design of dielectric environments, we have successfully mitigated the transmission losses of polaritons, enabling long-distance propagation.

Furthermore, by employing techniques such as heterostructures, chemical doping, and electrical modulation, we have achieved precise control over the transmission modes and directions of polaritons. These research findings address the challenge of efficient optoelectronic modulation beyond the diffraction limit, offering a novel pathway for the development of highly integrated optoelectronic interconnect chips.

Merging 2D materials and atomically smooth gold crystals: challenges and opportunities

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Revealing the Secrets of 2D Materials: Nanospectroscopy and Nano-Imaging Illuminate Structure-Property Relationships in Complex Materials

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Synchrotron infrared nanospectroscopy (SINS) combines the broad bandwidth and brightness of synchrotron infrared radiation with scanning near-field optical microscopy (s-SNOM), enabling direct probing of elementary excitations of functional materials spanning the mid- and far-infrared with ~ 20 nm spatial resolution. The Advanced Light Source (ALS) at Lawrence Berkeley National Laboratory operates two infrared beamlines (Beamlines 2.4 and 5.4) with SINS instruments that are freely available to users with an approved scientific proposal.
I will discuss the capabilities of the ALS infrared beamlines by highlighting some recent collaborative measurements on 2D materials, focusing on light-matter coupling [1], lattice strain [2], and carrier density [3]. I will also discuss some recent advances in the technical capabilities at the beamlines, which have direct applications to the study of 2D materials specifically and quantum materials in general.

References

[1]. S.-J. Yu, Y. Jiang, J. A. Roberts, M. A. Huber, H. Yao, X. Shi, H. A. Bechtel, S. N. Gilbert Corder, T. F. Heinz, X. Zheng, J. A. Fan, ACS Nano 16 (2), 3027-3035 (2022).
[2]. B. Lyu, H. Li, L. Jiang, W. Shan, C. Hu, A. Deng, Z. Ying, L. Wang, Y. Zhang, H. A. Bechtel, M. C. Martin, T. Taniguchi, K. Watanabe, W. Luo, F. Wang, Z. Shi. Nano Letters 19 (3), 1982-1989 (2019).
[3]. X. W. Lu, O. Khatib, X. T. Du, J. H. Duan, W. Wei, X. L. Liu, H. A. Bechtel, F. D'Apuzzo, M. T. Yan, A. Buyanin, Q. Fu, J. N. Chen, M. Salmeron, J. Zeng, M. B. Raschke, P. Jiang, X. H. Bao, Adv. Electron. Mater. 4, 1700377

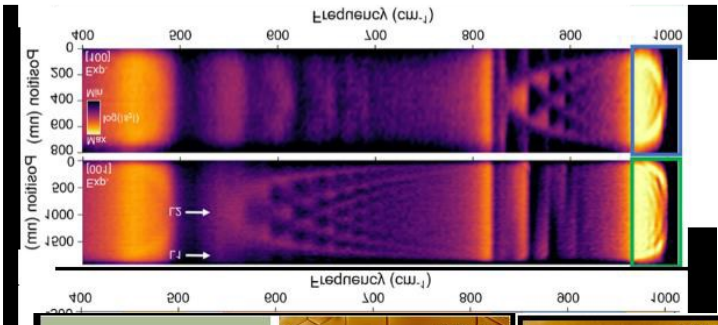


Figure 1. Nanospectroscopy of -MoO3nanoribbon on ultra-smooth gold. The real part of the permittivity (top) is shown with four Reststrahlen bands. High-quality phonon-polariton modes along the [001] and [100] directions are shown in the middle and lower panels. [1]

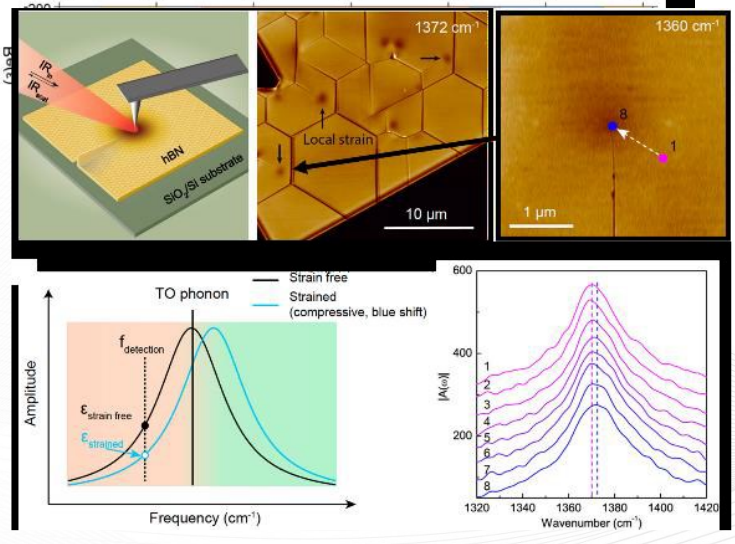


Figure 2. A wrinkle in the hBN is probed with SINS and nano-imaging (upper panel). The absolute value of the dielectric function of strain-free and compressive-strained hBN is shown for the TO phonon mode schematically and experimentally (lower panel). [2]

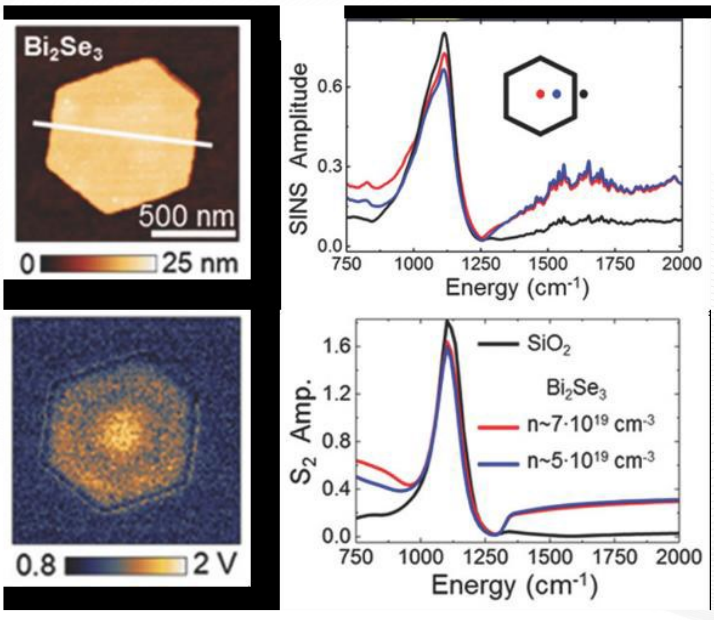
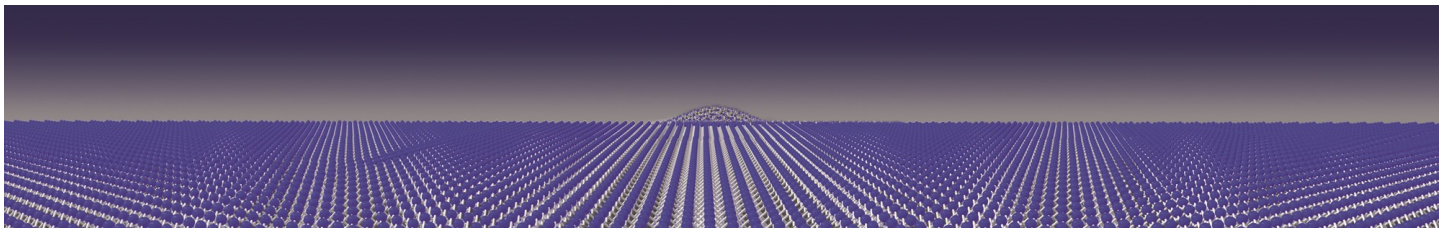


Figure 3. A Bi2Se3nanocrystal on SiO2/Si substrate. Topography and near field imaging response (left). The broadband SINS response in different locations (top right) and the simulation of the interaction between the SiO2and Bi2Se3with different carrier concentrations is shown



Plenary Talk: Antiferromagnetic Spintronics with Multiferroics

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Over the past decade the oxide community has been exploring the science of ferroic materials as crystals and in thin film form by creating epitaxial heterostructures and nanostructures. Among the large number of materials systems, there exists a small set of materials which exhibit multiple order parameters; these are known as multiferroics, particularly, the coexistence of ferroelectricity and some form of ordered magnetism (typically antiferromagnetism). The scientific community has been able to demonstrate electric field control of both antiferromagnetism and ferromagnetism at room temperature. There are some very intriguing new developments in SOT based manipulation of magnets. Particularly, the role of epitaxy and electronically perfect interfaces has been shown to significantly impact the spin-to-charge conversion (or vice versa). Current work is focused on ultralow energy (1 attoJoule/operation) electric field manipulation of magnetism with both voltage and current, as the backbone for the next generation of ultralow power electronics. We are exploring many pathways to get to this goal. In this talk, I will describe our progress to date on this exciting possibility.

Oxide Materials for Spintronics

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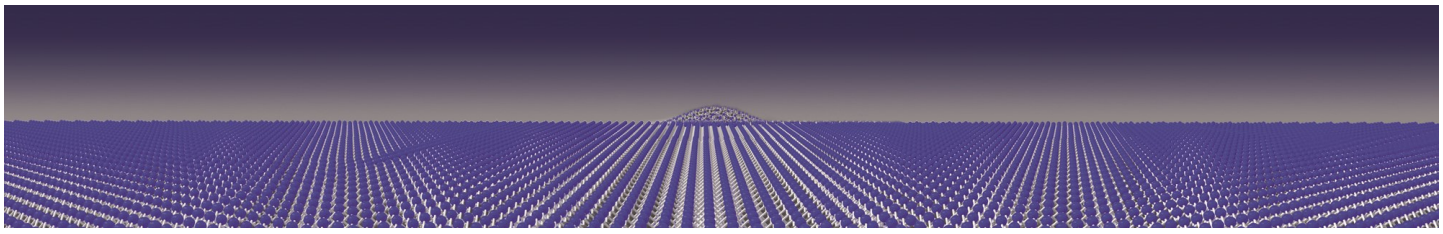
For magnetic oxides, competition between various types of exchange interactions has often led to striking physical properties that are highly tunable by external fields. Such tunability is desirable for spintronic applications. In this talk, I will show how one can use electric field to control magnetic domain structures and interfacial ferroelectricity in oxides thin films and heterostructures, giving rise to the ability to control spin-dependent transport using electric field. The electric field control of magnetic domain structures in oxides is achieved based on the understanding of the physical origin of domain formation in oxides, which is well beyond conventional Landau-Lifshitz theory. We have successfully fabricated various oxides-based spintronic devices, which all exhibit promising functionality with low energy consumption. To finish, I will discuss the future of oxides spintronics from my own perspective.



Functional topological defects: materials at the edge of order

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Topological structures in ferroic functional materials such as domain walls and skyrmions attract attention due to their intriguing properties and application potential in nanoelectronics. I will discuss our recent work on various ferroelectric and multiferroic materials systems using scanning probe microscopy as the main investigative tool, which is combined with insight from electron microscopy and ab-initio theory, and discuss future prospects of this evolving research field.

Sliding Ferroelectricity

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Achieving atomically thin ferroelectric materials for the use in ferroelectric non-volatile memory remains a significant challenge in materials science, primarily due to the depolarization effects in ultra-thin scales. To address this challenge, we present a novel approach to engineering atomically thin ferroelectrics using van der Waals heterostructures. Our method involves artificially inducing ferroelectricity by manipulating the stacking angle of non-ferroelectric materials such as bilayer boron nitride and bilayer transition metal dichalcogenides. This technique enables us to produce atomically out-of-plane ferroelectrics that operates as a non-volatile memory at room temperature.

We specifically highlight its device performance as a ferroelectric field effect transistor. The artificial ferroelectrics offers atomically thin devices that enables ultrafast (< 1 ns) and high-endurance switching (> 10^{11} cycles without any degradation), which outperforms the traditional constraints conventional ferroelectrics. This exceptional performance stems from the unique ferroelectric mechanism, where the polarization is switched by the interlayer sliding motion between the van der Waals layers.

Additionally, we introduce the novel concept of moiré ferroelectrics achieved by twisting the two layers. This results in a unique ferroelectric state characterized by an alternating out-of-plane polarization network. We further discuss the utility of moiré ferroelectrics as substrates to modulate the band structure of 2Dmaterials in momentum space.

Quantum microscopy of antiferromagnetic and ferroelectric materials

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Diamond has emerged as a unique material for a variety of applications, both because it is very robust and because it has defects with interesting properties. One of these defects, the nitrogen-vacancy center (NV center), has a single spin associated with it that shows quantum behavior up to room temperature. Our group is harnessing the properties of single NV centers for high-resolution magnetic sensing applications. In this talk, I will introduce the basic technology and concepts of diamond-based quantum sensors and their integration into scanning probe microscopes. I will then present examples of applications to nanoscale materials, including the magnetic imaging of domains and domain walls in antiferromagnets, and the electrical imaging of domains in ferroelectrics and multiferroics.

Visualizing supersonic electron flow in an electronic de Laval nozzle

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Electronic properties arise from phenomena at a multitude of length scales from sub-atomic to macroscopic. Atomic force microscopy provides a multimodal lens on the rich mesoscale electronic, magnetic, optical, and mechanical structure of 2D materials to bridge the gap between nanoscale local properties and global device properties.

Clean materials systems with strong carrier-carrier interactions can reach a regime in which current flow is hydrodynamic, opening the possibility of realizing a variety of interesting phenomena long understood in macroscopic fluids, in microscopic electronic systems. To date, compressible flow, where the drift velocity of the carriers is comparable to the sound velocity of the fluid, and the fluid density is no longer constant, has been unexplored in electronic systems. In this work, we implement an electronic de Laval nozzle [1], designed to accelerate electrons to supersonic speeds which then relax abruptly at a shock. We observe electronic transport discontinuities consistent with supersonic flow and use Kelvin probe force microscopy to image the associated potential profile through the encapsulated device and localize signatures of compressible flow.

References

[1] K. Moors, O. Kashuba, T. L. Schmidt, arXiv:1905.01247

Excitonic insulator in atomic double layers

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Exciton, charge and spin lattices in moiré heterostructures

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Semiconductor van der Waals heterostructures with near-resonant band alignment and non-commensurate lattices such as MoSe2/MoTe2 [1] and MoSe2/WS2 [2] constitute peculiar model systems for excitons, charges and spins localized on moiré lattices. Being robust against mesoscopic lattice reconstruction [3] due to sizable lattice mismatch, they exhibit canonical periodic moiré potentials, while near-resonant band alignment induces hybridization of exciton states across the constituent layers. Using cryogenic optical spectroscopy of moiré excitons, we study the effects of correlated charge and spin ordering in such moiré heterostructures with different twist-angle configurations, highlighting emergent magnetism phenomena on effective monolayer and bilayer Hubbard triangular lattices [4]. Moreover, by employing open cavities, we establish control over neutral and charged moiré exciton-polaritons in the regime of strong light-matter coupling, thereby expanding the realm of moiré phenomena in van der Waals heterostacks.

References

[1] S. Zhao, X. Huang, R. Gillen, Z. Li, S. Liu, K. Watanabe, T. Taniguchi, J. Maultzsch, J. Hone, A. Högele, and A. S. Baimuratov, Hybrid moiré excitons and trions in twisted MoTe2-MoSe2 heterobilayers, Nano Lett. DOI: 10.1021/acs.nanolett.4c00541 (2024).
[2] B. Polovnikov, J. Scherzer, S. Misra, X. Huang, C. Mohl, Z. Li, J. Göser, J. Förste, I. Bilgin, K. Watanabe, T. Taniguchi, A. Högele, and A. S. Baimuratov, Field-Induced Hybridization of Moiré Excitons in MoSe2/WS2 Heterobilayers, Phys. Rev. Lett. 132, 076902 (2024).
[3] S. Zhao, Z. Li, X. Huang, A. Rupp, J. Göser, I. A. Vovk, S. Yu. Kruchinin, K. Watanabe, T. Taniguchi, I. Bilgin, A. S. Baimuratov, and A. Högele, Excitons in mesoscopically reconstructed moiré heterostructures, Nat. Nanotechnol. 18, 572 (2023).
[4] B. Polovnikov, J. Scherzer, S. Misra, H. Schlömer, J. Trapp, X. Huang, C. Mohl, Z. Li, J. Göser, J. Förste, I. Bilgin, K. Watanabe, T. Taniguchi, A. Bohrdt, F. Grusdt, A. S. Baimuratov, and A. Högele, Implementation of the bilayer Hubbard model in a moiré heterostructure, arXiv:2404.05494 (2024).

Revealing intrinsic domains and fluctuations of moiré magnetism by a quantum microscope

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Moiré magnetism featured by stacking engineered atomic registry and lattice interactions has recently emerged as an appealing quantum state of matter at the forefront of condensed matter physics research. Nanoscale imaging of moiré magnets is highly desirable and serves as a prerequisite to investigate a broad range of intriguing physics underlying the interplay between topology, electronic correlations, and unconventional magnetism. In this talk, I will present our recent work on using nitrogen-vacancy (NV) centers to perform nanoscale quantum sensing and imaging of magnetic domains and spin fluctuations in twisted double trilayer (tDT) chromium triiodide CrI_3. We show that intrinsic moiré domains of opposite magnetizations appear over arrays of moiré supercells in low-twist-angle tDT CrI_3 [1]. In addition, spin fluctuations measured in tDT CrI_3 reveal two distinct magnetic phase transitions with separate critical temperatures within a moiré supercell. Our results enrich the current understanding of exotic magnetic phases sustained by moiré magnetism and highlight the opportunities provided by quantum spin sensors in probing microscopic spin related phenomena on two-dimensional flatland. Lastly, I will extend my discussion to briefly present our ongoing efforts on exploring next-generation van der Waals quantum sensing technologies using color centers beyond NVs [2, 3].

References:

[1] M. Huang et al., *Nat. Commun.* 14, 5259 (2023).
[2] M. Huang et al., *Nat. Commun.* 13, 5369 (2022).
[3] J. Zhou et al., *Science Advances* 10, eadk8495 (2024).

Magnetic properties of orbital Chern insulators in graphene moiré heterostructures

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Moiré superlattices, which arise from small rotational misalignment between layers in van der Waals heterostructures, provide a powerful way to control the interactions and topology of electronic bands. For example, small-angle twisted monolayer-bilayer graphene (tMBG) features narrow moiré minibands with Chern numbers that could be tuned by the electric displacement field. My talk will focus on quantum anomalous Hall (QAH) states that emerge in tMBG. In contrast to magnetically doped topological insulators, these QAH states are driven by intrinsic strong interactions, which polarize the electrons into a

single moiré miniband with Chern number of C = 2. The magnetization of these “orbital Chern insulators” (OCI) arises predominantly from the orbital motion of the electrons rather than the electron spin. This orbital character of the magnetization allows one to control its magnitude and even change the sign by gate-tuning the chemical potential. Such curious magnetic properties of OCIs enable non-volatile electrical switching of the magnetic and topological orders. In addition to QAH states at integer fillings of the moiré superlattice unit cell, tMBG also features QAH states at half-integer fillings. These states are consistent with topological charge density wave states that partition a C=2 spin- and valley-polarized band into two C=1 sub-bands by the spontaneous doubling of the superlattice unit cell.

Layered materials for (quantum) photonics

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Exciton-polaron spectroscopy of moiré heterostructures

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In transition metal dichalcogenide semiconductors, momentum-direct electrons and holes at ±K valleys form tightly bound intralayer excitons. When dressed by a Fermi sea, these excitons form many-body states described as attractive exciton–polarons (AP) and repulsive exciton–polarons which exhibit distinct behavior depending on the valley hosting the Fermi sea. For doping at ±K, dominant phase-space-filling effects cause an overall blueshift in the AP, whereas doping at other valleys leads to a continuous redshift due to bandgap renormalization. Contrasting properties in an applied magnetic field also manifest for excitons dressed by carriers in different valleys: K-valley holes are highly spin polarized and exhibit strong magnetic interactions with excitons at ±K whereas magnetic interactions are substantially reduced for carriers located at non- K-valleys. Here we will use the signatures of exciton-polaron behavior to uncover different band-structures in homo-TMD devices (monolayers and bilayers) as well as in moiré heterostructures where strongly correlated states are observed in both K-valley and Γ-valley derived moiré bands.

Extended spatial coherence of interlayer excitons in $MoSe_2/WSe_2$ heterobilayers

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We report on the spatial coherence of interlayer exciton ensembles as formed in $MoSe_2/WSe_2$ heterostructures and characterized by point-inversion Michelson-Morley interferometry below a bath temperature of 10 K. The measured spatial coherence length of the interlayer excitons reaches values equivalent to the lateral expansion of the exciton ensembles. I will discuss how this coherence can be understood as a fingerprint for a possible exciton condensation at low temperature.
I thank the very fruitful collaboration with M. Troue, J. Figueiredo, A. Knorr, and U. Wurstbauer, and acknowledge financial support from the DFG and MCQST.

Slip avalanche and non-volatile optical switch in rhombohedral stacked MoS_2

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The tunability of the stacking order in van der Waals materials provides a new and powerful method to engineer their physical properties. In parallel-stacked transition metal dichalcogenides, also known as the rhombohedral stacking order, the equilibrium atomic structure is asymmetric between layers, leading to a spontaneous electrical polarization. Under an external electric field, the layer configuration and its associated polarization can be switched - a phenomenon recently termed as sliding ferroelectricity. We experimentally measured the polarization strength and its spatial distribution in chemically synthesized rhombohedral MoS_2. We observed that the domain size distribution follows a power-law distribution, suggesting that the shear strain occurring during the mechanical exfoliation can induce an avalanche of domain wall motion. These pre-existing domain walls were found to be crucial for the polarization switching behavior and we leveraged them to achieve a non-volatile control over the optical response of these layered semiconductors.

Exciting Moiré Materials for Quantum Matter

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The study of strongly interacting electrons in moiré heterostructures of semiconducting transition metal dichalcogenides (sTMDs), such as WSe2 and WS2, has led to the discovery of long sought-after quantum phases and behavior. In addition, strong light-matter interactions in sTMDs give rise to robust optically active excitons and their charged complexes. However, a system of strongly interacting excitons in TMDs remains largely unexplored.

In this talk, I will begin by presenting our recent observation of many-body interaction-induced transition between quadrupolar and dipolar excitons in a trilayer van der Waals heterostructure of sTMDs. This many-exciton transition can be attributed to anisotropic nature of dipolar interactions. Next, I will present a system of correlated electrons and moiré excitons as a rich platform to study and create quantum matter in a driven-dissipative setting.

Near-coherent Quantum Emitters in Hexagonal Boron Nitride with Discrete Polarization Axes

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Coherent single photon sources are a central component of scalable photonic quantum technologies [1]. Among solid state sources, the 2D material hexagonal boron nitride (hBN) has attracted increasing interest due to reports of bright, stable linearly-polarized quantum emitters with a broad range of emission wavelengths [2,3]. However, none of the hBN quantum emitters reported to date possess the combination of properties needed for deterministic incorporation in scalable on-chip devices – in particular a consistent, reproducible emission energy, near-lifetime-limited linewidths, and discrete polarization axes within the hBN crystal lattice. Whilst each of these properties has been observed for some hBN emitters in isolation [4,5], all three are needed for their deterministic integration in quantum coherent devices.

Of the various quantum emitters observed in hBN, the B center defect is compelling because it can be engineered on demand with a site-specific fabrication technique, and it has a highly-reproducible emission wavelength [6,7]. Consequently, the defect was used in preliminary demonstrations of photon indistinguishability [8] and of incorporation in rudimentary devices [9]. However, exploitation of the B center in practical quantum coherent systems requires the combination of a long photon coherence time, and a discrete number of well-defined polarization axes within the hBN crystal lattice.

Here we use spectral hole burning (SHB) spectroscopy to sidestep linewidth broadening caused by spectral diffusion [10], and observe near-lifetime-limited lines of a few hundred MHz. Dual resonant lasers are employed via coupling to a common single mode launching fiber, and resonance fluorescence from B centers is detected through the phonon sideband. A high power pump laser at fixed wavelength saturates a subensemble of the optical transition space, and a second lower power probe laser scans across the saturated region to produce a resonant photoluminescence spectrum with a characteristic Lorentzian dip or “hole”. The hole width is proportional to the homogeneous linewidth, i.e. the linewidth due only to energy-time uncertainty and electron-phonon interactions during spontaneous emission. In the low power limit (Fig 1a) the homogeneous linewidth is close to the lifetime limit, indicating a small presence of phonon dephasing.

To further analyse the extent of emission variation we perform resonant emission polarization measurements over dozens of B center sites. Orientation statistics show that the B center has one of three discrete in-plane polarization axes separated by 60° (Fig 1b). This clustering can be explained within the framework of Jahn-Teller (JT) distortion of the proposed negatively charged nitrogen split interstitial

defect. Density functional theory simulation shows that the ground state wavefunction inherits the threefold C_{2v} symmetry from the hBN crystal lattice, but JT distortion in the excited state breaks the symmetry leading to linearly polarized emission along one of three directions correlated with the host lattice.

These results are significant as they suggest that, absent spectral diffusion, the B center can be expected to source coherent single photons suitable for quantum photonics applications. The uniformity of emission extends to polarization, with only three possible orientations seen across a single flake domain region. This feature could be leveraged for optimal cavity coupling, opening up emission rate enhancement and further improving the coherence properties.

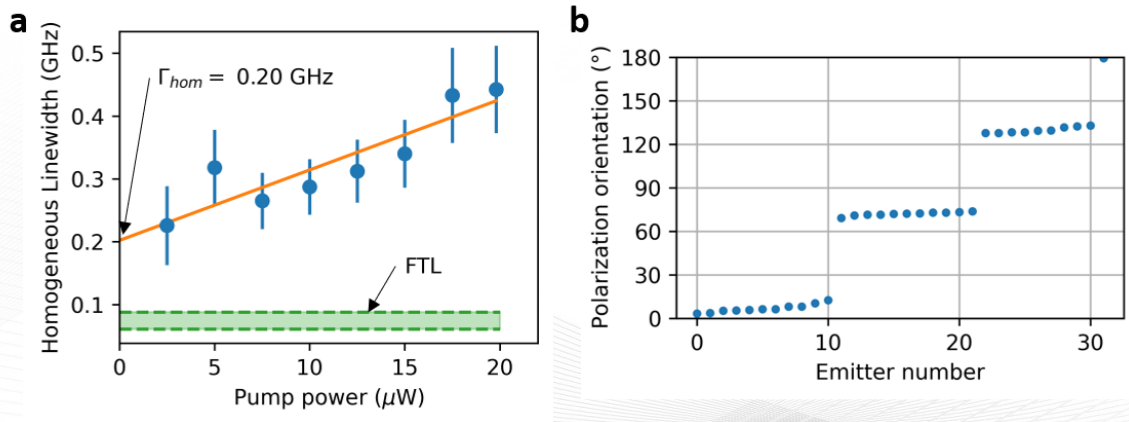

Fig. 1. Single photon coherence and polarization orientation. a) Homogeneous linewidth extracted from power dependent holes burned into the resonant luminescence spectrum from an ensemble of B centers. The power-independent linewidth Γ_{hom} = 200 MHz is close to the Fourier transform limit (FTL) of ~80 MHz. b) Emission polarization measurements under circularly polarized resonant excitation reveal a discrete clustering of values, indicating the in-plane optical dipole takes one of three orientations correlated with the hBN lattice symmetry.

References

[1] J. Wang, F. Sciarrino, A. Laing, and M. G. Thompson, Integrated Photonic Quantum Technologies, Nat. Photonics 14, 5 (2020).

[2] N. Chejanovsky et al., Structural Attributes and Photodynamics of Visible Spectrum Quantum Emitters in Hexagonal Boron Nitride, Nano Lett. 16, 7037 (2016).

[3] N. R. Jungwirth and G. D. Fuchs, Optical Absorption and Emission Mechanisms of Single Defects in Hexagonal Boron Nitride, Phys. Rev. Lett. 119, 057401 (2017).

[4] A. Dietrich, M. Bürk, E. S. Steiger, L. Antoniuk, T. T. Tran, M. Nguyen, I. Aharonovich, F. Jelezko, and A. Kubanek, Observation of Fourier Transform Limited Lines in Hexagonal Boron Nitride, Phys. Rev. B 98, 081414 (2018).

[5] D. Zhong, S. Gao, M. Saccone, J. R. Greer, M. Bernardi, S. Nadj-Perge, and A. Faraon, Carbon-Related Quantum Emitter in Hexagonal Boron Nitride with Homogeneous Energy and 3-Fold Polarization, Nano Lett. 24, 1106 (2024).

[6] C. Fournier et al., Position-Controlled Quantum Emitters with Reproducible Emission Wavelength in Hexagonal Boron Nitride, Nat. Commun. 12, 3779 (2021).

[7] J. Horder, S. J. U. White, A. Gale, C. Li, K. Watanabe, T. Taniguchi, M. Kianinia, I. Aharonovich, and M. Toth, Coherence Properties of Electron-Beam-Activated Emitters in Hexagonal Boron Nitride Under Resonant Excitation, Phys. Rev. Appl. 18, 064021 (2022).
[8] C. Fournier, S. Roux, K. Watanabe, T. Taniguchi, S. Buil, J. Barjon, J.-P. Hermier, and A. Delteil, Two-Photon Interference from a Quantum Emitter in Hexagonal Boron Nitride, Phys. Rev. Appl. 19, L041003 (2023).
[9] M. Nonahal, J. Horder, A. Gale, L. Ding, C. Li, M. Hennessey, S. T. Ha, M. Toth, and I. Aharonovich, Deterministic Fabrication of a Coupled Cavity–Emitter System in Hexagonal Boron Nitride, Nano Lett. 23, 6645 (2023).
[10] R. Purchase and S. Völker, Spectral Hole Burning: Examples from Photosynthesis, Photosynth. Res. 101, 245 (2009).

Quantum sensing at megabar pressures

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Pressure alters the physical, chemical and electronic properties of matter. By compressing a material between two opposing brilliant cut diamonds, the diamond anvil cell enables tabletop experiments to reach pressures more than a million times that of atmospheric pressure. Since its development over half a century ago, it has enabled experiments to directly access pressure as a thermodynamic tuning parameter and has had a dramatic impact on quantum science, chemistry and materials physics. Among these impacts, a tremendous amount of recent attention has focused on the discovery of superconductivity in a class of hydrogen-based materials. When compressed to megabar pressures, these so-called super-hydrides are believed to exhibit the highest known critical temperatures, and have led to a nascent field that is equal parts exciting and controversial. Part of this controversy stems from the nature of the tool itself: especially at high pressures, it is tremendously challenging to extract local information from within a diamond anvil cell.
In this talk, I will describe a new approach to directly "see" the physics inside the science chamber of a diamond anvil cell at ultra-high pressures. The basic idea is deceptively simple: We directly integrate a thin layer of sensors into the surface of the diamond anvil that is actually applying the pressure. I will demonstrate the ability to perform diffraction-limited imaging of both stress fields and magnetism, with the latter allowing us to image the magnetic field expulsion associated with superconductivity. Applying our techniques to cerium hydride, we observe the dual signatures of superconductivity: diamagnetism characteristic of the Meissner effect and a sharp drop of the resistance to near zero. By locally mapping both the diamagnetic response and flux trapping, we directly image the geometry of superconducting regions, showing marked inhomogeneities at the micron scale.

Bound exciton complexes as single photon sources

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Atomic defects in semiconductors are an attractive building block for solid-state quantum technology. In 2015, defects in two-dimensional (2D) semiconductors such as monolayer WSe_2 were found to exhibit single photon emission, attracting great attention as promising candidates in quantum photonic devices. These 2D semiconductors, characterized by strong excitonic effects, are expected to host a variety of defect-bound excitons that are rich in physics, inheriting the unique properties of the host crystal. However, the structural and physical origin of bound excitons remains elusive, hindering strategic defect engineering. I will discuss determination of the many-body nature of bound excitons through electro- and

magneto-optical spectroscopy [1-3]. In monolayer WS_2 substitutionally doped with Nb at parts-per-million (ppm) levels, we find that individual dopants manifest as narrow emission lines. These peaks show common features of quantum emitters such as spectral jittering, homogeneous broadening and antibunching as verified by second-order autocorrelations. Magnetic field dependence of the emitters reveal their origin to be bound exciton complexes comprising dark excitons and negatively charged Nb.

References

[1] Loh et al. "Impurity-induced emission in Re-doped WS_2 monolayers" Nano Lett. 21, 5293 (2021).
[2] Chen et al. "Gate-tunable bound exciton manifolds in monolayer $MoSe_2$" *Nano Lett*. 23, 4456 (2023).
[3] Loh et al. "Impurity-bound excitons as quantum emitters in monolayer semiconductor" Under review.

Novel Instrumentation for 2D Characterization: Combined Magneto-Optical Magneto-Transport

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Raman spectroscopy, imaging, and mapping are powerful non-contact, non-destructive optical probes of quasiparticles and fundamental physics in graphene and other related two-dimensional (2D) materials, including layered, quantum materials. An amazing amount of information can be quantified from the Raman spectra, including layer thickness, disorder, edge and grain boundaries, doping, strain, thermal conductivity, magnetic ordering, and unique excitations such as magnons and charge density waves. Most interestingly for quantum materials is that Raman efficiently probes the evolution of the electronic structure and the electron-phonon, spin-phonon, and magnon-phonon interactions as a function of laser energy and polarization, temperature, and applied magnetic field. Our unique magneto-Raman spectroscopic capabilities will be detailed, enabling spatially-resolved optical measurements while simultaneously measuring electrical transport in a back-gated graphene Hall bar device. Raman and electrical data from an hBN-graphene-hBN device operating in the quantum Hall regime will demonstrate our novel capabilities. In addition, unconventional quantization plateaus from a PNP junction created via spatial photodoping by the Raman laser will be presented. Lastly, results from a series of 2D magnetic material systems showing multi-quasiparticle interactions observable in our novel measurement system will be highlighted.

Cryomagnetic Raman and PL micro-spectroscopy of 2D materials using chiral light

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Controlling Excitons in van-der-Waals materials in tunable optical cavities

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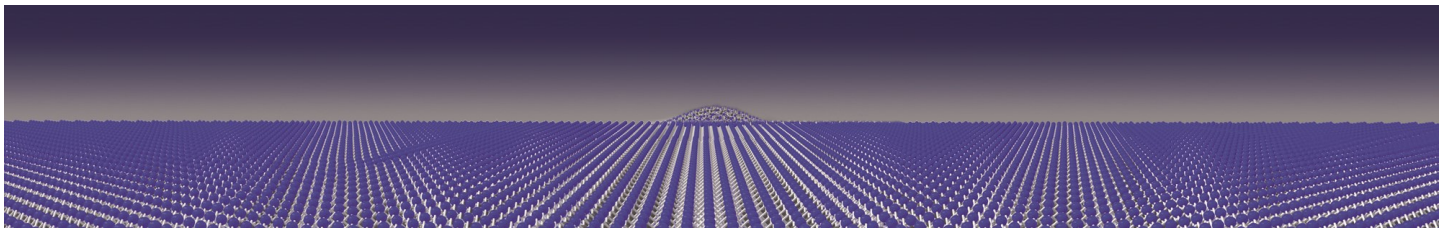
Two dimensional materials have emerged as a new and interesting platform for studies of tightly bound exciton in ultimately thin materials. Meanwhile, various types of 2D- or quasi 2D materials have become available that feature giant light-matter interactions, charge tunability, and intriguing magnetic and topological properties. These features can all be exploited for implementing novel photonic devices, and for fundamental, as well as quantum photonic investigations in the framework of cavity quantum electrodynamics [1].

I will discuss the implementation of open optical cavities in liquid helium free optical cryostats [2], which are ideally suited for the study of exciton-polaritons using 2D materials. I will address examples of such experiments, including cavity-controlled temporal dynamics of trapped excitons in the weak coupling regime, the magnetic properties of charge-correlated exciton-polaritons in the regime of strong light-matter interaction and give perspectives towards polaritonics at telecommunication wavelength.

References

[1] C. Schneider et al. *Nature Comm.* 9, 2695 (2018)
[2] M. Syperek et al. *Nature Comm.* 13, 6313 (2022)
[3] J. Drawer, V. Mitryakhin et al. *Nano letters,* 23 8683 (2023)



Scan-probe Imaging Optical Quasiparticles in 2D Materials

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Landau phonon polaritons in Dirac heterostructures

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The ability to create and control polaritons, which are hybrid light-matter quasiparticles, is crucial for advancing the field of nanophotonics. In this talk, I will demonstrate the creation and modulation of a novel collective excitation mode referred to as Landau-phonon polariton (LPP) in a quantized manner using magnetic fields. This mode is rooted in the strong coupling between Landau polaritons (inter-Landau level magnetoexcitons) in charge-neutral graphene and phonon polaritons in its adjacent hBN layers. We show the total 'shutdown' of LPP propagation using magnetic control and the probing of ‘forbidden’ Landau level transitions. Our approach establishes magneto-nanoscopy, an s-SNOM coupled with a high magnetic field up to 7T, as a versatile platform for exploring polaritons and quantum Hall physics at the nanoscale. Our preliminary research also sets the stage for future spectroscopic investigations of the topological and chiral photonic phenomena in complex quantum materials using low-energy photons.

IR and THz nanoscopy of ultra-confined phonon and plasmon polaritons

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Phonon and plasmon polaritons – light strongly coupled to optical lattice vibrations and electron oscillations, respectively - can exhibit ultra-short wavelengths, long lifetimes and strong field confinement, which allows for manipulating IR and THz fields at the nanometer scale. Here we use scattering-type scanning near-field optical microsocpy (s-SNOM) and nanoscale Fourier transform (nano-FTIR) spectroscopy to study in real space stong light-matter interaction between IR phonon polaritons in h-BN nanoresonators and molecular vibrations in adjacent organic layers, IR phonon polaritons in large-scale CVD grown h-BN multilayers and in-plane anisotropic THz plasmon polaritons in monoclinic silver telluride platelets.

Structurally engineered α-MoO3 materials for anisotropic phonon polaritonics

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Manipulating photons at the nanoscale and developing low-loss on-chip photonic and optoelectronic devices are the focus of research in the field of nanophotonics. The key issue is how to achieve high confinement and propagation control of light in the 2D plane. Polaritons, hybrid light-matter waves, enable nanoscale control of light. Particularly large polariton field confinement and low losses have been found in graphene and 2D van der Waals materials.
Here, we present our recent progress in manipulating in-plane hyperbolic phonon polaritons from the perspective of material engineering. Firstly, by fabricating twisted α-MoO_3 bilayers [1] and van der Waals heterostructures, we experimentally observed photonic magic angles and tunable topological transitions of phonon polaritons. At the transitions, the photonic dispersion flattens, exhibiting low-loss tunable polariton canalization and diffractionless propagation. Secondly, via structural engineering, we demonstrate unidirectional excitation and diffraction of hyperbolic polaritons [2] and low-symmetry Bloch modes in hyperbolic polaritonic crystals [3]. Lastly, we show monolithic-structured van der Waals hyperbolic crystals for planar refraction and focusing of volume-confined phonon polaritons. [4].

References

[1] G. Hu, Q. Ou, G. Si, Y. Wu, J. Wu, Z. Dai, A. Krasnok, Y. Mazor, Q. Zhang, Q. Bao, C.-W. Qiu, A. Alù, *Nature* **2020**, *582*, 209.
[2] Q. Zhang, Q. Ou, G. Si, G. Hu, S. Dong, Y. Chen, J. Ni, C. Zhao, M. S. Fuhrer, Y. Yang, A. Alù, R. Hillenbrand, C.-W. Qiu, *Sci. Adv.* **2022**, *8*, eabn9774.
[3] J. Lv, Y. Wu, J. Liu, Y. Gong, G. Si, G. Hu, Q. Zhang, Y. Zhang, J. X. Tang, M. S. Fuhrer, H. Chen, S. A. Maier, C. W. Qiu, Q. Ou, *Nat. Commun.* **2023**, *14*, 3894.
[4] Y Wu, J Liu, W Yu, T Zhang, H Mu, G Si, Z Cui, S Lin, B Zheng, CW Qiu, H. Chen, Q. Ou, **2024**, https://doi.org/10.21203/rs.3.rs-3891525/v1. Accepted by *ACS Nano*.

Engineer polaritons in van der Waals materials

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The manipulation of light at small scales is one of the ultimate goals for nanophotonics. For this purpose, polaritons—hybrid light-matter waves propagating in a confined length scale—are typically involved. Recent results of polaritons in van der Waals (vdW) materials reveal a series of advances, including atomic-scale localization, dynamic tunability, relative low-loss, and topologically protected states. These advances are attributed to the unique physical properties of reduced dimensions. In this talk, I will describe the new

advances of polaritons by van der Waals engineering. I will start with the vdW stacking, where dynamic tunability, loss elimination, and charge transfer can be implemented to control polaritons. In addition to stacking, the polariton wavefronts can be delicately engineered by twisting extremely anisotropic biaxial crystals. Moreover, microstructuring vdW crystals lead to evident alteration of the reflection phase of nano-polaritons following a fundamental math principle. Furthermore, a new materials engineering method can be established by strategically positioning various isotopes into isotope heterostructures, where we showcased this method in engineered new energy-momentum dispersions for hyperbolic polaritons.

Scanning SQUID-on-tip microscopy of 2D and chiral magnetism

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The ability to map magnetic field sensitively and on the nanometer-scale – unlike global magnetization or transport measurements – overcomes ensemble or spatial inhomogeneity in systems ranging from arrays of nanometer-scale magnets, to superconducting thin films, to strongly correlated states in van der Waals heterostructures. Local imaging of nanometer-scale magnetization, Meissner currents, or current in edge-states is the key to unraveling the microscopic mechanisms behind a wealth of new and poorly understood condensed matter phenomena.
I will discuss efforts in our group aimed at developing and applying high-sensitivity, high-resolution, non-invasive magnetic scanning probes. In particular, we have been developing superconducting sensors, based on nanometer-scale superconducting quantum interference devices fabricated at the apex of a scanning probe tip. I will discuss recent imaging experiments with these tools on 2D and chiral magnets, including $Cr_2Ge_2Te_6$, CrSBr, Cu_2OSeO_3, which yield new insights into their underlying magnetism.

Magnetic imaging of integer and fractional Chern insulating states in $tMoTe_2$

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Fractional Chern insulators (FCIs) [1–7] are topologically ordered two-dimensional (2D) electronic ground states that generalize the fractional quantum Hall (FQH) effect to partially occupied lattice bands. Crucially, the electron–electron Coulomb interaction in FCIs is controlled by the lattice spacing rather than the magnetic length, thus potentially enabling higher energy scales. Recently, twisted bilayers of molybdenum ditelluride ($tMoTe_2$) have been shown via transport and optical measurements to host FCI states that persist to zero external magnetic field [3–6], but the direct local characterization of the magnetic order and associated thermodynamic gaps is still lacking. Here, we use nanoSQUID-on-tip microscopy to measure the local magnetization of $tMoTe_2$ as a function of the gate-tuned charge carrier density and electric displacement field. We observe robust signatures of orbital magnetization originating from chiral edge modes at filling factors of −1, −2/3, and −3/5, consistent with previous reports of integer and fractional Chern insulating states. Samples typically exhibit a high degree of disorder on the sub-micrometer length scale, attributable to spatial variations in twist angle, displacement field offset, and charge carrier density offset. Quantitative analysis allows us to locally determine the thermodynamic gap associated with each

insulating state, revealing significantly greater values compared to those obtained through optical and transport experiments that average over larger spatial areas.

References

[1] Spanton, E.M., Zibrov, A.A., Zhou, H. et al. Science 360, 62–66 (2018).
[2] Xie, Y., Pierce, A.T., Park, J.M. et al. Nature 600, 439–443 (2021).
[3] Cai, J., Anderson, E., Wang, C. et al. Nature 622, 63–68 (2023).
[4] Zeng, Y., Xia, Z., Kang, K. et al. Nature 622, 69–73 (2023).
[5] Park, H., Cai, J., Anderson, E. et al. Nature 622, 74–79 (2023).
[6] Xu, F., Sun, Z., Jia, T. et al. Phys. Rev. X 13, 031037 (2023).
[7] Lu, Z., Han, T., Yao, Y. et al. Nature 626, 759–764 (2024).

Correlated kinetic magnetism of electrons in semiconductor moiré materials

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Since the discovery of magic-angle twisted bilayer graphene, moiré bilayers consisting of two monolayers of van der Waals materials have emerged as a highly-tuneable platform for accessing novel correlated phases of matter. A small twist angle and/or a lattice mismatch between the constituting monolayers in these structures gives rise to a superlattice potential that breaks the electronic bands into a series of flat moiré minibands, which in turn sizably enhances the stability of correlated electronic phases. Recently, this approach has led to the observation of a plethora of exotic electronic states, ranging from Mott-Wigner crystals to fractional Chern insulators.

In this talk, I will describe our low-temperature spectroscopic experiments on magnetism of electrons in the vicinity of a Mott insulating state in angle-aligned, AA-stacked $MoSe_2/WS_2$ heterobilayer [1]. Owing to a strong, triangular moiré superlattice potential, the electrons forming a Mott state in such a structure are deeply localized within their moiré lattice sites, which renders their exchange interactions to be vanishingly small. However, as soon as the Mott state is doped with electrons that form doublons at already-occupied sites, the system begins to exhibit prominent ferromagnetic correlations, with the corresponding Curie-Weiss temperature being proportional to the number of doublons. As proven by our density-matrix-renormalization-group (DMRG) calculations, this ferromagnetism is not driven by inter-electron exchange interactions, but by the minimization of the kinetic energy of doublons through the Nagaoka mechanism. Such a kinetic origin of ferromagnetic correlations in our system is further confirmed a sizable drop in critical temperature that we observe at 4/3 filling factor of the moiré lattice, where the doublons form a Mott-Wigner state in which their mobility is strongly suppressed. These observations constitute a direct evidence for kinetic Nagaoka magnetism in an extended, two-dimensional system.

References
[1] L. Ciorciaro, T. Smoleński, I. Morera, N. Kiper, S. Hiestand, M. Kroner, Y. Zhang, K. Watanabe, T. Taniguchi, E. Demler, A. Imamoğlu, Kinetic Magnetism in Triangular Moire Materials. Nature 623, 509 (2023)

Intrinsic exchange bias effect in $MnBi_2Te_4$ family

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As an A-type antiferromagnetic materials, the interlayer coupling of $MnBi_2Te_4$ materials can be extensively tuned by inserting non-magnetic Bi_2Te_3 layers or introducing Mn-Bi site-mixing defects. The combination of strong interlayer ferromagnetic coupling and tunable interlayer antiferromagnetic will result rich magnetic ground orders. Through reflection magnetic circular dichroism spectroscopy, we elucidate the antiferromagnetic-ferromagnetic coexisting magnetic orders in $MnBi_4Te_7$ and $MnBi_6Te_{10}$ and explore the tunable exchange bias induced by these antiferromagnetic-ferromagnetic coexisting magnetic orders. We further report an unprecedented exchange bias phenomenon with unique characteristics induced in ultrathin uncompensated antiferromagnetic $MnBi_2Te_4$, in which the magnitude and direction of the exchange bias field can be intentionally controlled by designing a magnetic field sweep protocol without the need for a complicated field cooling process.

Novel 2D magnets and dielectrics

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The recent progress in methods of high quality and low defect 2D magnetic materials will be discussed. Beside the group of transition metal halides and chalcogens also the rapidly growth family of mixed halogen-chalcogenides will be introduced. The dominantly explored material, chromium sulfo-bromide adopt FeOCl structure and possess A type antiferromagnetic ordering at low temperature. By various methods of exfoliation or defect formation, this material can be converted to ferromagnetic state. The chemistry of CrSBr including doping and possible covalent and non-covalent functionalization and its effect on magnetic and optical properties will be presented together with possible applications in electronic devices. Beside the two dimensional magnets, the 2D dielectric exhibit important group of materials with crucial rule in device fabrication. The broad spectra of novel high-k 2D dielectric materials growth and applications will be presented together with large scale crystal growth of hexagonal boron nitride at atmospheric pressure using various metal flux.

Adaptive learning for quantum sensing

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I will describe our effort to develop "smart" spin-based quantum sensors that self-optimise themselves to operate in the regime of maximum sensitivity [1-4]. I will present an adaptive approach, based on Bayesian estimation, to estimate the key decoherence timescales (T1, T2* and T2) and the corresponding decay exponent for a single qubit, using information gained in preceding experiments. This approach reduces the time required to reach a given uncertainty by a factor up to an order of magnitude, depending on the specific experiment, compared to curve fitting data taken on a pre-determined parameter range. I will further describe our current work on real-time optimization with pulse sequences developed by model-aware reinforcement learning [5]. Smart quantum architectures, that self-optimise themselves to automatically operate with optimal settings, will significantly facilitate the adoption of quantum technologies by non-expert users.

In the last part of my talk, I will describe our new Attocube/QZabre scanning probe single-spin quantum sensing system, and how it can be used to investigate novel physics in 2D heterostructures.

References

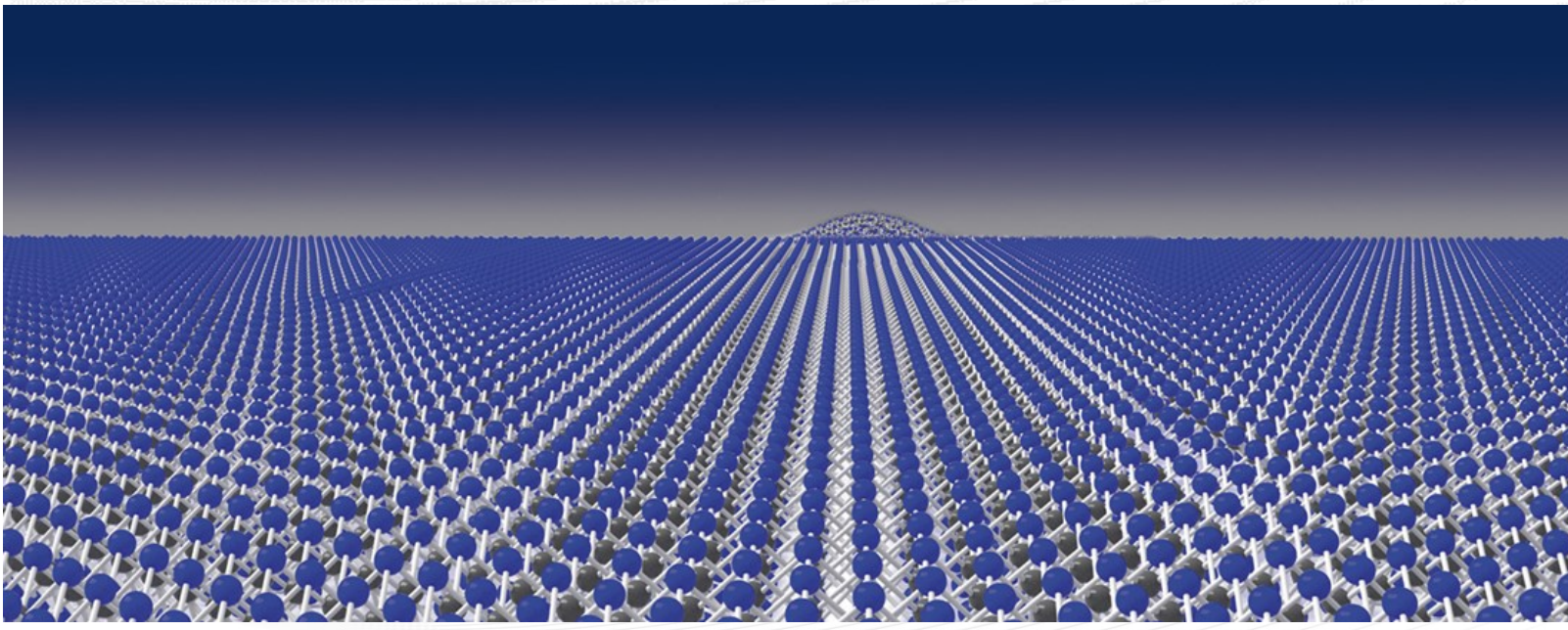
[1] C. Bonato et al, “Optimized quantum sensing with a single electron spin using real-time adaptive measurements”, Nature Nanotechnology 11, 247-252 (2016)

[2] H. Dinani et al, “Bayesian estimation for quantum sensing in the absence of single-shot detection”, Phys. Rev. B 99, 125413 (2019)

[3] M. J. Arshad et al, “Online adaptive estimation of decoherence timescales for a single qubit”, Physical Review Applied 21, 024026 (2024)

[4] V. Gebhart et al, “Learning Quantum Systems”, Nature Reviews Physics 5, 141 (2023)

[5] F. Belliardo et al, “Applications of model-aware reinforcement learning in Bayesian quantum metrology”, arXiv: 2403.05706 (2024)



Poster Session

Thursday | June 6, 2024

P1. Controlled Growth of BiSb(Te1-ySey)3 Nanocrystals 3D Topological Insulator by Chemical Vapor Transport

Nour Abdelrahman[1,2], Titouan Charvin[1], Samuel Froeschke[1], Romain Giraud[1], Alexey Popov[1], Sandra Schiemenz[1], Daniel Wolf[1], Bernd Büchner[1], Michael Mertig[1], Silke Hampel[1]

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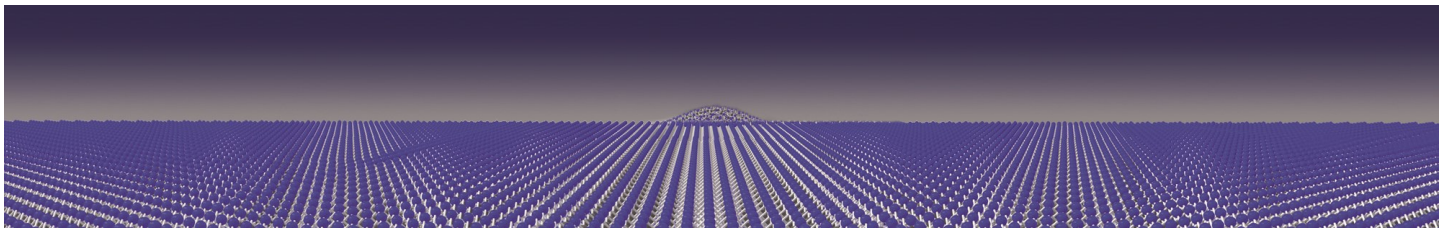
Since its discovery, three-dimensional (3D) topological insulator (TI) attracted attention with their unique spin-momentum locked surface states. 3D TI materials are characterized by a full insulating gap in the bulk and gapless surface states which are protected by time-reversal symmetry caused by strong spin-orbit interactions. Charge transfer in these surface states is less sensitive to defects and disorder compared to the ordinary conductive materials. A number of materials have been studied to be 3D TI, as the prototypical Bi_2Te_3, Bi_2Se_3, and Sb_2Te_3 compounds, followed by ternary compunds $(Bi_{1-x}Sb_x)_2Te_3$ or $Bi_2(Se_{1-x}Te_x)_3$ and the more complicated quaternary compounds as $(Bi_{1-x}Sb_x)2Te_{1-y}Se_y)_3$ (BSTS). Quaternary system BSTS is an attractive candidate to study the nature of surface states by tuning the Dirac point through controlling the proportion of pnictogen (Bi and Sb) and chalcogen (Se and Te) atoms. Here very high-quality nanocrystals are required which were synthesised by chemical vapour transport (CVT) without adding a transport agent and resulting in well-faceted single crystals. We studied the structural and magnetotransport properties of the system $BiSb(Te_{1-y}Se_y)_3$ (Se = 0.0, 0.01, 0.02,....0.09). The chemical composition and structure of the nanocrystals were analyzed by energy dispersive X-ray spectroscopy, scanning electron microscopy, and atomic force microscopy. The high quality of the grown nanocrystals and the $R\bar{3}m$ crystal structure was confirmed by high-resolution transmission electron microscopy as well as magnetotransport measurement.



P2. Near - field optical microscopy of complex plasmonic excitations

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In this work, we experimentally and theoretically study surface plasmon polaritons (SPPs) on atomically flat single crystalline gold platelets of both long- and short-range types. Short-range surface plasmon polaritons are difficult to observe compared to long-range SPPs due to high attenuation losses, which shorten their propagation length. To investigate the complete SPP interference pattern on single crystalline gold platelets, we utilize a reflection s–SNOM combined with a tunable broadband laser source. We disentangle excitations coming both from the scanning tip and the gold platelet edges by applying a Fourier analysis method. This allows us to determine the SPP wavelength and furthermore identify hidden excitations covered by interference of other channels. Fourier filtering makes it possible to identify the propagation direction of short-range surface plasmon polaritons, as well as their propagation length. We explore the impact of platelet thickness on the short-range SPP wavelength, which in the future will give us another tuning parameter for scaling and combining complex near-field optical microscopy with topological plasmonics. In addition to this, we delve into the analysis of how the excitation of surface plasmon polaritons is influenced by polarization. Towards the end of this research work, we explore methods to manipulate the interference patterns of SPPs by employing focused ion beam milling to fabricate structures such as circles or hexagons on the surface of gold platelets.

P3. Multiple & spectrally robust photonic magic angles in reconfigurable □-MoO3 trilayers

José Álvarez-Cuervo[1], J. Duan[1,2], G. Álvarez-Pérez[1,2], C. Lanza[1,2], K. Voronin[3], A.I.F. Tresguerres-Mata[1,2], N. Capote-Robayna[3], A. Tarazaga Martín-Luengo[1,2], J. Martín-Sánchez[1,2], V.S. Volkov[4], A. Y. Nikitin[3,5], P. Alonso-González[1,2]

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The assembling of twisted stacks of van der Waals (vdW) materials had led to the discovery of a profusion of remarkable physical phenomena, as it provides a means to accurately control and harness electronic band structures. This has given birth to the so-called field of twistronics. An analogous concept has been developed for highly confined polaritons[1], or nanolight, in twisted bilayers of strongly anisotropic vdW materials [2−4]. The emergence of exotic topological transitions of the polaritonic dispersion at a given twist angle (photonic magic angle) results in the propagation of nanolight along one specific direction (canalization regime), holding promises for unprecedented control of the flow of energy at the nanoscale. However, there is a fundamental limitation in current twistoptics that critically impedes such control: there is only one photonic magic angle (and thus canalization direction) in a twisted bilayer and it is fixed for each incident frequency. Here, we overcome this fundamental restriction by demonstrating the existence of multiple spectrally robust photonic magic angles in reconfigurable twisted vdW trilayers. As a result, we show that canalization of nanolight can be programmed at will along any desired in-plane direction in a single device, and, importantly, within broad spectral ranges of up to 70 cm-1. Our findings lay the foundation for robust and widely tunable twistoptics, opening the door for applications in nanophotonics where on-demand control of energy at the nanoscale is crucial, such as bio-detection, thermal management, or nanoimaging.

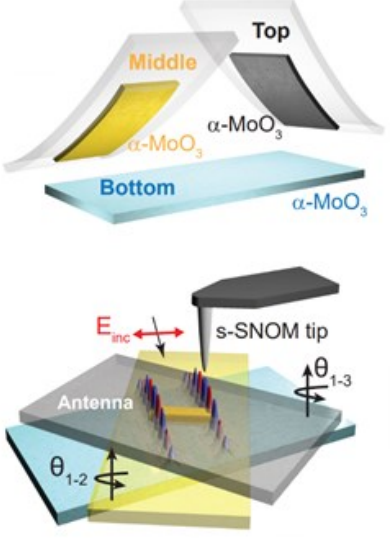

Figure 1: (a) Schematic of a twisted biaxial system made of three α-MoO3 layers. (b) Schematic of the excitation of polaritons in a twisted biaxial system by a scattering-type scanning near-field optical microscopy (s-SNOM).

References

[1] Ma, W.; Alonso-González, P.; Li, S.; et al. Nature, 562, 557−562. (2018)
[2] Duan, J.; et al. Nano Letters, 20, 5323–5329. (2020)
[3] Chen, M.; et al. Nature Materials, 19, 1307−1311. (2020)
[4[Hu, G.; et al. Nature, 582, 209−213 (2020)

P4. Hybridization of moiré excitons and trions

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We report combined experimental and theoretical studies of transition metal dichalcogenide heterobilayers with rigid moiré superlattices controlled by the twist angle. Using an effective continuum model that combines resonant interlayer electron tunneling with stacking-dependent moiré potentials, we identify the nature of moiré excitons and the dependence of their energies, oscillator strengths and Landé factors on the twist angle. Using the same framework, we interpret distinct signatures of bound complexes among electrons and moiré excitons in nearly collinear heterostacks. Our work provides fundamental understanding of hybrid moiré excitons and trions in heterobilayers, and establishes material systems like $MoTe_2/MoSe_2$ and $MoSe_2/WS_2$ as prime candidates for optical studies of correlated phenomena in moiré lattices.

P5. Imaging of quasi-bound-state-in-the-continuum properties of dielectric metasurfaces by near-field microscopy

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We study the near-field of quasi-bound-states-in-the-continuum (BIC) array metasurfaces via transmission mode scattering scanning near-field microscopy (s-SNOM). We show that the collective modes of the resonator arrays depend heavily on the array size, as well as the direction and asymmetry of its elements. We find that 10x10 is the minimum size at which the collective modes exhibit behaviours characteristic of quasi-BICs.

As an excellent tool to enhance light-matter interactions, dielectric metasurfaces supporting quasi-bound-states-in-the-continuum enable extreme field confinement and ultra-high quality factors [1] as they do not experience detrimental intrinsic absorption loss as is the case with metallic metasurfaces utilizing plasmonic modes. Except from studies using electron energy loss spectroscopy or cathodoluminescence spectroscopy [2], the near-field response of individual resonators has so far not been experimentally studied, specifically how dimensions, shape of arrays and resonator asymmetry could impact the collective quasi-BIC mode. Here we introduce imaging of quasi-BIC arrays using mid-infrared scattering scanning near-field optical microscopy (s-SNOM) in transmission mode, a technique successfully used previously to characterize the near-field response of dielectric nanostructures [3] and thus proven as an excellent tool to map the near-field distribution of single, few-µm sized resonators. Using s-SNOM, we recorded near-field images of optical amplitude and phase of pairs of tilted Silicon ellipses on CaF2 substrate at a wavelength of 5.9 µm.

We combine simulations and experimental data to determine the minimum array size at which the collective mode expresses behaviours typically associated with BICs and show that these characteristic field distributions are already detected at much smaller array sizes than far-field microscopy methods would suggest. This is done by introducing a convolution method which compares simulation and experimental images pixel-by-pixel to construct a figure of merit (FOM) which shows the strength of the collective mode. Using this method, we also examine the effects of structural defects, directional coupling and asymmetry on the near-field response. The goal of this study is to unite the domains of near-field optical microscopy and BICs and to optimise the design of future metasurfaces with respect to near-field enhancement, spatial footprint and defect tolerance.

References

[1] Kirill Koshelev, Sergey Lepeshov, Mingkai Liu, Andrey Bogdanov, and Yuri Kivshar, "Asymmetric Metasurfaces with High-Q Resonances Governed by Bound States in the Continuum," Phys. Rev. Lett. 121, 193903 (2018).
[2] Dong, Z., Mahfoud, Z., Paniagua-Domínguez, R. et al., "Nanoscale mapping of optically inaccessible bound-states-in-the-continuum," Light Sci Appl 11, 20 (2022).
[3] Yuanqing Yang, Vladimir A. Zenin, and Sergey I. Bozhevolnyi, "Anapole-Assisted Strong Field Enhancement in Individual All-Dielectric Nanostructures, " *ACS Photonics 5*, 1960-1966 (2018).

P6. Moiré Chern insulators in van der Waals bilayers

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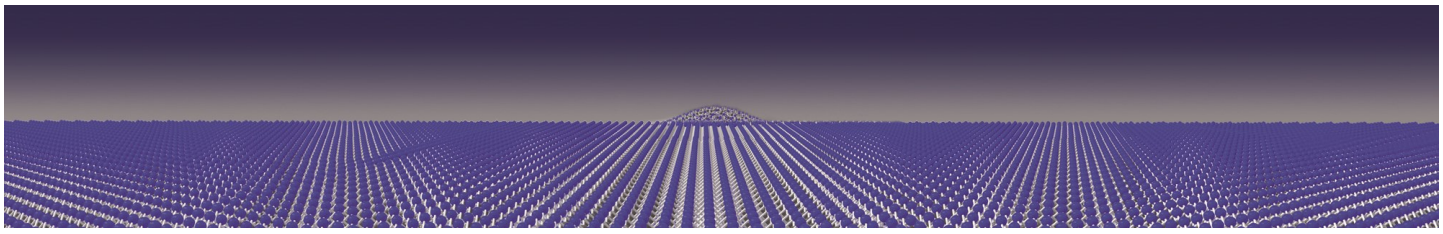
Moiré bilayers of van der Waals (vdW) materials are a versatile playground for studying the properties of Chern insulators. We present here a selection of remarkable results achieved with attocube systems technology in labs of attocube customers with emphasis on integer and fractional moiré Chern insulators (MCIs) in vdW bilayers: Scanning magnetometry of an integer MCI, $MoTe_2/WSe_2$ shows that its magnetization can be flipped with a very low current [1], which is appealing for utilization in energy-efficient magnetic memories. A magneto-optical study of the same heterostructure discovered a valley-coherent nature of the quantum anomalous Hall state in this material [2]. A scanning single electron transistor (SET) study [3] established the high field flavor phase diagram of the magic angle twisted bilayer graphene (MATBG), identified earlier as an integer MCI at high field [4]. Scanning magnetometry also reveals the mosaic of MCIs with different Chern numbers induced by local variations in the Berry curvature as a function of the filling factor [5]. Moreover, MATBG can also host fractional Chern insulating states (FCIS) even in low magnetic fields B ~ 5T [6]. Finally, FCIS that survive at B = 0 have been identified magneto-optically in twisted bilayer MoTe2 using trion sensing [7].

References

[1] C.L. Tschirhart, E. Redekop, L. Li, T. Li, S. Jiang, T. Arp, O. Sheekey, T. Taniguchi, K. Watanabe, M.E. Huber, K.F. Mak, J. Shan and A.F. Young, Nature Physics 19, 807 (2023)
[2] Z. Tao, B. Shen, S. Jiang, T. Li, L. Li, L. Ma, W. Zhao, J. Hu, K. Pistunova, K. Watanabe, T. Taniguchi, T.F. Heinz, K.F. Mak and J. Shan, Physical Review X 14, 011004 (2024)
[3] J. Yu, B.A. Foutty, Z. Han, M.E. Barber, Y. Schattner, K. Watanabe, T. Taniguchi, P. Phillips, Z.-X. Shen, S.A. Kivelson and B.E. Feldman, Nature Physics 18, 825 (2022)
[4] K.P. Nuckolls, M. Oh, D. Wong, B. Lian, K. Watanabe, T. Taniguchi, B.A. Bernevig and A. Yazdani, Nature 588, 610 (2020)
[5] S. Grover, M. Bocarsly, A. Uri, P. Stepanov, G. Di Battista, I. Roy, J. Xiao, A.Y. Meltzer, Y. Myasoedov, K. Pareek, K. Watanabe, T. Taniguchi, B. Yan, A. Stern, E. Berg, D.K. Efetov and E. Zeldov, Nature Physics 18, 885 (2022)
[6] Y. Xie, A.T. Pierce, J.M. Park, D.E. Parker, E. Khalaf, P. Ledwith, Y. Cao, S.H. Lee, S. Chen, P.R. Forrester, K. Watanabe, T. Taniguchi, A. Vishwanath, P. Jarillo-Herrero and A. Yacoby, Nature 600, 439 (2021)
[7] J. Cai, E. Anderson, C. Wang, X. Zhang, X. Liu, W. Holtzmann, Y. Zhang, F. Fan, T. Taniguchi, K. Watanabe, Y. Ran, T. Cao, L. Fu, D. Xiao, W. Yao and X. Xu, Nature 622, 63 (2023)



P7. Ultrafast THz-STM on Single Atomic Defects in 2D Semiconductors

Laric Bobzien[1,2], Jonas Allerbeck[1], Eve Ammerman[1], Lysander Huberich[1], Bruno Schuler[1]

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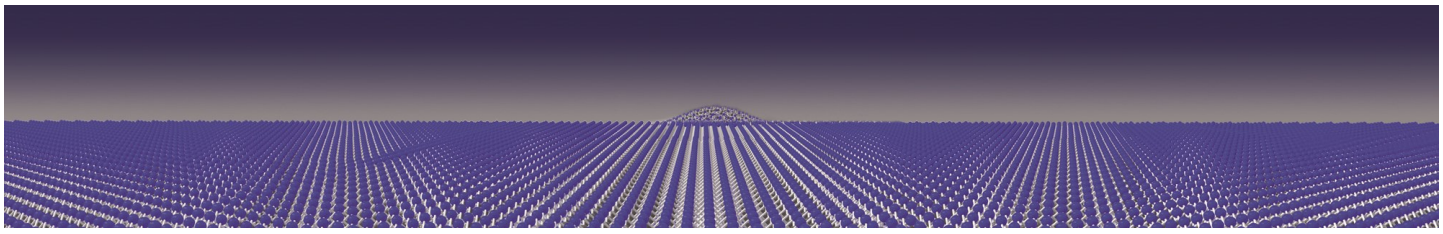
Semiconductor quantum technology has become a promising platform for next-generation electronics, enabling ultimate device miniaturization, efficiency and speed as well as chip-based optical interfacing. The robust quantum phenomena enabled by reduced dimensionality can be harvested on wafer scale platform. In our group, we strive to characterize technologically relevant 2D materials, in particular transition metal dichalcogenide (TMD) monolayers, at the atomic level by means of a low-temperature scanning tunneling microscopy (STM) and ab-initio simulations. The fundamental microscopic understanding of point defects and local quasiparticle excitations is crucial for tailoring and exploiting the electronic[1,2] and opto-electronic[3] properties of these materials for future devices.
Our group developed a cutting edge ultrafast STM designed to investigate ultrafast dynamics on the atomic scale[4]. In our lab, we generate single-cycle THz pulses for light-wave driven tunneling with picosecond time resolution while maintaining atomic spatial resolution. Ultrafast optical pulses allow us to study transient dynamics to explore TMD defects at the space-time limit. In my PhD, I aim to investigate ultrafast electron dynamics and their coupling to the lattice and light degrees of freedom to challenge our understanding of the nature at the nanoscale.

References

[1] Robinson, J. A. & Schuler, B., Applied Physics Letters 119, 140501 (2021)
[2] Feifei, X., Huberich, L. et al., Nat Commun 15, 2738 (2024)
[3] Schuler, B. et al. Science Advances 6, eabb5988 (2020)
[4] Allerbeck, J. et al., ACS Photonics (2023)



P8. A twist on 2D spintronics: orthogonally twisted CrSBr

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2D magnetic materials offer unprecedented opportunities for fundamental and applied research in spintronics and magnonics. Of particular interest is the layered metamagnet CrSBr, a relatively air-stable semiconductor formed by antiferromagnetically-coupled ferromagnetic layers (Tc∼150 K) that can be exfoliated down to the single-layer. It presents a complex magnetic behaviour with a dynamic magnetic crossover, exhibiting a low-temperature hidden order below T*∼40 K. In this work, the magneto-transport properties of CrSBr vertical heterostructures in the 2D limit are inspected. The results demonstrate the marked low-dimensional character of the ferromagnetic monolayer, with short-range correlations above Tc and an Ising-type in-plane anisotropy, being the spins spontaneously aligned along the easy axis b below Tc. By applying moderate magnetic fields along a and c axes, a spin-reorientation occurs, leading to a magnetoresistance enhancement below T*. In multilayers, a spin-valve behavior is observed, with negative magnetoresistance strongly enhanced along the three directions below T*[1]. Moreover, we fabricate an artificial magnet by twisting 90 degrees two CrSBr ferromagnetic monolayers, thus forming an 'orthogonally-twisted bilayer'[2]. The magneto-transport properties reveal multistep spin switching with a magnetic hysteresis opening, which is absent in the pristine case. By tuning the magnetic field, we modulate the remanent state and coercivity and select between hysteretic and non-hysteretic magneto-resistance scenariosThese results show that CrSBr monolayer/bilayer provides an ideal platform for studying and controlling field-induced phenomena in two-dimensions, offering new insights regarding 2D magnets and opening a fruitful playground for creating artificial magnetic symmetries and manipulating non-collinear magnetic textures their integration into vertical spintronic devices.

References

[1[Boix-Constant, C. et al. Adv. Mater. 34, 1–8 (2022).
[2] Boix-Constant, C. et al. Nat. Mater. (2023) doi:10.1038/s41563-023-01735-6.

P9. Tuning high-lying excitons in twisted WSe_2 bilayer dual-gate devices

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Interlayer excitons within few-layer systems of transition metal dichalcogenides (TMDCs) have received significant attention due to their distinctive optical and electronic characteristics. These excitons, composed of spatially separated electron-hole pairs, possess an out-of-plane dipole moment, enabling precise modulation of their emission energy by an applied electric field [1]. Moreover, interlayer excitons can occur as trions involving three particles and are not confined to band-edge states. Notably, electrons from higher conduction bands can interact with valence-band holes to form high-lying excitons emitting in the ultraviolet spectral region. Recently, our experiments have revealed the pronounced interlayer nature of these high-lying excitons and trions in bilayer WSe_2 [2]. Here, we demonstrate that the interlayer character of these species, discernible by their out-of-plane dipole moment, is remarkably tunable by the twist angle between the layers.

References

[1] Zefang Wang et al., Electrical tuning of interlayer exciton gases in WSe_2 bilayers, Nano Lett. 18, 1, 137 (2018)

[2] Kai-Qiang Lin et al., Ultraviolet interlayer excitons in bilayer WSe_2, Nat. Nanotechnol. 19, 196 (2024)

P10. Generation of luminescent defects in hBN by various irradiation methods

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Hexagonal Boron Nitride (hBN) is a van der Waals (vdW) crystal with a very wide bandgap and often used as insulating layer for other vdW materials, like graphene. Luminescent centres in hBN have recently been gathering much attention because of their brightness and their excellent quantum properties at room temperature, which would make them competitive with state-of-the-art quantum emitters [1], like the NV center in diamond.
Among the most studied luminescent centres in hBN, there is the charged Boron vacancy (VB-), which features a very broad photoluminescence (PL) spectrum centered around 850 nm, along with magnetic properties which have important applications in quantum sensing schemes [2].
In the present work, we use a Helium Ion Microscope (HIM) for irradiating hBN flakes, either on bare Si/SiO2 substrate or stacked on thick Graphite flakes, to generate luminescent centres like the VB-. We perform in-depth PL characterization of these centres at different laser excitation wavelengths, power and polarization, and at cryogenic temperature, for different hBN thicknesses and for varying HIM irradiation fluences. Our results show that this technique can systematically produce high-quality luminescent emitters, in good agreement with literature [3], and allow us to have a good benchmark for further studies on VB- emitters in hBN.

References

[1] Tran, T., Bray, K., Ford, M. et al. Quantum emission from hexagonal boron nitride monolayers. Nature Nanotech 11, 37–41 (2016). https://doi.org/10.1038/nnano.2015.242
[2] Gottscholl, A., Kianinia, M., Soltamov, V. et al. Initialization and read-out of intrinsic spin defects in a van der Waals crystal at room temperature. Nat. Mater. 19, 540–545 (2020). https://doi.org/10.1038/s41563-020-0619-6
[3] H. Liang, Y. Chen, C. Yang, et al. High Sensitivity Spin Defects in hBN Created by High-Energy He Beam Irradiation. Adv. Optical Mater. 11, 2201941 (2023). https://doi.org/10.1002/adom.202201941

P11. Developments for Synchrotron-based Infrared Near-Field Nanospectroscopy at NSLS-II*

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The study of excitations in 2D materials has benefitted greatly from near-field infrared nanospectroscopy using both lasers and broadband synchrotron infrared sources. With the exception of some highly advanced lasers, including FELs, the spectral range has been mostly limited to wavelengths shorter than 16 µm (i.e. above ~650 cm 1 or 80 meV). Recognizing that the synchrotron source performs well to much longer wavelengths, we have developed a near-field infrared nanospectroscopy capability at the 22IR2/MET beamline of the National Synchrotron Light Source II of Brookhaven Nat'l Lab (Upton, LI, NY, USA) that is now reaching wavelengths just beyond 55 µm (~180 cm^{-1}) using VLWIR MCT operating at liquid helium temperatures†. Though operation time is currently limited, due to several measurement programs sharing a single source extraction, plans are underway to develop "INF", which will be a new beamline suite dedicated mostly to nanospectroscopy. The design will allow it to cover the spectral range from near-visible down to 100 cm^{-1} (to overlap with coherent THz methods) and serve up to three endstations simultaneously.

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† See ACS Photonics, 10, 4329-4339 (2023), (https://doi.org/10.1021/acsphotonics.3c01148

P12. Full quantitative near-field characterization of plasmon-exciton polaritons in hybrid WSe_2-gold platelets devices

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Exciton-plasmon polaritons (EPPs) are hybrid states emerging from the coupling between excitons and surface plasmons. The subwavelength field localization of these polaritons makes them attractive both for the exploration of fundamental phenomena and applications in nanophotonics. While the dispersion relation of EPPs has been retrieved [1], to date no near-field experiment reported the quantitative measurement of their propagation length, associated to losses. Here, we present near-field measurements of EPPs in 13-nm-thick WSe_2 deposited on a monocrystalline gold platelet. By measuring the EPPs at different excitation energies, we reconstruct their dispersion relation. From our experimental data, we extract a Rabi splitting of about 81 meV, compared to a experimental average loss of 55 meV, which demonstrates that our system is in the strong-coupling regime. Furthermore, we extract from our measurements the propagation length of EPPs at each excitation energy. These measurements give us for the first-time access to the full complex wavevector of these polaritons at visible wavelengths. To demonstrate the quality of our data, we use the complex-valued wavevectors obtained with our near-field measurements to predict the far-field reflectivity of our sample. Our predicted reflectivity agrees very well with the reflectivity measured directly with far-field methods.

References

[1] R.B. Iyer et al., Nanoscale 14, pp. 15663-15668 (2022). DOI: 10.1039/D2NR04321A

P13. High throughput imaging of thermal conductivity and interfacial thermal conductance at the nanoscale

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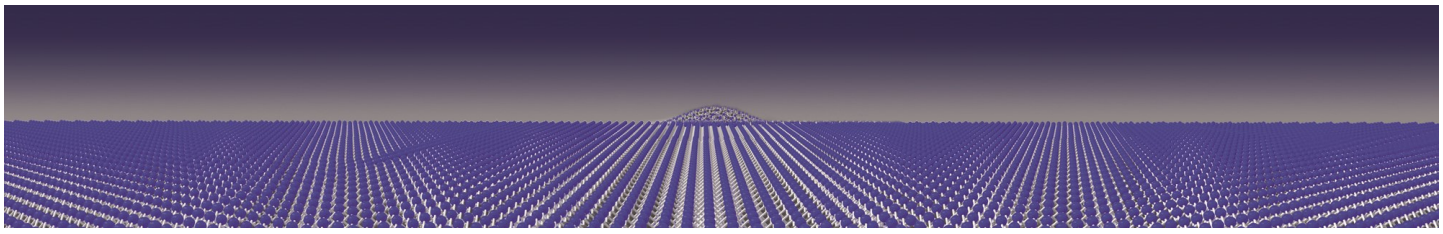
Accurate knowledge of thermal conductivity (η) and interfacial thermal conductance (G) at the nanoscale is critical for engineering thermoelectrics, memristors and other advanced electronic devices and for studying thermal transport in nanostructured or quantum materials. State of the art, time-domain thermoreflectance (TDTR) is a pump-probe technique that measures η and G by reconstructing the sample time-domain thermalization as a function of the probe delay time. However, TDTR spatial resolution is limited to the micrometer scale and requires long measurement times (≈ 120 s per point). Photothermal induces resonance (PTIR) [1,2,3], also known as AFM-IR is a scanning probe technique that uses the tip on an AFM to transduce the sample photothermal expansion and to enable IR spectroscopy at the nanoscale. However, conventional AFM probes do not have sufficient sensitivity or bandwidth to capture the fast sample thermalization linked to the sample thermal properties.
Here, we develop an optomechanical cantilever probe and customize PTIR setup to measure at the nanoscale and at once the entire time-domain sample thermal expansion that follows the absorption of IR laser pulses in the nanoscale. This novel setup measures thermalization events with ≈4 ns temporal resolution, ≈ 35 nm spatial resolution, and high sensitivity concurrently, thanks to a very low detection noise (≈ 1 fm/$Hz^{1/2}$) over a wide (125 MHz) bandwidth. Such high sensitivity, wide bandwidth measurement enables fast data acquisition (≈ 20 ms) and nanoimaging of η and G with a throughput ≈ 6000 × faster than macroscale-resolution TDTR and ≈ 500000 × faster than for measurements with conventional AFM cantilevers. [4, 5]
As a proof-of-principle demonstration, we obtain 100 × 100 pixel maps of η and G in 200 s with a small relative uncertainty (Δη ≈ 10 % and ΔG ≈ 5 %) on a ≈ 3 µm wide polymer particle. Importantly, such measurements do not require extensive probe calibration (as for other AFM-based measurements) or a metallic transducer layer on the sample (as for TDTR).
This work paves the way to study fast thermal dynamics in materials and devices with nanoscale resolution, which is critical, for example, to study the thermal properties of grain boundaries and of filaments in memristive devices.

References

[1] Centrone, A., Annu. Rev. Anal. Chem. 2015, 8 (1), 101-126.
[2] Kurouski, D. ; Dazzi, A.; Zenobi, R. ; Centrone, A, Chem. Soc. Rev., 2020, 49, 3315-3347
[3] Schwartz J.J., Jakob, D., Centrone A., Chem. Soc. Rev., 2022,51, 5248-5267
[4] Chae, J.; et al, Nano Lett. 2017, 17, 5587–5594.
[5] Wang et al. Nano Lett. 2022, 22, 11, 4325–4332



P14. Skyrmions and Josephson diode effect in 2D materials

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Atomically layered materials, held together by weak van der Waals forces, have garnered huge scientific interest ever since the isolation of high quality monolayers of graphene. These class of materials show a wide range of intriguing electrical, magnetic, and optical properties. Here we report on origin of the chiral skyrmions in Fe_3GeTe_2 (FGT) and the Josephson diode effect in Dirac semimetal $NiTe_2$.

The ferromagnetic metal FGT has a significantly high Curie temperature of ~ 220 K when compared to other 2D magnets. It has been reported earlier that FGT has a centro-symmetric crystal structure. Recently it was shown that Néel skyrmion can be stabilized in FGT as a result of interfacial Dzaloszynski-Moriya interaction (DMI). Using thorough X-ray diffraction analysis, we show that FGT lacks inversion symmetry as a result of asymmetric distribution of Fe vacancies. Furthermore, we confirm the presence of Néel skyrmions using Lorentz TEM. This vacancy- induced breaking of the inversion symmetry of this compound is a surprising new observation and a prerequisite for the bulk type of DMI, rather than interfacial DMI, responsible for the stabilization of Néel-Skyrmion [1].

In a completely different study, we demonstrate a large asymmetry (~80%) in the critical current in Josephson junctions formed from a type–II Dirac semimetal $NiTe_2$ under small magnetic fields (~10 mT). Our experimental data and theoretical analysis suggest that the 'Josephson diode effect' (JDE) is enabled by finite-momentum Cooper pairing in spin-helical topological surface states in an otherwise centrosymmetric system. The finite pairing momentum is further established, and its value determined, from the evolution of the interference pattern under an in-plane magnetic field. The observed giant JDE and a clear understanding of its underlying mechanism paves the way to building novel superconducting devices using Josephson junctions [2].

References

[1] Chakraborty, A., Srivastava, A.K., Sharma, A.K., Gopi, A.K. *et al.* Magnetic Skyrmions in a Thickness Tunable 2D Ferromagnet from a Defect Driven Dzyaloshinskii–Moriya Interaction. *Advanced Materials*, **34**, 2108637 (2022)

[2] Pal, B., Chakraborty, A., Sivakumar, P.K. *et al.* Josephson diode effect from Cooper pair momentum in a topological semimetal. *Nature Physics* **18**, 1228 (2022).

P15. Surface plasmon-polariton triggering of $Ti_3C_2T_x$ MXene catalytic activity

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The efficiency of producing green hydrogen by photo- or electrochemical water splitting highly depends on the catalyst used. As effective catalysts or cocatalysts several 2D materials have recently been proposed, and among them, oxygen-terminated MXenes deserve significant attention for electro- and photo-induced water splitting. In this work, we described a hybrid photo-electrochemical approach based on the coupling of $Ti_3C_2T_x$ MXene flakes on a plasmon-supported Au grating and light triggering of the electrocatalytic activity of the generated hybrid structure in a water splitting half reaction, namely, the hydrogen evolution reaction (HER). MXene flakes with fluor and oxygen surface terminations were deposited on a periodic patterned gold surface that was capable of supporting surface plasmon-polariton (SPP) excitation under visible and near-infrared (NIR) light illumination. SPP excitation allows sub-diffraction focusing of light energy and effective enhancement of the electrocatalytic performance of $Ti_3C_2T_x$ flakes. Under irradiation, a significant enhancement of the HER kinetics was observed, as well as tuning of the HER rate-determining step from the Volmer step to the Heyrovsky step. The several-fold enhanced hydrogen evolution was observed, which was attributed to plasmon assisted hot charge carrier injection, with an additional contribution from the plasmon heating effect. The proposed gold grating/ $Ti_3C_2T_x$ hybrid structure allows utilization of the NIR part of the solar spectrum, which is commonly not used in water photolysis but achieves better efficiency in renewable energy-assisted green hydrogen production [1]. In addition, the created Au/ $Ti_3C_2T_x$ structure exhibited good stability during long-term operation [2].

References

[1] DOI: 10.1039/d1ta04505a

[2] https://doi.org/10.1088/2053-1583/ac27c0

P16. Custom-made Scanning Gate Microscopy setups on NeaSCOPE™

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Scanning gate microscopy (SGM) is a universal tool to measure spatially resolved transconductance—modulation of drain current of the junction by varying gate voltage in a few tens of nm. The setup comprises a custom-made PCB and socket-type sample carrier. The gate voltage is locally applied by the PtIr-coated cantilever of the SGM, and weak modulation of the drain current is detected by a lock-in technique. In this experiment, we simultaneously measured the spatially resolved transconductance and the topography of the vertical graphene-WS_2-metal junction using the SGM. It could provide a unique opportunity to study the substantial carrier transfer through the vertical graphene-TMDC junction.

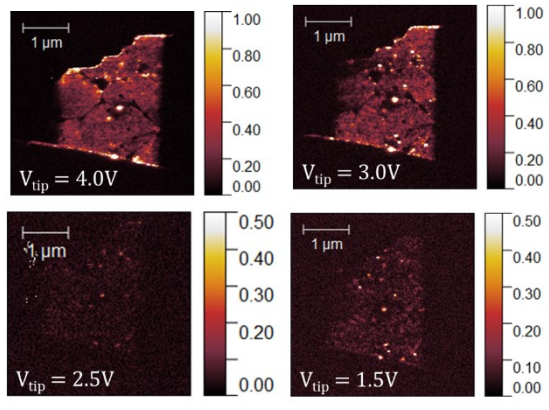

Figure 3 SGM images of graphene/WS2/metal junction barristor by varying V_{tip}.

P17. Magic-angle twisted bilayer graphene infrared single-photon detector

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The superconducting state of the magic-angle twisted bilayer graphene (MATBG) is constituted by only ~ 1011 carriers per square centimeter, five orders of magnitude lower than traditional superconductors. This ultra-low carrier density results in an exceptionally low electronic heat capacity and a large kinetic inductance [1]. These parameters make MATBG an ideal candidate for quantum sensing applications, such as thermal sensing [2] and single-photon detection (SPD). In this study, we take the first step to develop a SPD based on superconducting MATBG and perform a proof-of-principle experiment to demonstrate the capability of detecting single-photons. By voltage biasing a MATBG device near its superconducting phase transition we observe complete destruction of the SC state upon absorption of a single infrared photon even in a 16 µm2 device [3]. Our work offers insights into the MATBG-photon interaction and shows up pathways to use novel moiré superconductors as an exciting platform for revolutionary quantum devices and sensors.

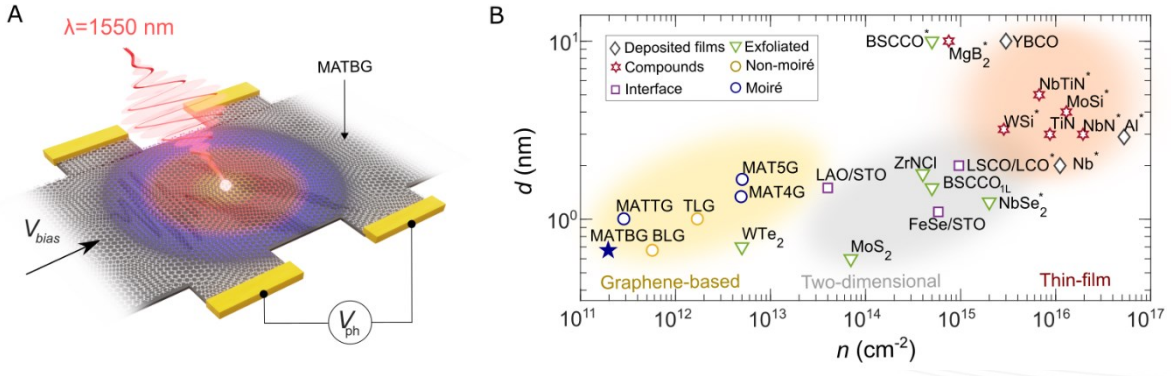

Fig. 1 Superconducting MATBG as an ultra-sensitive material for SPD. (A) The near-infrared photon, incident on the voltage-biased MATBG device, breaks Cooper pairs and generates a photovoltage output, Vph. (B) Logarithmic plot of film thickness d versus carrier density n for various superconductors. Notably, graphene-based superconductors exhibit the lowest carrier densities.

References

[1] P. Seifert et al., Nano Letters 20, 3459–3464 (2020).
[2] G. Di Battista et al., Nano Letters 22, 6465–6470 (2022).
[3] G. Di Battista et al., arXiv:2403.02049 (2024)

P18. Near-field investigations of shear phonon-polaritons in the monoclinic crystal gypsum

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Low symmetry crystals feature non-normal oscillations that result in non-zero off axis components in their permittivity tensor. Consequently, they have emerged as a new platform to study an unconventional polariton phenomena, the so-called shear polaritons, which exhibit distinct optical properties such as asymmetric light propagation and energy dissipation, and frequency-dependent optical axes.
Recently, hyperbolic shear polaritons have been observed in bulk monoclinic crystals like beta-gallium oxide and cadmium tungstate. Here, we demonstrate the observation of shear polaritons in gypsum, an exfoliable monoclinic sulphate mineral using scattering-type scanning near-field microscopy and nano-FTIR spectroscopy on mechanically cleaved flakes. We unveil hyperbolic shear polaritons and, more remarkably, elliptical shear polaritons, together with light canalization between both regimes in a narrow mid-IR frequency range. These discoveries expand the integration of low-symmetry crystals into heterostructures and photonic devices that could potentially reveal new nanoscale optical phenomena.

P19. Induced superconducting proximity effect in the flatbands of Magic Angle Twisted Bilayer Graphene

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The distinct electronic structure of magic angle twisted bilayer graphene (MATBG), marked by flat bands at specific twist angles, presents a unique platform for investigating the interplay between the Josephson effect and strong correlated states. Here we report on the creation of Josephson junctions (JJs) where the weak link is made of a MATBG sheet that is contacted on the edges by superconducting leads. This geometry, compared to previous works on gate-defined JJs [1-3], enables us to study all the phase diagram of MATBG under an induced superconducting proximity effect. First, we show how the Josephson effect behaves differently in the high dispersive bands as compared to the flat bands. Finally, we will report on a reversible superconducting diode effect, which is only observed in samples near the magic-angle and at certain fillings of the flat band.

References

[1] Rodan-Legrain, D. et al., Nature Nanotechnology 16, 769–775 (2021).
[2] de Vries, F. K. et al., Nature Nanotechnology 16, 760–763 (2021).
[3] Díez-Mérida, J. et al. Nat. Commun. 14, 2396 (2023).

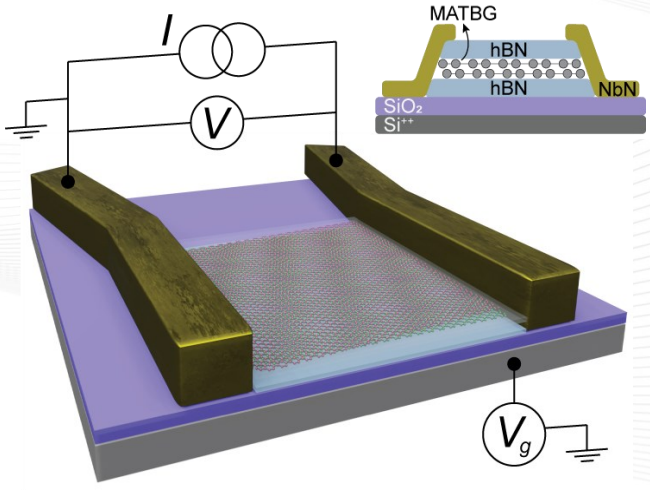

Figure 1: Schematic of our experiment, consisting of a MATBG sheet acting as the weak link of a Josephson junction.

P20. Observation of Current Whirlpools in Graphene at Room Temperature

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Classical hydrodynamics, where interparticle collisions dominate transport, can give rise to peculiar flow patterns. An analogous flow regime can also manifest itself in solid-state systems, most notably in graphene. Here we present an experiment where we imaged one of the most striking hydrodynamic transport patterns - stationary current whirlpools - in a room-temperature monolayer graphene device. Our experiment takes advantage of a scanning nitrogen-vacancy magnetometer, which is able to non-perturbatively image the current density with nanoscale resolution. We show that the appearance of vortices depends both on the characteristic device size and the carrier doping (electrons, holes) of graphene. Our demonstration opens exciting opportunities for investigating mesoscopic transport phenomena with local imaging techniques.

P21. Quantum beats between spin-singlet and spin-triplet interlayer exciton transitions in WSe_2-$MoSe_2$ heterobilayers

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The photophysical properties of the long-lived interlayer excitons (IXs) of semiconducting transition metal dichalcogenide (TMD) heterobilayers have been the focus of recent studies. These IXs have great potential to be the primary candidates for the advancement of valleytronics and optoelectronics devices in the future. Although the two IX spin states, namely spin-singlet and spin-triplet, have been experimentally confirmed1–4, the existence and the nature of the interaction between these states remain unknown to date. In this work, we demonstrate the presence of coherent coupling between the IX spin states of a WSe_2-$MoSe_2$ heterobilayer utilizing quantum beat spectroscopy via a home-built Michelson interferometer. The quantum beating signal as a signature of coherent coupling between the closely spaced transitions of IXs was observed, and corresponding dephasing times up to T_2 = 400 fs were measured. The calculated energy difference between the PL emission peaks of spin-singlet and spin-triplet IXs obtained by the measured beating period is in close agreement with the energy separation in the time-integrated PL spectrum and further confirms the coherent nature of the coupling between these states. Our findings further highlight the significance of coupled quantum states for the future engineering of exciton-based valleytronic and quantum photonic devices.

References

[1] Durmuş, M. A., Demiralay, K., Khan, M. M., Atalay, Ş. E. & Sarpkaya, I. Prolonged dephasing time of ensemble of moiré-trapped interlayer excitons in WSe_2-$MoSe_2$ heterobilayers. Npj 2D Mater. Appl. 7, 1–8 (2023).
[2] Wang, T. et al. Giant Valley-Zeeman Splitting from Spin-Singlet and Spin-Triplet Interlayer Excitons in WSe_2/$MoSe_2$ Heterostructure. Nano Lett. 20, 694–700 (2020).
[3] Zhang, L. et al. Highly valley-polarized singlet and triplet interlayer excitons in van der Waals heterostructure. Phys. Rev. B 100, 041402 (2019).
[4] Liu, E. et al. Signatures of moiré trions in WSe_2/$MoSe_2$ heterobilayers. Nature 594, 46–50 (2021).

P22. Towards resolving phase transitions in van-der-Waals materials with variable-temperature near-field microscopy

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Complex correlated phases in van-der-Waals materials such as transition metal dichalogenides (TMDCs) are a current interesting field of study. Studying phase transitions with high spatial resolution as function of temperature in parallel with charge transport experiments is especially interesting in this respect. A particularly intriguing system is the TMDC 1T-TaS_2, in which various charge density (CDW) states are known. Our focus is the controlling of the phases via temperature, electrical biasing or laser pulses while simultaneously resolving the change in physical properties. With our cryogenic scanning nearfield optical microscope (cryo-SNOM) we are able to track the optical conductivity with sub 100 nm lateral resolution while controlling the temperature. Additionally, applying electrical current through the device is another possibility to trigger CDW transitions in the material. It also allows to track phase transitions due to changes in the overall electrical resistance during temperature sweeps. The CDW domains exhibit two energetically equal chiralities, which can be formed by quenching the system or stacking layers on top of each other. Such interfaces of opposite chirality are one potential explanation for measured meta stable states. Creating artificially such interfaces and measuring electrical transport along them will give further inside in the forming of different CDW-Phases.

P23. Understanding the dielectric behaviour of $CuInP_2S_6$ and its thickness dependence

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Copper Indium Thiophosphate (CuInP2S6, commonly known as CIPS) is a van der Waals material that has captivated lots of interest due to its robust ferrielectricity at room temperature (TC ~ 315K), persisting in the thin limit, which is attractive for many applications, including non-volatile memory, nanoscale transistors or high dielectric capacitors.
In this work, we attempt to further understand the dielectric behaviour of CIPS as a function of its thickness dependence. We subjected our bulk CIPS flake to cycles of low angle/energy ion beam milling and ellipsometry, AFM and Raman spectroscopy characterisation, down to the nanometre scale. We found an anisotropic behaviour of the dielectric function with thickness dependence over the range of hundreds of nanometres to few nanometres. We also corroborated the presence of a critical thickness t_C ~ 100 nm where a change in dielectric behaviour is observed in both the in-plane and out-of-plane measurements, with a significant enhancement of the out-of-plane dielectric constant around t_C, analogous to the behaviour observed in the temperature dependent ferrielectric-paraelectric transition at T_C ~ 315K of bulk samples.

P24. Near field photocurrent nanoscopy at a biased graphene interface junction

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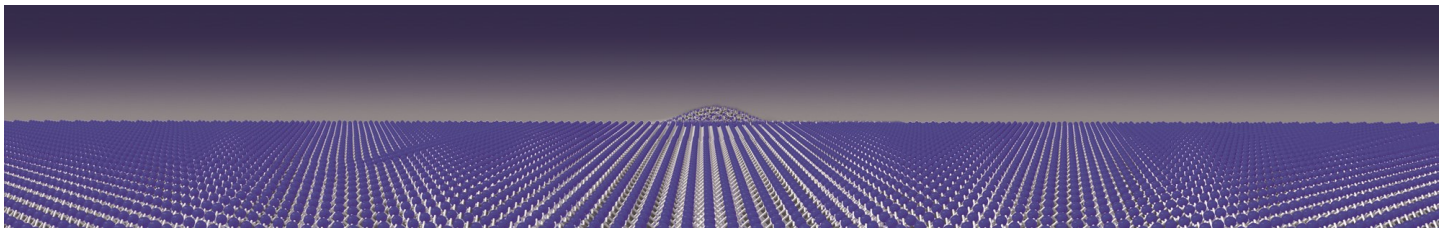
The nanoscale analysis of photocurrent is a versatile tool to gain information about electronic states, quantum processes, and device characteristics of quantum materials. When photocurrent is studied with a near-field scattering microscope (s-SNOM), it is possible to overcome the diffraction limit. Thus one can image the local characteristic of the devices with a 20 nm resolution. In this work, the analysis of s-SNOM images of the local photocurrent generated at mono-bi layer graphene interfaces is performed to gain a more profound knowledge of the specific mechanisms governing electronic flow and resistivity at a nanoscopic level. In particular, by analyzing the polarity of the photocurrent concerning the source-drain voltage applied across the device, it was possible to indirectly image the charge carrier accumulation around a defect during electronic charge flow, predicted by Landauer in 1957. It was found that for values of the Fermi energies in proximity to the charge neutrality point (i.e. at low hole or electron doping) the photocurrent has the same polarity as the applied source-drain voltage, as it would be expected for changes in carrier concentration induced by the Landauer resistivity dipoles.



P25. Manipulation of hybrid interlayer excitons in 2D materials

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Structures consisting of two stacked TMDC monolayers exhibit interlayer excitons, where the electron and hole are spatially separated in the two different layers. These interlayer excitons themselves have comparatively low oscillator strength, which may limit their use in the context of polaritonics [1].

However, in systems of two layers of TMDCs, the aforementioned interlayer exciton can couple to an intralayer exciton, leading to the formation of a hybrid interlayer exciton. Here, the electron in one layer interacts with a hole tunneling between both layers [2]. This configuration has an out-of-plane dipole moment and a high oscillator strength. The degeneration of the dipole orientation can be lifted by an external electric field, leading to a splitting into two different states. These two states can be attributed to the dipole moments parallel and antiparallel to the external electric field [3,4,5].
Furthermore, these hybrid interlayer excitons show a stronger interaction with each other compared to the A exciton. Thus, by increasing the exciton density, the blueshift of the hybrid interlayer exciton exceeds the blueshift of the A exciton [6,7].
We study the exciton resonances by introducing a high exciton density while applying an out-of-plane electric field and observe an enhanced blueshift of the hybrid interlayer exciton compared to the A exciton providing information on the interaction of the different excitons.

References

[1] P. Rivera, et. al., J. Nat. Comm. 6, 6242 (2015).
[2] I.C. Gerber, et. al., Phys. Rev. B 99, 035443 (2019).
[3] E. Lorchat, et. al., Phys. Rev. Lett. 126, 037401 (2021).
[4] N. Leisgang, et. al., Nat. Nano 15, 901-907 (2020).
[5] N. Peimyoo, et. al., Nat. Nanotechnol., 16, 888–893 (2021).
[6] B. Datta, et. al., Nat. Comm. 13, 6341 (2022).
[7] C. Louca, et. al., Nat. Comm. 14, 3818 (2023).

P26. Anisotropic Polaritons in Heterostructures made of Rotated Thin Layers and Dielectric Spacers

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Polaritons in van der Waals (vdW) crystals have recently emerged as a promising tool for controlling light at the nanoscale with unprecedented capabilities. Among them, phonon polaritons (PhPs) in biaxial vdW layers [1,2] are of special interest due to their strong anisotropic propagation, high confinement and ultra-low losses. More importantly, PhPs in twisted biaxial vdW layers have been recently demonstrated to exhibit extraordinary properties, such as optical topological transitions [3] and associated canalization phenomena [4]. Despite the importance of these results, a general theoretical model [5] that describes the propagation of polaritons in twisted heterostructures is lacking. Here, we report on such a model by considering an arbitrary number of rotated biaxial slabs separated by different dielectric media. By comparing with experiments and full-wave electromagnetic simulations we obtain a perfect agreement. This work lays the foundations for future experiments in the field of twistoptics, allowing for a theoretical prediction and justification of the propagation of polaritons in twisted heterostructures made of biaxial vdW slabs.

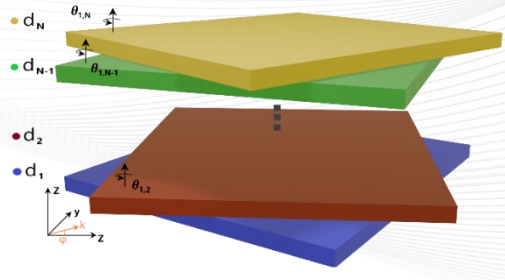

Fig. 1 Schematics of a heterostructure made of an arbitrary number N of biaxial slabs of finite thicknesses di and relative twist angles θ1,i, with θ1,i meaning the twist angle of the i-th slab with respect to the bottom slab (denoted by the index 1).

References

[1] Ma, W. et al. 2018. Nature, 562, 557−562..
[2] Álvarez-Pérez, G. et al. 2020. Adv. Mater., 32, 1908176.
[3] Duan, J. et al. 2021. Sci. Adv., 7, eabf2690.
[4] Duan, J. et al. 2020. Nano Lett., 20, 5323–5329.
[5] Álvarez-Pérez, G. et al. 2019. Phys. Rev. B, 100, 235408

P27. Topological Plasmonics on Atomically Flat Single Crystalline Gold Platelets

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During the last few years, topology has been combined with plasmonics by introducing boundary conditions into surface plasmon polariton (SPP) electric- or spin vector fields. In our work, we exploit the atomically flat surfaces of single crystalline gold platelets for SPP excitation, propagation, and interference. SPPs are excited on grooves that are milled into the ultra-smooth gold surface by utilizing a focused beam of Au2+-ions. According to the shape of the grooves, SPPs are excited and interfere, respectively, hence they exhibit characteristic topological features in their electromagnetic fields. We will introduce our sample fabrication as well as our measurement techniques, which are two-photon photo electron emission microscopy (2PPE PEEM) and scanning near-field optical microscopy (SNOM) and apply them to specific examples in topology.

P28. Tip-enhanced photoluminescence of 2D materials

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Two-dimensional (2D) materials have attracted special attention in recent years due to their outstanding properties, such as high stretchability, efficient light extraction and low cost, which make them a promising platform for applications in electronic and optoelectronic devices [1]. The use of experimental techniques to investigate their optical properties with nanometer resolution represents a rich resource for both exploring the performance of 2D material-based nanodevices and for fundamental studies. For example, the nature of quantum emission observed in low-dimensional transition metal dichalcogenides (TMDs) and hexagonal boron nitride (hBN) is still under debate, with no clear agreement on whether this emission is due to strain fields or the presence of defects in the material [2]. This unknown is due in part to the diffraction-limited spatial resolution achievable with commonly used photoluminescence (PL) systems.
In this regard, scattering-type scanning near-field optical microscopy (s-SNOM) provides both nanoscale resolution and enhancement of the emitted photoluminescence. In this work, preliminary images of WSe2 monolayers taken by tip-enhanced photoluminescence (TEPL) using s-SNOM are presented. As seen in the images, this method can resolve wrinkles, boundaries and edges of the monolayer. We anticipate the possibility to obtain nanoscale characterization of quantum emitters using this technique.

References

[1] S. I. Azzam, K. Parto, and G. Moody, “Prospects and challenges of quantum emitters in 2D materials”, Applied Physics Letters 118, 240502 (2021).
[2] S. Castelletto, F. A. Inam, S.-i. Sato, and A. Boretti, “Hexagonal boron nitride: a review of the Emerging material platform for single-photon sources and the spin–photon interface”, Beilstein Journal of Nanotechnology 11, 740–769 (2020).

P29. Record-high Anomalous Ettingshausen effect in a micron-sized magnetic Weyl semimetal on-chip cooler

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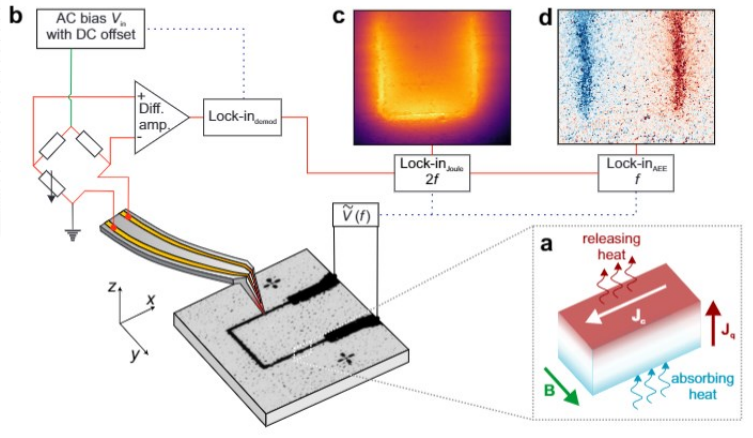
Solid-state cooling devices offer compact, quiet, reliable and environmentally friendly solutions that currently rely primarily on the thermoelectric (TE) effect. Despite more than two centuries of research, classical thermoelectric coolers suffer from low efficiency which hampers wider application. In this study, the less researched Anomalous Ettingshausen effect (AEE), a transverse thermoelectric phenomenon, is presented as a new approach for on-chip cooling. This effect can be boosted in materials with non-trivial band topologies as demonstrated in the Heusler alloy Co2MnGa. Enabled by the high quality of our material, in situ scanning thermal microscopy experiments reveal a record-breaking anomalous Ettingshausen coefficient of -2.1mV in µm-sized on-chip cooling devices at room temperature. A significant 37% of the effect is contributed by the intrinsic topological properties, in particular the Berry curvature of Co2MnGa, emphasising the unique potential of magnetic Weyl semimetals for high-performance spot cooling in nanostructures.



P30. Transient infrared nanoscopy deciphers the reversible photoswitching dynamics of a photolipid vesicles in an aqueous environment

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S-SNOM is a state-of-the-art super-resolution infrared (IR) microscopy and spectroscopy technique with a resolution of about 20 nm. It is applied to a wide range of materials from 2D materials to biomolecules. However, the studies are performed in a dried state, making it impossible to investigate dynamic systems in their native environment. Recently, we introduced a new in-situ s-SNOM method for studying complex dynamical phenomena, such as living biological cells in water over many hours. The method is based on an ultra-thin silicon nitride membrane (10 nm), enabling robust s-SNOM operation in reflection mode (Fig. 1a). Here, we show that the method enables the investigation of actively triggered dynamic process in the form of photoswitchable lipid vesicles of submicrometer size in their aqueous environment. Vesicles of such a dimension are challenging to study with conventional fluorescence or phase contrast microscopy, which further interferes with the photoswitching process of the vesicle. We demonstrate that we can actively photoswitch vesicles (Fig. 1b) between two morphologies and simultaneously image them. In addition, we report that it is possible to discriminate two photoisomeric states of the photoswitchable lipid molecules based on intensity differences in their nano-FTIR spectrum (Fig. 1c). Finally, we introduce a new transient s-SNOM method to monitor fast dynamic processes by tracking the IR near-field signal traces of a single wavelength at a defined tip position on a vesicle down to 50 ms resolution. We believe our findings will inspire researchers in the field of near-field microscopy to use the in-situ s-SNOM technique and the newly reported transient near-field signal trace to study complex time dynamics in their native environment on the nanoscale.

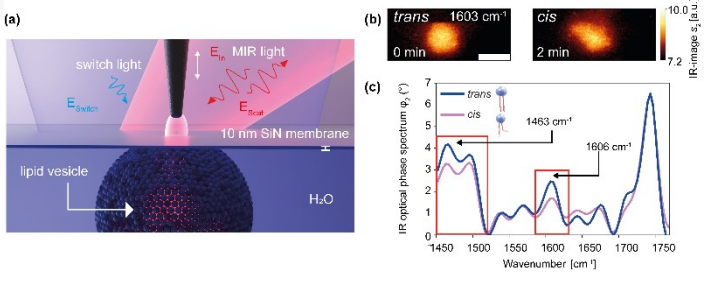

Figure 1 (a) Depiction of the in-situ s-SNOM method for photoswitching the lipid vesicle in aqueous solution with UV-VIS light (blue) and imaging the vesicle with IR-light (red). (b) Single wavelength near-field optical amplitude images s2 of a single lipid vesicle in trans- and cis-state, scale bar 500 nm. (c) Nano-FTIR phase spectrum of the trans-and cis-state of a lipid vesicle with switching resonances marked by the red boxes.

P31. Multi-modal Scanning Nitrogen-Vacancy Microscopy of Ferroic Materials

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Scanning Nitrogen-Vacancy (NV) microscopy is a well-established, versatile, and non-invasive imaging technique that senses stray fields above sample surfaces. The NV center, as a scanning magnetometer, is capable of nanoscale resolution and nanotesla sensitivities [1,2]. It is operable from room temperature down to cryogenic conditions and has therefore been used to study a wide range of materials and phenomena like skyrmions [3], spin waves [4] and superconductivity [5]. The NV center is also sensitive to electric fields, and its application for the detection of emanating electric stray fields in a scanning setup has been recently demonstrated using a gradiometric detection scheme [6]. The combination of both NV imaging techniques - Magnetometry and Electrometry - yields great potential in understanding complex physics like the ones present in ferroic materials and their underlying domain structures.
In this project we study materials with stable ferroic phases in both, magnetic and electric domains across different temperatures using a scanning NV microscope. Electrometry is being used to characterize and benchmark a series of samples ranging from the spin-cycloid in BiFeO3 (BFO) to the Aurivillius compound Bi5FeTi3O15 (BFTO), a ferroelectric material at room temperature with net in-plane polarization [7]. They provide a platform to study different types of ferroelectric domain structures and offer the possibility to develop NV Electrometry a step further into a more robust and reliable sensing scheme. Simultaneously, we use NV Magnetometry at cryogenic temperatures to observe magnetic textures in multiferroic hexagonal rare-earth manganites around their magnetic phase transition. Multiferroics are materials with more than one ferroic order in the same phase, for instance, ferroelectric and antiferromagnetic, and, as such, have been proposed as natural candidates for a low-energy-switching, non-volatile nanoscale magnetic memory [8], which is a burning demand in our highly digitalized society. The unique ability of the NV scanning microscope to resolve diverse magnetic textures and relate them to their ferroelectric counterparts will allow to study these materials from a brand-new perspective, by for example, observing antiferromagnetic and ferroelectric domains in a cross-correlative manner.

References

[1] R. Schirhagl et al., Annu. Rev. Phys. Chem., 65 (2014) 83-105
[2] W. Huxter et al., Nat. Commun., 13, (2022) 3761
[3] F. Casola et al., Nat. Rev. Mater., 3, (2018) 1-13
[4] van der Sar et al., Nat. Commun., 6 (2015) 7886
[5] P.J. Scheidegger et al., Appl., Phys. Lett., 120, (2022) 224001
[6] W. Huxter et al., Nat. Phys., 19 (2023) 644-648
[7] E. Gradauskaite et al., Chem. Mat., 34 (2022), 6468-6475
[8] H.M. Yau et al., Sci. Rep., 5 (2015) 12826

P32. Bottom-up Synthesis of 2D $CrCl_3/MoS_2$ van der Waals Heterostructures by Chemical Vapor Transport

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Two−dimensional (2D) materials and van der Waals (vdW) heterostructures have emerged as a powerful means to tune their physical properties, such as optical response, and to generate new intriguing phases, such as superconducting ones. Their unique properties mainly derive from strong interactions of electrons in Moiré bands that are highly sensitive to the stacking order and the interface of the stacked materials. In dependence of the material also strain and inhomogeneities can play a role here. Changing the nature of 2D materials of vdW and the interactions between layers leads to get different chemical and/or physical properties of these heterostructures. Diverse applications of 2D vdW heterostructures are based on the preparation of high-performance devices with a very clear interface between layers. For device fabrication, the conventional method of exfoliation is the favorite method although there are many limitations. Our alternative method of CVT is a bottom−up approach for highly crystalline few−layer structures with few defects.
Here, we grow our heterostructures by sequential or parallel CVT by a combination of thin MoS2 semiconductor and multilayer CrCl3 ferromagnet with in-plane easy-axis magnetization. The heterostructures will be comprehensively analyzed by SEM and TEM to resolve the atomic structure, including minute details on the interface as well as to investigate the physical properties e.g. by Raman spectroscopy, X-ray photoelectron spectroscopy and photoluminescence. With this new method, we can assemble transition metal trihalides/transition metal dichalcogenides heterostructure with high quality and different layer thicknesses.

P33. Ultrafast Phase-Control of the Non-Linear Optical Response of TMDs

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Monolayer semiconducting transition metal dichalcogenides (TMDs) feature particularly strong nonlinear light-matter interactions, which result from the large oscillator strength of tightly bound excitons. We investigate the third- and second-order nonlinear response of TMDs using phase-shaping of broadband laser pulses resonant with the lowest excitonic state. We find that the four-wave mixing response of TMDs can be coherently controlled and enhanced by manipulating the spectral phase profile of the laser pulse. Here, the optimum spectral phase profile crucially depends on the exciton resonance energy of the TMD and the laser fluence. Sum-frequency generation, on the other hand, is maximized for shortest laser pulses at the same experimental conditions. We then show that upon increasing the pump fluence pulsed laser excitation can induce a Mott transition from an excitonic regime to an electron hole plasma in TMDs [1].

References

[1] F. B. Sousa et al., Nanoscale 15, 7154 (2023)

P34. Effect of Chemical Doping of 2D TMDCs on Their Optical and Electrical Properties

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In the past decade, 2D Transition Metal Dichalcogenides (TMDs) have emerged as promising alternatives to Si-based technologies. A major challenge associated with TMDs is their high contact resistance. Several studies have aimed to mitigate this issue by doping TMDs with 1,2-dichloroethane (DCE) solution, and this has been successfully demonstrated for MoS_2. In this study, we provide an in-depth analysis of the optical consequences of this doping technique by employing photoluminescence (PL) and Raman measurements on MoS2 layers post-growth DCE treatment. Our findings indicate a significant drop, exceeding 50%, in the PL intensity of the indirect transition for 2-layer MoS_2 following only 1-minute DCE treatment. Notably, the direct transition remains unaffected. Comparable outcomes were observed for MoS_2 layers ranging from 4 to 7 and multi-layers exceeding 7 layers. Based on these results, we present a valuable guide detailing the thickness and time dependencies of DCE doping across various MoS_2 layers.

P35. Hyperlens enabled defect imaging in hexagonal boron nitride-covered few-layer graphene

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Most of the unique phenomena of few-layer graphene (FLG) FLG like half- and quarter-metals[1] and superconductivity[2] in rhombohedral trilayer graphene (TLG) can only be observed when the FLG flake is encapsulated in hexagonal Boron Nitride (hBN).[3] The fabrication process of encapsulated graphene devices can alter the stacking order and induce defects within the FLG flake.[4] The present stacking order and possible defects significantly influence the graphene sample's electronic properties. Therefore, the visualization of stacking domains and defects in graphene flakes before, during, and after the fabrication of a transport device is of great interest.
Conventionally, the stacking orders within an FLG flake are characterized by IR- or Raman spectroscopy.[5,6] However, being diffraction limited, both techniques cannot provide information about graphene's local, sub-micrometer-sized electronic structure. They are even worse when another material, such as hBN, covers the graphene, because the signal from the graphene is reduced. This makes it more difficult to identify defects in the FLG that may form during the stacking process.[4]

Recently, Liu et al.[7] showed that phonon assisted near-field imaging can visualize stacking domains in encapsulated four-layer graphene. However, the underlying coupling mechanism and the visualization of subdiffractional defects remains elusive. Here, we elucidate that the phonon assisted imaging is mediated by coupled hyperbolic phonon plasmon polaritons which we characterize with scattering-type scanning near-field optical microscopy in an hBN TLG heterostructure. We show that these coupled polaritons allow for super-resolution imaging of subdiffractional sized defects in graphene through the hBN cover-layer, the so-called hyperlensing effect.[8,9] We use the hyperlensing effect to identify defects in FLG below 33 nm of hBN and show the sliding of domains, before and after encapsulation of an FLG flake. Our work paves the way for characterization of FLG devices during fabrication, where the domains can be altered and defects may form due to mechanical stress and strain during stacking, heating, and electric fields.

References

1. Zhou *et al.* Nature **598,** 429–433 (2021).
2. Chen et al. Nature **572**, 215–219 (2019).
3. Dean et al., Nature nanotechnology **5**, 722–726 (2010).
4. Geisenhof et al., ACS Appl. Nano Mater. **2**, 6067–6075 (2019).
5. Mak et al., Proceedings of the National Academy of Sciences of the United States of America **107**, 14999–15004 (2010).
6. Lui et al., Nano letters **11**, 164–169 (2011).
7. Liu et al., Nature nanotechnology **19**, 188–195 (2024).
8. Dai et al. Nature communications **6**, 7963 (2015).
9. Li et al. Nature communications **6**, 7507 (2015).

P36. Near field investigation of GaN surface grating coupled plasmon phonon polaritons

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In this work we present our initial near field study of surface plasmon-phonon polaritons (SPPhPs) optically excited in n-GaN surface gratings of linear and circular geometries. Semiconductor based thermal radiation sources based on SPPhP excitation were recently developed demonstrating emission of high spatial quality in a far-field with high temporal coherence in the range of wavelengths near 570 cm^{-1} [1]. While far-field results show promising macroscopic behavior of the emitters, an understanding of underlying physics and extended applicability can be obtained by performing near-field studies of the SPPhPs. For the first time coupling and launch of the SPPhPs in the GaN gratings were achieved by performing s-SNOM measurements provided by Attocube systems AG with laser excitation in the spectrum from 570 cm^{-1} to 920 cm^{-1}, which covers the Restsrahlen band of doped GaN semiconductor.
Figure 1 demonstrates the polariton launch at the grating edge and propagation through the semiconductor surface in the maps of amplitude and phase of s-SNOM signals. The numerical modeling of SPPhP dispersion allowed us to refine the investigated grating designs and experimental configurations taking step further in the creation of means of improved electromagnetic energy control, emission, or field concentration at the surface of semiconductors.

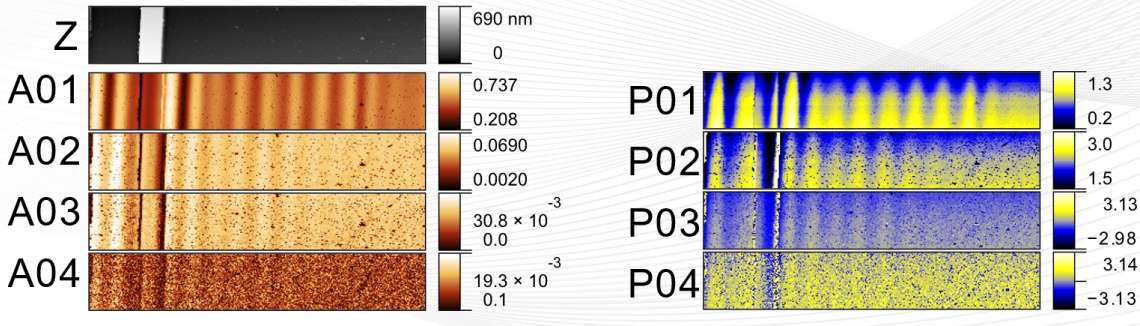

Figure 1. Topography (Z) Amplitude (A) and phase (P) maps of s-SNOM imaging results at the edge of periodic n-GaN surface grating at the laser excitation frequency of 920 cm^{-1}. Multiple s-SNOM harmonic results (01-05) are displayed.

References

1. V. Janonis et al. Opt. Mater. Express 13(9), 2662 (2023); https://doi.org/10.1364/OME.494777.
2. J. D. Caldwell et al. Nanophotonics 4(1), 44–68 (2015); https://doi.org/10.1515/nanoph-2014-0003.

P37. Preparation of extremally large monolayers of 2D materials in UHV

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The two-dimensional (2D) transition metal dichalcogenide (TMD) family has the potential to be used as an active material for the next-generation p-n junction (opto-) electronics devices because of its fascinating electronic, optical, and physical properties. The main obstacle is the lack of homogenously p- and n-type doped 2D-TMD due to the doping challenge during growth. Beyond the conventional doping techniques during growth, several approaches have been employed to achieve p- and n-type 2D-TMDs. In this study, n- and p-type WS2 and WSe2 based p-n junction diodes were fabricated, and the effect of traditional doping and post-growth doping (dichloroethane and ultraviolet ozone for n- and p- type, respectively) on the diode parameters and emission profile of the devices were investigated. It has been observed superior emission properties in the conventionally doped 2D-TMDs-based junctions, while the post-growth doped materials-based p-n junctions exhibit better diode characteristics in terms of electrical properties.

P38. Atomically thin p–n junctions based on two-dimensional materials

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The two-dimensional (2D) transition metal dichalcogenide (TMD) family has the potential to be used as an active material for the next-generation p-n junction (opto-) electronics devices because of its fascinating electronic, optical, and physical properties. The main obstacle is the lack of homogenously p- and n-type doped 2D-TMD due to the doping challenge during growth. Beyond the conventional doping techniques during growth, several approaches have been employed to achieve p- and n-type 2D-TMDs. In this study, n- and p-type WS2 and WSe2 based p-n junction diodes were fabricated, and the effect of traditional doping and post-growth doping (dichloroethane and ultraviolet ozone for n- and p- type, respectively) on the diode parameters and emission profile of the devices were investigated. It has been observed superior emission properties in the conventionally doped 2D-TMDs-based junctions, while the post-growth doped materials-based p-n junctions exhibit better diode characteristics in terms of electrical properties.

P39. Investigation of 2D plasmons in graphene on grating-gated AlGaN/GaN HEMT structures grown on SiC substrate

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In this work we report the investigation of surface polaritons launched in CVD-grown graphene transferred on to grating-gated AlGaN/GaN high-electron-mobility transistor (HEMT) structures [1]. Heterostructure consisted of (top-down) 1.5 nm GaN cap, 21 nm $Al_{0.25}Ga_{0.75}N$ barrier, 200 nm GaN channel, and 1.8 µm GaN buffer with AlN nucleation layers on 4H-SiC. Gold surface grating of 4×4 mm^2 area with a period of 1020 nm and metal line width of 550 nm were deposited on top of heterostructure before graphene transfer. The two-dimensional electron gas formed at interface of $Al_{0.25}Ga_{0.75}N$/GaN was characterized to have carrier density of 1.0×10^{13} cm^{-2} and mobility of 1.8×10^{3} $cm^2V^{-1}s^{-1}$ at room temperature. While near field coupling of graphene surface plasmons has been reported before [2], we investigated the interaction between graphene surface plasmons and optical phonons in buried polar-semiconductor layers of a novel plasmonic HEMT heterostructure [1].
For this s-SNOM system from a*ttocube systems AG* was used for the near field experiments registering amplitude and phase of the coupled light, using a QCL source laser operating in spectral range from 920 to 1500 cm^{-1}. The selected spectral range covered the LO phonon range of SiC allowing to tune off the interaction between the surface plasmon and underlying phonon. Large area mapping was investigated. The excitation of surface plasmon polaritons by different surface morphology features including graphene grain boundaries, graphene wrinkles and gold surface grating was demonstrated (see Fig. 1). Qualitative differences were observed between differently coupled plasmons showing “long” propagation distance for the “active” graphene grain boundary and grating coupled plasmons and “local inactive” scattering from defects currently identified as graphene wrinkles [3]. Experiments at different frequencies revealed that with the increase of laser frequency from 917 cm^{-1} to 1550 cm^{-1}, the plasmon propagation distance as well as its amplitude decreased significantly, indicating probable decrease of plasmon localization at the surface of the structure.

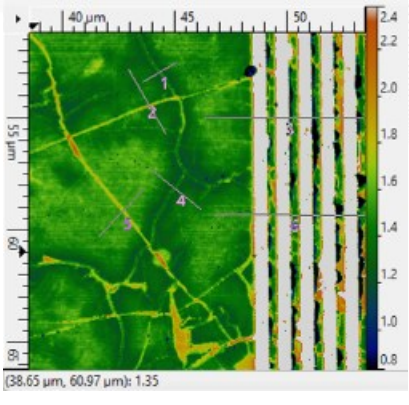

Figure 1. Near field amplitude map of graphene plasmons excited on AlGaN/GaN HEMT structures on SiC substrate at the laser frequency of 917 cm^{-1}. Surface coupled by different surface morphology features are

observed: 1 and 4 “active” plasmons launched from graphene grain boundaries; 2 and 5 “inactive” regions at graphene wrinkles; 3 and 6 plasmon excitation from gold grating.

References
1. D. Pashnev et al. Appl. Phys. Lett. **117**, 051105 (2020), https://doi.org/10.1063/5.0014977.
2. D. N. Basov et al., Nanophotonics **10**(1), 549–577 (2020), https://doi.org/10.1515/nanoph-2020-0449.
3. M. Schnell, et al. Nat. Commun. **5**, 1–10 (2014), https://doi.org/10.1038/ncomms4499.

P40. Nanoscale patterned superlattices in topological insulator thin films

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Nanoscale patterned superlattices in topological insulators are predicted to renormalize the Dirac velocity of the surface states and correspondingly enhanc electronic interactions, which may ultimately result in the emergence of correlated stated, such as topological superconductivity [1]. To fabricate superlattices with the required lattice constants on the order of 10 nm, we discuss the application of He-ion beam milling. The helium ion microscope has evolved as a versatile tool for both nanoanalytics and nanoscale fabrication with a resolution well below 10 nm [2]. We characterize the transport in the superlattices by magneto- and optoelectronic transport. For the latter, we extend optoelectronic measurements from near-infrared (from 0.8 µm) to mid-infrared wavelengths (up to 20 µm). The latter may allow a selective excitation and read-out of the surface state and its quantum geometric properties [3] without contribution from bulk bands. The research is supported through the European Union’s Horizon Europe Research and Innovation Programme under Grant Agreement No 101076915 (2DTopS).

References:
[1] J. Cano et al., Phys. Rev. B 2021, 103, 155157.
[2] E. Mitterreiter et al., Nano Lett. 2020, 20, 4437–4444.
[3] G. Topp et al., Phys. Rev. B. 2021, 104, 064306.

P41. Angular dependence of magnetic field on superconductivity in layered 2D $NbSe_2$

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Two dimensional (2D) materials have garnered increasing attention due to their unique and extraordinary electronic and optoelectronic capabilities in their layered form. A novel class of atomically thin 2D materials includes the transition metal dichalcogenides (TMDC) exhibiting fascinating properties in their metallic, semiconducting, superconducting and insulating phases opening doors towards stacking heterostructures to see novel physics in applications, such as, superconductivity, non-linear optical phenomena and exciton dominated light-matter interaction. One such TMDC based superconductor is 2H-NbSe2 with a bulk critical temperature around 7K and showing exceptional Ising superconductivity in the monolayer form. Unlike conventional superconductivity in metals and alloys, unconventional superconductors such as the TMDC superconductors have an anisotropic order parameter. The present study, hence, aims to study 2D NbSe2 in light of the unconventional superconductivity by realizing its macroscopic transport with superconducting critical fields.
In this study, we conducted an extensive investigation of the electronic properties of 2D superconductor NbSe2 showing an existence of charge density wave and superconducting phase, respectively. The superconducting phase varies as a function of temperature, applied external magnetic field and input bias. In addition, a nonreciprocal transport is observed for an in-plane and out-of-plane direction of the magnetic field. The knowledge gained from the present investigation alongwith understanding the optoelectronic properties of MoSe2/NbSe2 heterostructure serves as a foundational understanding for realizing the polaritonic mediated superconductivity and Andreev-Baskin effect in semiconductor-superconductor heterostructures where exciton polaritons replace the conventional Cooper pairs as binding agents resulting in exciting physics at the quantum regime.

References:
[1] A. Hamil et al, Nat. Phy. **17,** 949-954 (2021)
[2] L. Bauried et al, Nat. Comm. **13**, 4266 (2022)
[3] A. Aminov et al, Quantum **6**, 787 (2022)

P42. Scanning Nitrogen-Vacancy Magnetometry Down to 350 mK

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We report on the implementation of a scanning nitrogen-vacancy (NV) magnetometer in a dry dilution refrigerator. Using pulsed optically detected magnetic resonance combined with efficient microwave delivery through a co-planar waveguide, we reach a base temperature of 350 mK, limited by experimental heat load and thermalization of the probe. We demonstrate scanning NV magnetometry by imaging superconducting aluminum and niobium thin-film microstructures at nanoscale resolution. The sensitivity of our measurements is approximately 12μT per square root Hz. Our work demonstrates the feasibility for performing noninvasive magnetic field imaging of two-dimensional micro- and nanostructures with scanning NV centers at sub-Kelvin temperatures.

P43. The Dynamics of Surface Plasmon Polaritons Explored Through s-SNOM Fourier Analysis of WS2 Nanophotonic Antennas

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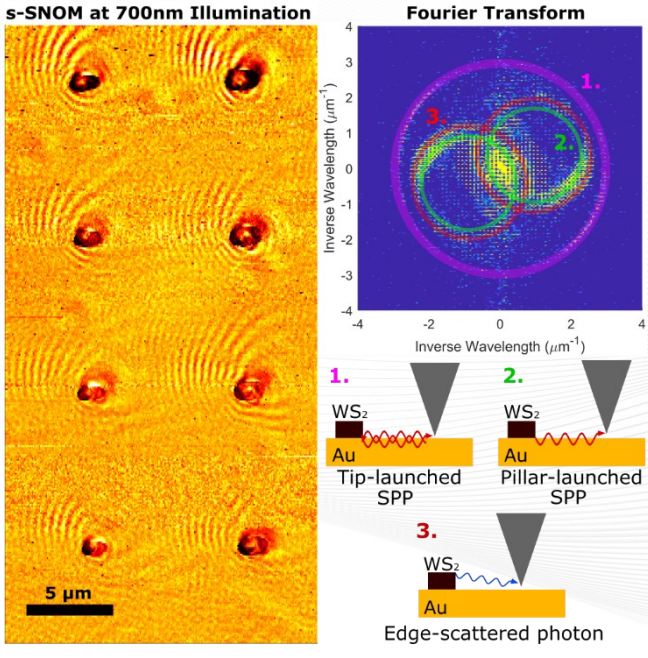
Transition-metal dichalcogenides (TMDs) represent an exciting class of materials with a variety of properties such as high refractive indices, low-dimensionality, and excitonic features that make them highly suitable for research into cutting-edge nanophotonics and twistronics. For example, stacks of TMD material with sub-micron spatial dimensions can act as nanoantennas, interacting with incident light via near-field electromagnetic modes, and presenting a fertile environment for exploring near-field electromagnetism and other nanophotonic effects. Additionally, these TMD nanoantennas are readily able to adhere to many surfaces, allowing for the engineering of hybrid dielectric-gold structures whose properties depend on the TMD material and the geometry of the nanoantennas. Here we study cylindrical WS2 pillars on gold, showing that these nanoantennas can interact with near-field quasiparticles such as surface plasmon polaritons (SPPs) hosted by the gold-air interface. These nanophotonic structures were studied using scattering-type, scanning near-field optical microscopy (s-SNOM) in conjuncture with a tunable laser source, allowing for information to be collected at individual wavelengths across the visible and near-IR spectral ranges. SPP reflection and launching mechanisms were observed from the nanoantennas at these different wavelengths, likely due to the coupling of the Mie modes within the antennas to the SPP modes in the gold-air interface, leading to complicated interference patterns recorded in the s-SNOM data. Utilising a novel Fourier analysis method, we are able to separate out the effects of each individual mechanism from the data, allowing a deeper and more accurate analysis of the polariton properties than commonly achieved. This method has further applications in the s-SNOM study of other polaritons species (such as exciton polaritons and phonon polaritons), and for the research of 2D materials and photonic structures.



(Left) s-SNOM data taken from WS2 pillars on gold, measured at 700nm illumination. (Top right) 2D Fourier transform of the s-SNOM data, highlighting the different interference patterns observed. (Bottom right) Summary of interference-pattern sources in the data, correlated to the patterns observed in the Fourier transform.

P44. 2D WSe_2 (MoS_2)-Phototransistors Using Mist CVD High-κ Al-Ti Composed oxides Gate Dielectric

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Two-dimensional (2D) transition metal dichalcogenides (TMDCs) such as MoS_2 and WSe_2 and their alloys have been extensively studied with an ever-growing interest due to their superior transport properties for ultimate device scaling. To attain a high performance electronic and photonic characteristic in ultrathin 2D TMD-channel field effect transistor (FETs) devices, leakage free high-k gate dielectric is inevitable issue. Herein, we report the synthesis of high-κ amorphous (α)- $Al_xTi_{1-x}O_y$ thin films showing an adjustable dielectric constant of 6.23–25.12 and band gap of 4.25–6.38 eV from $Al(acac)_3$ and $Ti(acac)_2OiPr_2$ co-precursors by solution processed mist CVD [1,2]. A 0.015 M $Al(acac)_3$ and $Ti(acac)_2OiPr_2$ solution with CH_3OH dilution was placed directly above a 3 MHz atomizer, N_2 was used as a generator and dilution gas (500 and 2400 sccm) to transport the mist. Further, an exfoliated TMD-channel MOSFET has been fabricated on $Al_{0.74}Ti_{0.26}O_y$ gate insulator with Au as source and drain electrodes. The mobility of 85 cm^2/Vs, threshold voltage of 0.92 V, and an on/off current ratio of 10^8 [3]. However, high-quality defect-free large area TMDCs films and transfer-free device fabrication are still in interest towards nano device applications. Thus, we will present prospect of controlled mist CVD process to be applied for the growth of high-k gate dielectric and TMD channel layer towards optoelectronic applications.

References

1) A. Kuddus et al. Nanotechnology 33,045601 (2022).
2) A. N. Hoffman et al. 2D Mater. 6, 045024 (2019).
3) C. S. Pang et al. Adv. Electron. Mater 6:1901304 (2020).

P45. Exciton Polaritons in Ångström thick van der Waals Materials

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Transition metal dichalcogenide (TMDC) monolayers support excitonic states in the visible at room temperature with strong binding energies, which makes them interesting for polariton based devices. Polariton propagation in thin slabs of TMDCs down to 10 nm in thickness have been shown[1], however, they have never been imaged in ångstrom thick samples in real space, due to the requirements on the refractive indices of the cladding media to support propagating modes. Here we study exciton-polariton waveguiding in a freestanding WS_2 monolayer by imaging their propagation in real space using scattering-type scanning near-field optical microscopy (s-SNOM). Combined with a fully tunable laser in the visible for excitation we obtain the dispersion relation, which shows pronounced backbending around the binding energies of the A and B exciton, alluding to strong light-matter coupling between excitons and polaritons. This is further supported by modelling the dispersion of a TE_0 mode in monolayer WS_2.

P46. Determining the Crystal Orientation of Noncentrosymmetric 2D Materials from Second-Harmonic Generation Images

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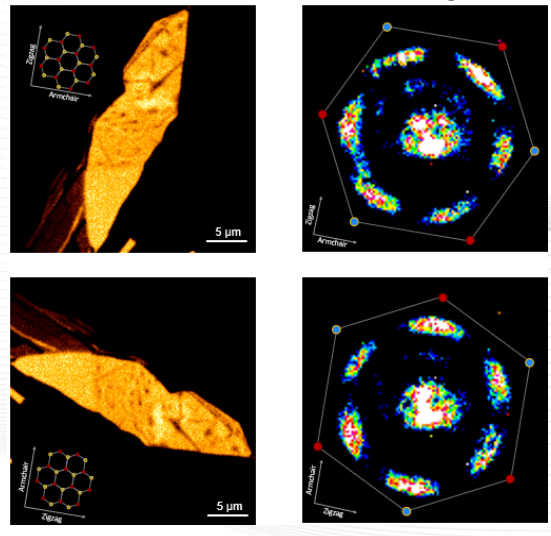
In the established procedure for determining the crystallographic orientation, the Second-Harmonic Generation (SHG) is recorded while the polarization of the incident laser field, together with that of the generated SHG, is rotated with respect to the fixed monolayer orientation [1,2]. In our work, we show that the crystal orientation can be probed by recording a single SHG image generated by a tightly focused laser beam. For a focused Gaussian laser beam, the crystal orientation can be inferred from the ellipticity of the detected SHG image. Moreover, in the case of an azimuthally polarized laser beam, the SHG image directly reflects the hexagonal structure of the D_{3h} crystal lattice together with its orientation in one single measurement, as shown in the figure below. This could be useful for diverse techniques of nanofabrication that need an accurate and fast method to determine the relative angles between the layers.



References
[1] Li, Y. et al., Nano Letters 2013, 13, 3329–3333.
[2] Malard, L. M. et al., Phys. Rev. B 2013, 87, 201401.

P47. Berezinskii-Kosterlitz-Thouless transition in monolayer antiferromagnet

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Berezinskii-Kosterlitz-Thouless (BKT) transition is an unconventional phase transition in a two-dimensional (2D) system, which has been extensively studied for trapped atomic Bose gases, superconductors, and quasi-2D magnets.[1,2] In the latter case, the experimental studies have been complicated by the presence of interlayer or substrate interactions, which impede realization of an ideal 2D system, masking the hallmarks of BKT transition.[3,4] With the recent experimental advances in exploring 2D van der Waals magnets, a finite-size BKT transition was observed in quasi-freestanding ferromagnetic monolayer $CrCl_3$, making it nearly ideal 2D-XY ferromagnetic system.[5] In addition to ferromagnets, materials with antiferromagnetic coupling are equal candidates for probing XY magnetism, however experimental manifestation of BKT transition in monolayer antiferromagnets still remains elusive due to difficulties in probing atomically thin samples with no net magnetization. In addition to faster dynamics compared to ferromagnetic counterparts, easy-plane antiferromagnets enable a richer variety of topological excitations in BKT phase, such as antiferromagnetic skyrmions and merons.[6]

Here, we present a systematic investigation of magneto-transport in 2D layered van der Waals XY-type antiferromagnet. We observe spin-flop transition and anisotropic magnetoresistance down to bilayer thickness, which is a clear indication of long-range magnetic order with weak in-plane easy-axis magnetic anisotropy. We find that monolayer samples undergo a phase transition from the paramagnetic phase but show no signs of magnetoresistance or in-plane magnetic-field-driven phase transitions unlike thicker counterparts. We interpret such behavior as the absence of the long-range magnetic order, which points towards the BKT transition in monolayer 2D XY antiferromagnet.

References

1. Berezinskii, V. Sov. Phys. JETP, 1971, 32, 493.
2. Kosterlitz, J.M. & Thouless, D.J. J. Phys. C Solid State Phys., 1973, 6, 1181.
3. Vaz, C.A.F.; Bland, J.A.C.; Lauhoff, G., Rep. Prog. Phys. 2008, 71, 056501.
4. A. Taroni, S. T. Bramwell, P. C. W. Holdsworth, J. Phys. Condens. Matter 2008, 20, 275233.
5. Bedoya-Pinto, A. et al. Science, 2021, 374, 616.
6. Barker, J. & Tretiakov, O.A. Phys. Rev. Lett., 2016, 116, 147203.

P48. The interfacial thermal properties of single- and few-layer graphene regarding rotation

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Understanding the impact of structural features, such as twist angles, on the thermal boundary conductance (TBC) of supported single- and few-layer graphene (Gr), is crucial for optimizing the performance of devices comprising these materials. Time-domain thermoreflectance (TDTR) has emerged as a powerful technique to investigate the interfacial thermal properties of two-dimensional materials. In this work, we employed TDTR to study the TBC of single- and few-layer graphene grown by chemical vapor deposition with different stacking arrangements, i.e., Bernal stacked and randomly oriented graphene, respectively. We found that the weak van der Waals interactions do not damper the thermal transport between the TDTR transducer (Al) and the substrate (SiO2/Si). Instead, the presence of a single-layer graphene can enhance the TBC in Al-Gr-SiO2-Si devices as compared to pristine Al-SiO2-Si. For Bernal stacked few-layer graphene, our results suggest an increase in TBC as a function of the number of layers, indicating ballistic heat transport across the layers. On the other hand, when introducing a large twist angle between the adjacent graphene layers, the TBC decreases as a result of increased phonon scattering at the interface between each layer, indicating that diffusive heat conduction dominates in randomly oriented graphene. These findings pave the way for engineering heat transport in graphene-based devices.

P49. Topological valley plasmons in twisted monolayer-double graphene moiré superlattices

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Graphene plasmons, hybrids of Dirac quasiparticles and photons, exhibit low-loss, strong electromagnetic confinement and electrical tunability. Graphene plasmons provide excellent opportunities for exploring light-matter interactions at the nanoscale, which is promising for applications in integrated photonics and biosensing. By introducing the concept of topology, unidirectional propagation of graphene plasmons protected against disorder and backscattering can be realized. However, the requirements of complex artificial geometries and configurations obstruct the experimental realizations of topological graphene plasmons. On the other hand, by stacking and twisting different layers of Van der Waals materials, two-dimensional (2D) moiré superlattices are emerging as an important avenue for engineering quantum materials with novel properties.

In this work, plasmon properties of small-angle twisted monolayer-bilayer graphene (tMBG) is investigated, whose moiré superlattices consist of triangular domains with the Bernal (ABA) and the rhombohedral (ABC) stacking. The ABA and ABC graphene have different electronic bandstructures where the ABA graphene is a semi-metal with a tunable band overlap, while the ABC one is a semiconductor with a gate-tunable band gap and a flat band. Here we demonstrate theoretically that tMBG moiré superlattice provides a natural platform for GPC, where complete plasmonic bandgap occurs. Furthermore, the effects of nontrivial chiral valley topology of the GPC are emphasized. Finally, robust transport of graphene plasmon waves with suppressed inter-valley scattering is shown at the interfaces separating two GPCs with opposite valley Chern numbers. Our study motivates further explorations of novel photonic phenomena in the rich platform of reconstructed moiré superlattices.

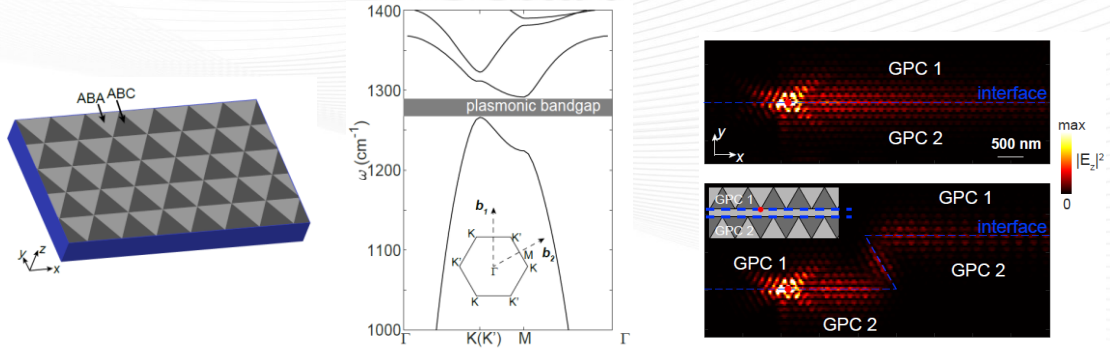

Fig.1 Topological valley plasmons in twisted monolayer-double graphene moiré superlattices. (a) Moiré superlattices of TMBG is consisted of triangular domains of the ABA and ABC stacking graphene. (b) Plasmonic bandgap occurs in the moiré superlattices of TMBG. (c) Backscattering-free propagation of graphene plasmons for the valley topologically protected edge states.

P50. Electrically switchable in-plane anisotropic exciton-polariton in a van der Waal semiconductor

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Tailoring of the propagation dynamics of exciton-polaritons in two-dimensional quantum materials has shown extraordinary promise to enable nanoscale control of electromagnetic fields. Varying permittivities along crystal directions within layers of material systems, can lead to an in-plane anisotropic dispersion of polaritons. Exploiting this physics as a control strategy for manipulating the directional propagation of the polaritons is desired and remains elusive. Here, we explore the in-plane anisotropic exciton-polariton propagation in a group-IV monochalcogenide semiconductor which forms ferroelectric domains and exhibits room-temperature excitonic behavior. Exciton-polaritons with their propagation dynamics and dispersion studied. This propagation of exciton-polaritons allows for nanoscale imaging of the in-plane ferroelectric domains. Finally, we demonstrate the electric switching of the exciton-polaritons in the ferroelectric domains of this complex vdW system. The study suggests that systems like group-IV monochalcogenides could serve as excellent ferroic platforms for actively reconfigurable polaritonic optical devices

P51. Lowering the energy of anisotropic polaritons in van der Waals crystals

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Hyperbolic materials, characterized by extreme anisotropy in their optical properties, have been explored thanks to their unique light-propagation properties with unbounded wavevectors isofrequency contours. Their unique property of having permittivities with opposite signs along different directions enabled the demonstration of negative refraction[1] and hyperlensing[2] in artificial metamaterials. However, these systems can work only in the effective medium approximation and are as such confined to low wavevector applications due to the limits imposed by nanofabrication resolution.
Recently, natural van der Waals (vdW) crystals exhibiting natural hyperbolicity in the mid-infrared have been investigated for nanophotonic applications. The high structural anisotropy of vdW results in the presence of optical phonons with strongly different energies, which lead to the presence of frequency regions where the permittivity assumes positive and negative values along distinct crystal directions. At these frequencies, light strongly couples with optical phonons, leading to the formation of mixed light-matter states called phonon polaritons (PhP). Out-of plane PhPs hyperbolicity was first reported in hBN flakes[3,4], followed by the discovery of in-plane hyperbolic PhPs in MoO_3 thin films[5,6]. Since then, lower symmetric crystals led to the observation of shear[7] and ghost polaritons[8], enhancing the possibilities of nanoscale light control below the diffraction limit.
While PhPs are highly attractive for their low-losses, they are inherently confined to the far and mid-infrared part of the spectrum because of the characteristic energy of optical phonon. Here we consider the possibility of lowering the operational frequency of hyperbolic polaritons by employing novel vdW crystals.

References

[1] High, Alexander A., et al. "Visible-frequency hyperbolic metasurface." Nature, 522.7555, 192-196, 2015.
[2] Liu, Zhaowei, et al. "Far-field optical hyperlens magnifying sub-diffraction-limited objects." Science, 315.5819, 1686-1686, 2007.
[3] Dai, Siyuan, et al. "Tunable phonon polaritons in atomically thin van der Waals crystals of boron nitride." Science, 343.6175, 1125-1129, 2014.
[4] Ambrosio, Antonio, et al. "Selective excitation and imaging of ultraslow phonon polaritons in thin hexagonal boron nitride crystals." Light: Sci. Appl., 7.1, 27, 2018.
[5] Ma, Weiliang, et al. "In-plane anisotropic and ultra-low-loss polaritons in a natural van der Waals crystal." Nature, 562.7728, 557-562, 2018.
[6] Zheng, Zebo, et al. "A mid-infrared biaxial hyperbolic van der Waals crystal." Sci. Adv. 5.5, eaav8690, 2019.
[7] Passler, Nikolai C., et al. "Hyperbolic shear polaritons in low-symmetry crystals." Nature, 602.7898, 595-600, 2022.
[8] Ma, Weiliang, et al. "Ghost hyperbolic surface polaritons in bulk anisotropic crystals." Nature, 596.7872, 362-366, 2021.

Acknowledgements

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P52. Dry-flip stacking for imaging moiré patterns

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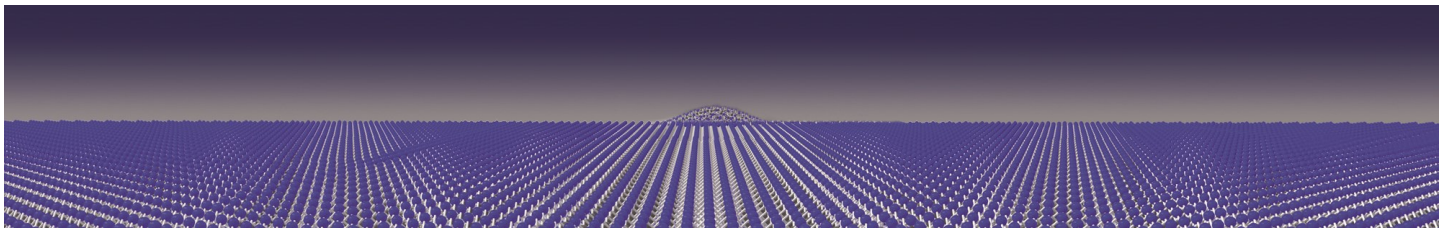
The recent discovery of magic angle twisted bilayer graphene (MATBG), in which two sheets of monolayer graphene are precisely stacked to a specific angle, has opened up a plethora of new opportunities in the field of topology, superconductivity, and other strongly correlated effects. The most conventional way of preparing twisted bilayer devices is by using a polycarbonate (PC) pick up method at 100°C - 110°C. At higher temperatures, around 180°C, PC melts, and is later dissolved in choloroform and IPA. This method does not work well for samples which need to be flipped to be compatible with characterization techniques like STM, ARPES, PFM, SThM etc. Here, we demonstrate a very simple polymer-based method using Polyvinyl Chloride (PVC), which can be used for making flipped twisted bilayer graphene devices. To this end, the pickup temperatures were optimized by changing the thickness of the PVC layer. This allowed us to produce flipped twisted samples, which were deposited without the use of any additional solvent. Eventually, to evaluate the quality our devices, we used Piezo Force Microscopy (PFM) to image moire patterns. We believe that this dry flip technique can be extended for twisting 2D materials other than graphene, especially air- sensitive materials and would be effective in probing exotic states in twisted materials.



P53. Time-Resolved Scanning NV Magnetometry of Dynamic Domain Walls in Magnetic Thin Films

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Novel spintronic devices exploit the motion of magnetic textures in thin films, promising denser packing, higher speeds, and lower power consumption than conventional electronics [1]. A key element in advancing such devices is to understand the mechanisms governing the motion of magnetic domain walls (DW), such as the current-induced spin–orbit torque (SOT). As the resulting DW motion depends critically on the internal magnetic structure [2], microscopic sensing methods are necessary. While established techniques like electrical transport measurements and optical methods only provide a macroscopic picture, microscopic imaging methods such as X-ray and electron scattering require complex instrumentation. In contrast, scanning diamond magnetometry has been established as a suitable platform for nanoscale imaging of electric and magnetic properties of thin films [3-5] and can be operated non-invasively under ambient conditions with a compact table-top setup. The method is based on sensing the local magnetic stray field using a single nitrogen–vacancy (NV) defect in a diamond tip, allowing for the reconstruction of microscopic features such as the chirality and width of DWs. However, NV magnetometry is not a single-shot method [6], which has restricted its scope to static structures.
In this work we aim to surmount this limitation by enabling time-resolved NV magnetometry of dynamic DWs. At the initial stages of the project, we have laid the groundwork for implementing stroboscopic pump-probe techniques, focusing on reproducible injection and geometrical confinement of DWs in ferromagnetic Co/Pt and ferrimagnetic GdCo/Pt multilayers. Both systems exhibit perpendicular magnetic anisotropy and strong interfacial Dzyaloshinskii-Moriya interaction, stabilizing chiral DWs that can be manipulated through current-induced SOT. Subsequently, we will proceed towards pump-probe measurements by driving the DWs with current pulses and synchronizing the stray field readout with the DW motion. By enabling time-resolved scanning NV magnetometry of dynamic DWs, our sensing method can be employed to improve our microscopic understanding of the current-induced DW motion, aiding the development of novel spintronics devices.

References

[1] S. A. Wolf et al., Science, 294 (2001) 1488-1495
[2] A. Manchon et al., Rev. Mod. Phys., 91 (2019) 035004
[3] S. Vélez, et al., Nat. Commun., 10 (2019) 4750
[4] J.-P. Tetienne et al., Nat. Commun., 6 (2015) 6733
[5] W. S. Huxter et al., Nat. Phys., 19 (2023) 644–648
[6] R. Schirhagl et al., Annu. Rev. Phys. Chem., 65.1 (2014) 83-105

P54. Ultrafast and Ultracold Nanoscopy of 2D-Materials

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We introduce ultrafast nanoscopy based on scattering-type scanning near-field optical microscopy (s-SNOM) for the infrared and THz spectral ranges, and at temperatures below 10K.
Scattering-type scanning near-field optical microscopy (s-SNOM) [1] uses a metallized scanning probe tip to focus light of terahertz, infrared, or visible spectral range down to the nanoscale (~10-20 nm), beating the diffraction-limited spatial resolution by several orders of magnitude (Figs. 1a, 1b). Interferometric detection of the tip-scattered light allows for amplitude- and phase-resolved imaging and spectroscopy of the sample dielectric function as well as electric fields such as caused by surface polaritons. Recent advances extend the capabilities of s-SNOM towards being a versatile platform for 2D material characterization by combining electrical, thermal and optical measurements in the same device – while also allowing for more active control of the sample properties via external electrical signals, full environmental enclosure and temperature control from 375 K down to 10 K.
Here, we introduce ultrafast and ultracold nanoscopy based on infrared and terahertz s-SNOM that allows for optical pump and optical probe measurements with femtosecond temporal and nanometer spatial resolution. Ultrafast nanoscopy enables study of dynamic processes in nanomaterials such as InAs nanowires [2] or 2D heterostructures [3]. More specifically we demonstrate *i*) pump-probe spectroscopy of carrier excitation in InAs at 8K temperature, using ultrafast nano-FTIR transient spectroscopy and imaging, as well as *ii*) optical pump – THz probe nanoscopy on MoS2 crystals at room-temperature.

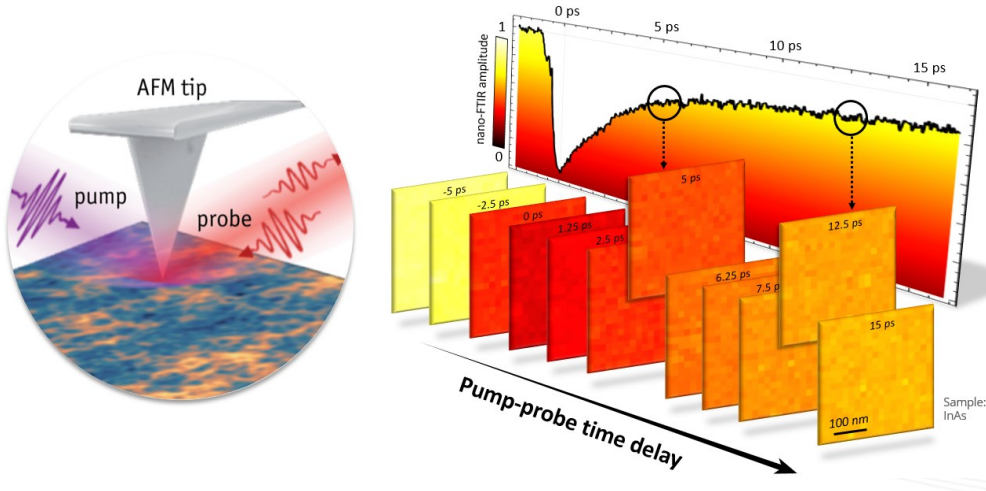

Fig. 1: Ultrafast nanoscopy: Left: Illustration of ultrafast nanoscopy setup. Right: Ultrafast nano-FTIR time trace and white light image series for differnet pump-probe time delays. Taken on InAs substrate. 780 nm pump wavelength.

References

[1] F. Keilmann, R. Hillenbrand. 2004. Phil. Trans. A, 362, 787–805.
[2] M. Eisele et al. Nature Photonics 8, 841-845 (2014).
[3] M. Plankl et al. Nature Photonics 15, 594-600 (2021).

P55. Ultra-sensitive hyperspectral imaging of 2D materials with an open micro-cavity

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Optical-fiber-based micro-resonators (micro-cavities) offer a variety of applications in research and technology [1]. Within the spin-off company Qlibri GmbH, we work on transforming this cutting-edge technology to a standalone lab device in ambient and cryogenic conditions. Using an open scanning-cavity approach, a broad range of experimental needs can be addressed. Here, we highlight the possibilities of cavity enhanced absorption microscopy with detection sensitivities that surpass any current commercial solutions. Certain use cases are presented here which include manipulation of the decay characteristics of two-dimensional van der Waals heterostructures (MoSe2-WSe2) [2]. Furthermore, two-dimensional scanning capabilities are highlighted, which enable spatial correlation of polariton properties with intrinsic and extrinsic effects [3]. Finally, the sensitivity of the scanning micro-cavity is illustrated through measurements of extinction spectra of atomistic defects in monolayer MoS2 [4].

References

[1] Hunger, D. et al., New Journal of Physics 12, 065038 (2010).
[2] FÖRG, M. et al., Nature Communications 10, 3697 (2019).
[3] GEBHARDT, C. et al., Scientific Reports 9 (1), 1-9 (2019).
[4] SIGGER, F. et al., The Journal of Physical Chemistry Letters 13 (44), 10291-10296 (2022).

P56. Phonon dynamics and out-of-plane heat transport in layered quantum materials probed through time-resolved Raman spectroscopy

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The high thermal conduction anisotropy of layered quantum materials makes them a strong candidate for the development of integrated devices with improved thermal management [1]. Some of these materials, such as graphene and hBN present excellent in-plane thermal conductivities, that ensures a good dissipation of heat through in-plane diffusion, combined with out-of-plane thermal conductivities up to several orders of magnitude smaller, offering the possibility of out-of-plane thermal insulation [2]. While in-plane heat transport can be observed efficiently by established methods, such as Raman thermometry, and a new technique developed in our group, based on spatiotemporal pump-probe microscopy [3, 4], new experimental methods need to be developed in order to properly assess the out-of-plane transport of heat in layered quantum materials and van der Waals stacks. We present our work towards the development of such a new technique, which is based on time-resolved Raman spectroscopy (TRRS) [5]. This technique can be used to either probe the phonon dynamics of one specific layer [6, 7] or track the out-of-plane transport of heat with a layer by layer precision by monitoring the changes in the Raman modes features as the heat flows through the sample.

References

[1] Z. Yan et al., Nat. Commun. 3, 827 (2012)
[2] S. Kim et al., Nature 597, 660 (2021)
[3] G. D. Brinatti Vazquez et al., Adv. Electron. Mater. 2300584 (2023)
[4] S. Varghese et al., Rev. Sci. Instrum. 94, 034903 (2023)
[5] H. Hamaguchi & K. Iwata., Encyclopedia of Spectroscopy and Spectrometry, 3rd edition, p.463-468, Academic Press (2017)
[6] S. Wu et al., Nano Letters, 12, 5495-5499 (2012)
[7] C. Ferrante et al., Nat. Commun. 9, 308 (2018)

P57. Vibrational and Optical Properties of Quasi-1D CrSBr : Impact of Encapsulation and Atomic Layer Thickness

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Recent advancements in the study of van der Waals (vdW)-bonded layered materials have opened new avenues for understanding fundamental physics and exploring potential applications in quantum technologies [1][2][3]. Particularly intriguing are correlated quantum phenomena observed in one-dimensional (1D) systems exhibiting competing electronic and magnetic orders, notoriously challenging to realize experimentally [4]. Among these materials, semiconducting CrSBr has great potential due to its remarkable stability in ambient conditions and captivating magnetic properties [5], featuring robust interactions between magnons and excitons [6]. CrSBr is a layered magnetic semiconductor, exhibits quasi-1D behaviour due to its lattice structure within magnetically ordered environments [7].
In this work we investigate optical properties of CrSBr, with focus on excitonic behaviour and the exciton-phonon interaction. Utilizing techniques such as atomic force microscopy and optical spectroscopy, we meticulously characterize exfoliated CrSBr samples of different thickness from monolayer to bulk. We capture the influence of anisotropic lattice structure of the material on the optical processes and quasiparticle interactions through polarization-resolved photoluminescence and Raman spectroscopy. We investigate in ambient conditions the impact of the number of layers on the optical and material properties and the impact of encapsulation with hexagonal boron nitride.
Our comprehensive study sheds light on the intricate interplay between excitons and phonons in both encapsulated and non-encapsulated CrSBr samples in the context of vdW-bonded layered magnets for next-generation spintronics, magneto-electric devices, and quantum technologies.

References

[1] Juan F. Sierra, Jaroslav Fabian, Roland K. Kawakami, Stephan Roche et al. Nature Nanotechnology 16, no. 8 (2021).
[2] Mete Atatüre, Dirk Englund, Nick Vamivakas, Sang-Yun Lee et al. Nature Reviews Materials 3, no. 5 (2018).
[3] Alejandro R-P. Montblanch, Matteo Barbone, Igor Aharonovich, Mete Atatüre et al. Nature Nanotechnology 18, no. 6 (2023).
[4] Vikram V. Deshpande, Marc Bockrath, Leonid I. Glazman, and Amir Yacoby. Nature 464, no. 7286 (2010).
[5] Fangchao Long, Kseniia Mosina, René Hübner, Zdenek Sofer et al. Applied Physics Letters 123, no. 22 (2023).
[6] Youn Jue Bae, Jue Wang, Allen Scheie, Junwen Xu et al. Nature 609, no. 7926 (2022).
[7] Julian Klein, Benjamin Pingault, Matthias Florian, Marie-Christin Heißenbüttel et al. ACS nano 17, no. 6 (2023).

P58. Imaging Magnetism at the Nanometer Scale with Scanning NV Magnetometry

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Nitrogen-vacancy centres are defects in a diamond lattice that are capable of sensing magnetic and electric fields at the nanometer scale and with great sensitivity, from room temperature all the way down to milli-Kelvin. When they are located at the very apex of a diamond pillar, they can be used to perform scanning probe microscopy and become excellent probes to perform surface characterization.
I will present use cases and measurements taken using scanning NV magnetometry. These include FMR resonances, Skyrmions, stray field maps from weak antiferromagnets, large area BFO scans and much more.

P59. Near-field imaging of anisotropic and highly-confined phonon polaritons with a free-electron laser

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Hyperbolic phonon polaritons are currently actively explored for their ability to strongly confine and guide IR and THz light on the nanoscale. The optical anisotropy of 2D materials and the ability to stack and twist different materials opens opportunities to engineer material resonances and realize highly directional polariton propagation. Here, we explore polariton waveguiding in the THz and far-IR through near-field imaging with a neaSNOM attached to a widely tunable narrowband free-electron laser. We image hyperbolic polaritons in thin flakes of the van der Waals material $HfSe_2$ in the 3-5 THz spectral range, with confinement factors up to 80 below the free-space wavelength. We demonstrate how the dispersion of these THz polaritons is modulated by strong coupling with an intrinsic epsilon-near-zero-mode (ENZ) mode, that can be tuned by the substrate permittivity. Furthermore, we engineer in-plane hyperbolic polaritons of the van der Waals material α-MoO_3 by the coupling with polaritons in the highly-anisotropic material β-Ga_2O_3. By twisting thin slabs of α-MoO_3 on top of a β-Ga_2O_3 substrate we achieve highly-directional and strongly asymmetric polariton propagation that can be tuned by the twist angle and excitation frequency.

P60. Surface phonon polariton bound states in the continuum metasurfaces

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To integrate photonic technologies on chips, it's crucial to shrink light into dimensions smaller than its wavelength. One method is coupling light to material excitations, forming polariton states. In our study, we highlight how low-loss mid-infrared surface phonon polaritons enable metasurfaces that support quasi-bound states in the continuum (qBICs) with extremely small unit cells. Using 100 nm thick free-standing silicon carbide membranes, we achieve highly confined qBIC states with a unit cell volume ~ 10^4 times smaller than the diffraction limit. This grants our platform remarkable robustness against incident angles, a unique feature among qBIC systems. Furthermore, we demonstrate vibrational strong coupling with a thin layer of spin-coated molecules, taking advantage of the small mode volume. This research introduces phononic qBICs as an innovative nanophotonic platform, promising the miniaturization of mid-infrared devices for applications in molecular sensing and thermal radiation engineering.

References

[1] Mancini, A., Nan, L., Wendisch, F.J., Berté, R., Ren, H., Cortés, E. and Maier, S.A., 2022. Near-field retrieval of the surface phonon polariton dispersion in free-standing silicon carbide thin films. ACS Photonics, 9(11), pp.3696-3704.

[2] Mancini, A., Nan, L., Berté, R., Cortés, E., Ren, H. and Maier, S.A., 2024. Multiplication of the orbital angular momentum of phonon polaritons via sublinear dispersion. Nature Photonics, pp.1-8.

[3] Nan, L., Mancini, A., Weber, T., Seah, G.L., Cortés, E., Tittl, A. and Maier, S.A., 2024. Highly confined incident-angle-robust surface phonon polariton bound states in the continuum metasurfaces. arXiv preprint arXiv:2403.18743.

P61. Nanoscale mapping of carrier densities in intercalated MoS_2

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Scattering-type scanning near-field optical microscopy (s-SNOM) and nanoscale IR point spectroscopy (nano-FTIR) allow for nanoscale optical mapping of manifold material properties. Both techniques are based on elastic light scattering from an atomic force microscope tip that is illuminated with monochromatic or broadband laser illumination. Acting as an optical antenna, the tip converts the illuminating field into a strongly concentrated near-field at the very tip apex. Interferometric recording of the tip-scattered field as a function of sample position yields near-field amplitude and phase s-SNOM images (employing monochromatic laser illumination), which encode information about the local dielectric function of the sample, while Fourier-transform spectroscopy of the tip-scattered field (employing IR broadband illumination) allows for nano-FTIR spectroscopy [1,2]. Intercalation of 2D layered semiconductors with molecules can drastically change the electric, optical, and magnetic properties of the host crystal. Recently, we found that MoS_2 bulk crystals become superconducting when intercalated with Tetraethylammonium (TEA) molecules [3]. Surprisingly, the superconducting state is not fully reached in few-nm-thick samples. To get a deeper understanding of the molecule distribution in the material we performed IR and THz s-SNOM and nano-FTIR spectroscopy to map the local carrier density of pristine and intercalated MoS_2. In the s-SNOM images of the intercalated MoS_2 we find a drop of the amplitude signals with increasing frequency and a change of the phase contrast, resembling a Drude-like response, while the pristine MoS_2 shows no changes with frequency. Furthermore, the amplitude and phase images of the intercalated MoS_2 flakes are not homogeneous, indicating a spatial variation of the local conductivity, i.e., the carrier concentration (Fig. 1). In addition, we use nano-FTIR to confirm the Drude-like response and to measure the molecular vibrations, showing the presence and amount of the TEA molecules. By modeling the near-field spectra we can extract the local conductivity of the sample. Our work shows the potential of IR/THz nanoimaging as a noninvasive technique to map the carrier concentration together with molecular vibrations, thus allowing for correlating the presence of molecules (strength of the molecular feature) with the conductivity (Drude-like response) of the system.

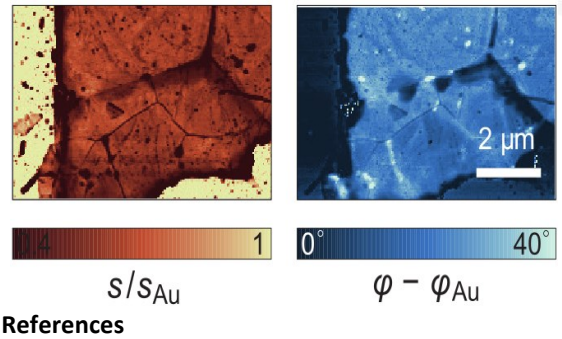

Fig. 4: s-SNOM amplitude (left) and phase (right) image of the intercalated MoS_2 flake recorded at 1000 cm^{-1}.

References

[1] N. Ocelic, et al., Appl. Phys. Lett. 89, 101124 (2006)
[2] M. Schnell, et al., Nat. Commun. 5, 349 (2014)
[3] J. M. Pereira, et al. Adv. Funct. Mater. 32, 208761 (2022)

P62. Electric field effect in twisted WSe_2/WS_2 TMDCs heterostructures

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Transition metal dichalcogenides (TMDCs) heterostructures (HSs) offer a dynamic platform where artificially stacked monolayers of different TMDCs materials may reveal intriguing quantum behaviors. The alignment or twist between these monolayers generates a periodic moiré pattern, endowing the presence of the quasi-particle intralayer exciton, within the same material and an interlayer exciton characterized by charge carriers originating from different monolayers. Moiré superlattices in two-dimensional (2D) HSs induce quantum phenomena by fundamentally altering the electronic hybridizations by controlling the twist angle between atomically thin layers. This paradigm shift provides a unique avenue for precisely tailoring interactions between quantum particles and their coupling to electromagnetic fields. Moreover, beyond their discernible effects on single-particle states, strong moiré superlattices manifest excited states, such as the formation of moiré minibands of excitons [1]. In this study, we comprehensively explore the optoelectronic characteristics of twisted WSe_2/WS_2 van der Waals HSs and demonstrate the potential of electric field manipulation for controlling the behavior of excitons. The insights obtained contribute to establishing a foundational understanding essential for realizing many-body states in moiré superlattices, such as exciton condensates, and bosonic insulating states via electric field manipulation.

Reference

[1] Jin, Chenhao, et al. Nature 567.7746 (2019): 76-80

P63. Vertical Field Effect in the Luminescence of a TMDC Heterostructure

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Two dimensional (2D) materials have garnered increasing attention due to their unique and extraordinary electronic and optoelectronic capabilities. A novel class of atomically thin 2D materials includes the transition metal dichalcogenides (TMDC) exhibiting fascinating properties, such as, superconductivity, non-linear optical phenomena and exciton dominated light-matter interaction, an essential requirement for quantum technologies. The utilization of van der Waals heterostructures composed of different two-dimensional materials offers a distinct advantage over conventional III-V semiconductors by mitigating the strain originating from lattice mismatch between diverse materials. This capability presents opportunities for integrating intricate device functionalities that are unattainable with conventional materials. However, TMDC based devices often suffer due to high resistance of metal – 2D contacts, resulting in issues, such as, significant quenching of photoluminescence (PL) emission through interlayer charge or energy transfer (ICT or IET) to the adjacent layer [1,2]. Hence, our work aims to study 2D systems to address the above issues. In this investigation, we have carried out a comprehensive study of the optoelectronic characteristics exhibited by $MoSe_2/NbSe_2$ semiconductor-superconductor heterostructures (HSs) under the influence of a vertical electric field. Our findings unveil a notable resurgence in the PL intensity, concerning the $MoSe_2$ excitons in the regions of the HSs with $NbSe_2$, by more than 20 times and surpassing the levels observed in pristine monolayer $MoSe_2$. This phenomenon can be attributed to the establishment of a potential barrier, specifically a Schottky barrier, between $MoSe_2$ and $NbSe_2$, which effectively regulates charge separation dynamics and determines the transfer of charges between two constituent materials depending on the direction of the applied electric field. The study provides a clear distinction between ICT and IET, a pertinent phenomenon observed in all TMDC/metal heterostructures. While our primary research focus remains on the intralayer exciton dynamics of $MoSe_2$, distinguished by its non-permanent dipole moment, we envision that investigating the investigation of dipolar exciton phenomena in bilayer TMDC with $NbSe_2$ under electrostatic gating may shed light on the photon-induced modifications in superconductivity.

Reference

[1] E. Lorchat et al., Nat. Nanotechnol. 15, 283 (2020)
[2] G Froehlicher et al., Phys. Rev. X 8, 011007 (2018)

P64. Twisted hyperbolic van der Waals crystals for full Stokes mid-infrared polarization detection

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Investigating the polarization properties of light in the mid-infrared (mid-IR) spectrum is crucial for molecular sensing, biomedical diagnostics, and IR imaging system technologies. Traditional methods, limited by bulky size and intricate fabrication, utilize large rotating optics for full Stokes polarization detection, impeding miniaturization and accuracy. Van der Waals materials (vdW) based devices can address these challenges due to their lithography-free fabrication, ease of integration with chip-scale platforms and room-temperature operation. This study introduces a chip-integrated polarimeter device leveraging the in-plane biaxial hyperbolic vdW crystal properties for mid-infrared light manipulation. The spatial division measurement scheme incorporates six meticulously designed linear and circular polarization filters, achieving high extinction ratios exceeding 30 dB and transmittance surpassing 50%, with fabrication tolerance of film thickness up to 100 nm. The proposed device represents a significant advancement in polarimetric detection, providing a compact, cost-effective solution and opens new avenues for on-chip mid-IR polarimetric detection in next-generation ultra-compact optical systems.

P65. Imaging Current Flow in Commercial Graphene Devices with Scanning NV magnetometry

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Graphene, the prototypical 2D material, was originally produced by mechanical exfoliation, a time-consuming process. While mechanical exfoliation often remains the method of choice for high quality devices, graphene can also be synthesized on wafer scale and readymade devices are commercially available from several sources. We investigate the current flow in an off-the-shelf graphene field effect transistor using scanning NV magnetometry, which can reconstruct the 2D current density from the measured stray field with sub 50 nm resolution and high sensitivity. This enables a visualization of non-uniform current flow caused by defects and grain boundaries in the graphene device, both of which can limit device performance.

P66. Quantum sensing of RF signals with VB- defects in hBN

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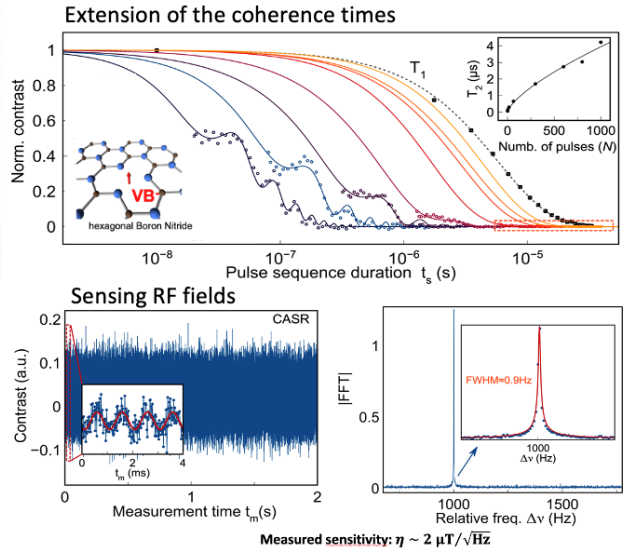
Negatively-charged boron vacancy centers ($VB-$) in hexagonal Boron Nitride (hBN) are attracting increasing interest since they represent optically-addressable qubits in a van der Waals material. In particular, these spin defects have shown promise as sensors for temperature, pressure, and static magnetic fields. However, their short spin coherence time limits their scope for quantum technology. Here, we apply dynamical decoupling techniques to suppress magnetic noise and extend the spin coherence time by two orders of magnitude, approaching the fundamental T1 relaxation limit. Based on this improvement, we demonstrate advanced spin control and a set of quantum sensing protocols to detect radiofrequency signals with sub-Hz resolution. The corresponding sensitivity is benchmarked against that of state-of-the-art NV-diamond quantum sensors. This work lays the foundation for nanoscale sensing using spin defects in an exfoliable material and opens a promising path to quantum sensors and quantum networks integrated into ultra-thin structures.



Reference

[1] Rizzato, R., Schalk, M., Mohr, S. et al. Extending the coherence of spin defects in hBN enables advanced qubit control and quantum sensing. *Nat Commun* **14**, 5089 (2023). https://doi.org/10.1038/s41467-023-40473-w

P67. Observation of near-field photoluminescence in WSe_2-gold nanoparticle hybrid system by enhanced exciton-plasmon interaction

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Monolayer (1L) transition metal dichalcogenides (TMDs), such as tungsten diselenide (1L-WSe_2), have gained significant attention in recent years due to their direct bandgap and reduced dielectric screening, that result in strong photoluminescence and high exciton binding energy. These features make 1L-TMDs promising candidates for next-generation optoelectronic devices, photodetectors, and quantum emitters. Tailoring the absorption and emission characteristics of TMDs requires the manipulation of excitonic transitions by some external means such as temperature, surrounding medium, or by coupling them to resonant nanoparticles. In this study, we use gold nanoparticle arrays to enhance the near-field light-matter interaction of 1L-WSe_2 and experimentally demonstrate the detection of the demodulated near-field photoluminescence signal and the manipulation of the optical properties of 1L-WSe_2 [1]. We observe reduced exciton lifetime and increased PL intensity, which can be explained by the Purcell effect [2]. For the first time, the demodulated photoluminescence near-field mapping with unprecedent resolution is demonstrated. This research provides insights into the exciton-plasmon coupling phenomenon, critical for developing advanced nanophotonic devices.

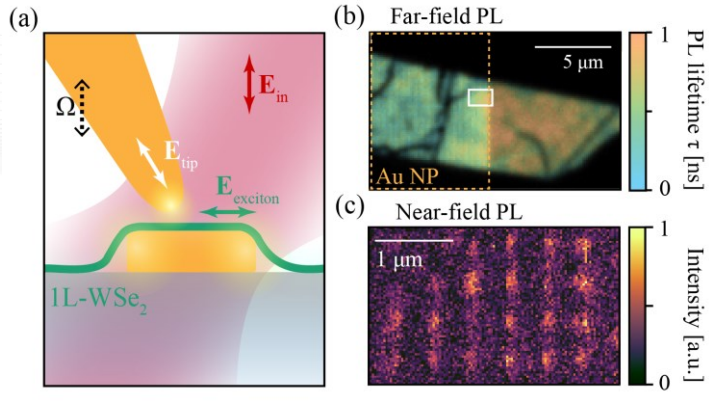

Figure 1: a) Scheme of near-field photoluminescence detection; b) Far-field PL intensity and lifetime map, rectangle covers the area presented in Fig.1c; c) Demodulated PL map.

Reference

[1] Pelton, M. *et al.* (2019) Nanoscale, 11, 14540-14552
[2] Zhao, W *et al.* Adv. Mat., 2016, 28(14), 2709–2715

P68. Detection of cw THz radiation by photomixing in graphene

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Photoconductive antennas are optoelectronic photomixers which can be used for the generation and detection of continuous-wave THz radiation. They are usually made from III/V semiconductors grown in such a way that the carrier lifetime is ultrashort and the background conductivity as low as possible. Here, we employ standard CVD graphene in the gap of a metallic antenna structure and show that such a device can be used as photoconductive antenna for the coherent detection of THz radiation. For the nonlinear mixing process, the device exploits the ultrafast conductivity modulation which graphene exhibits due to periodic carrier heating and cooling, when subjected to the intensity beat note of the two-color optical radiation, of which a part was used to generate the THz radiation in an emitter device. While for biased THz emitters the dark current of the detector would pose a serious detriment for performance, we show that this is not the case for bias-free THz detection and demonstrate detection up to frequencies of at least 700 GHz at room temperature, even without optimized tuning of the doping.

P69. Mesoscopic reconstruction in semiconductor van der Waals structures

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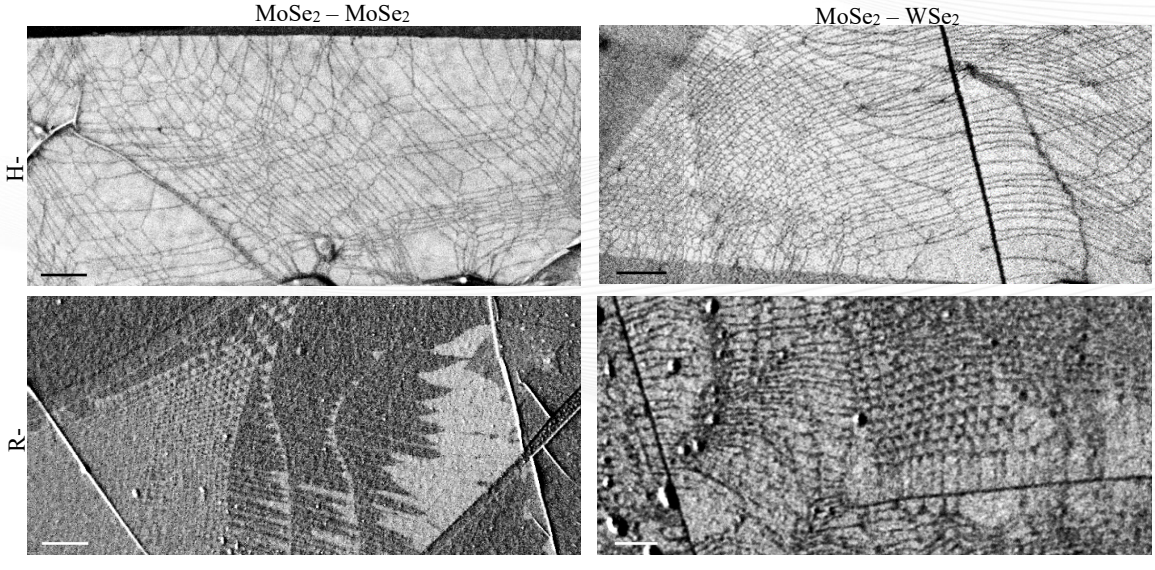
Transition metal dichalcogenide semiconductors represent essential building blocks of van der Waals heterostructures. Vertical stacks of multiple monolayers give rise to physical properties that depend sensitively on the choice of materials, the rotation angle between the individual layers, and the emergent band structure. Here, we present reconstruction phenomena in $MoSe_2$-WSe_2 heterobilayers with small lattice mismatch and marginal-angle deviations away from parallel (rhombohedral R-type, or 0° twist) and antiparallel (hexagonal H-type, or 60° twist) alignment. Due to finite elasticity of lattice bonds, we find mesoscopic reconstruction of canonical moiré patterns into domains of different dimensionality. Secondary electron imaging in scanning electron microscopy was optimized to visualize the resulting morphology of domain landscapes, and optical spectroscopy was used to assign exciton characteristics to 2D, 1D and 0D domains.



Related publications

[1] S. Zhao et al., *Nat. nanotechnol*., **18** 572-579 (2023).

[2] A. Rupp et al., *2D Mater*., **10,** 045028 (2023).

[3] Z. Li et al., *Nano Lett*., **23.10**, 4160–4166 (2023).

P70. Excitation of in-plane hyperbolic polaritons in far-field via engineered nanostructured van der Waals Crystals

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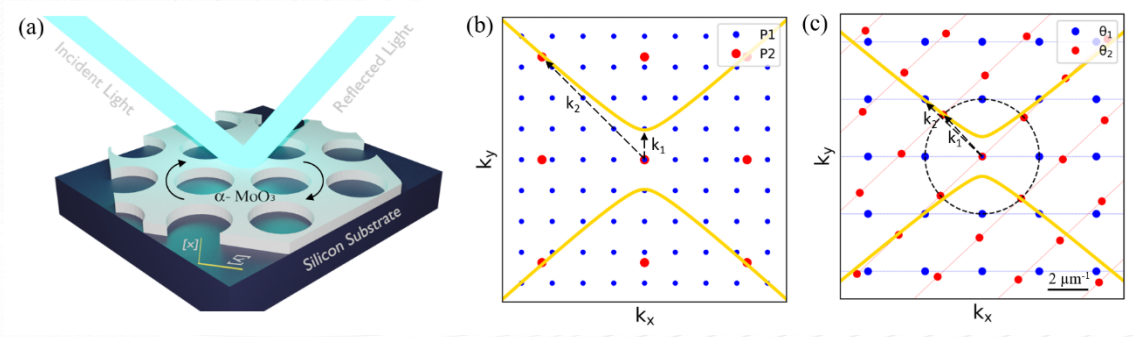
In-plane Hyperbolic Phonon polaritons (HPhPs) are quasiparticles formed via coupling of photons and optical phonons in in-plane hyperbolic materials and offer unique applications in sensing, thermal emitters and high resolution imaging. However, the large momentum mismatch between photons and these in-plane HPhPs has restricted their technological potential as most experimental demonstrations rely on sophisticated and expensive near-field detection schemes. In this work, using the example of α-MoO_3, we demonstrate that by constructing photonic hypercrystals of this material, one can not only excite these in-plane HPhPs in the far field but also tune the far field response via twisting the hypercrystal lattice with respect the lattice of α-MoO_3. Our findings will pave the way for the development of practical in-plane HPhP devices as well as provide access to new fundamental physics of such materials via conventional and well developed far field measurement techniques.



P71. Functionalization of 2D materials for electronic and optoelectronic applications

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In recent years, semiconducting two-dimensional transition metal dichalcogenides (2D-TMDs) have become a group of highly demanded materials for next-generation optoelectronic devices such as photodetectors and light emitters because of their unique optical, electronic, and structural properties. Despite many advantages of these semiconducting materials, there are some drawbacks such as low carrier concentration and mobility, which result in low electrical conductivity and poor diode characteristics compared to the materials already widely used in electronic/optoelectronic technologies, such as Si and GaAs. Their high sensitivity against environments/external effects which is thought of as a weakness, can be turned to be an advantage to dope them and to tailor their properties by using post-growth defect engineering methods. Focused ion beam (FIB) has shown great potential in material/surface modification and defect engineering in 2D materials more recently, to tailor their optical and electronic properties. On the other hand, UV-ozone (UV-O_3) exposure is another powerful technique for a wide range of applications such as controllable doping, layer-by-layer thinning, etc. A better understanding and control of defects are important to move forward in the field of defect engineering for potential electronic and optoelectronic applications of 2D-TMDs. In this study, we discussed fabrication details for controllable defect engineering and the effect of ion beam and UV-O_3 exposure on the optical and electrical properties of 2D-TMDs.

P72. Commercial scanning nitrogen vacancy magnetometer in a closed-cycle cryostat

Clemens Schäfermeier[1], Christopher Kelvin von Grundherr[1], Patrick Ebermann[1], Dominik Irber[1], Saddem Chouaieb[1], Andrea Morales[2], Gabriel Puebla-Hellmann[2], Khaled Karraï[1]

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Nitrogen vacancy (NV) centres in diamond are used to sense magnetic fields by means of optically detected magnetic resonance (ODMR). The quantum properties of NV centres are subject of research since decades and are found to be especially exploitable for quantum sensing. To use NV centres for nanometre scale sensing of magnetic fields, NV centres in nanodiamonds have been attached to atomic force microscopy (AFM) tips. Today, diamond AFM tips with a single NV centre, along complete microscope setups, are commercially available and are used in academic and industrial applications. These microscope setups all operate at room temperature. As the NV centre is capable of sensing magnetic fields also at cryogenic temperatures, and studying magnetic fields at such temperatures is particularly important for novel materials of quantum devices, amongst others, we have developed a cryogenic NV magnetometer. The magnetometer is commercially available, and a first demonstrator has been installed in a research facility.We present the key features and measurement results achieved with diamond tips and a fully remote controllable microscope platform. We show µT per √Hz sensitivity, low noise AFM imaging and ODMR scans in a closed-cycle cryostat.

P73. Towards cavity-mediated coupling of confined excitons in 2D materials

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Excitons in monolayer transition-metal dichalcogenides (TMD) exhibit large oscillator strengths and hence are well-suited for strong light-matter coupling. While for free excitons strong coupling to photonic cavities has been demonstrated in numerous experiments, nonlinearities in those systems are relatively weak. The recently demonstrated quantum confinement of excitons to length scales of about 20nm is a promising route towards enhancing nonlinearities [1].We want to realize confined excitons with the prospect of embedding them into a high-finesse microcavity and reach the strong coupling regime. To confine the excitons in transverse direction and tune their energy, we develop a specific electric gate configuration. Our microcavity will be fiber-based and tunable at cryogenic temperatures. With this platform we aim for the realization of a quantum emitter in a cavity by harvesting the enhanced nonlinearity combined with a cavity-enabled photon blockade.

Reference

[1] Thureja et al., Nature 606, 298-304 (2022)

P74. Field-induced hybridization of moiré excitons in MoSe2/WS2 heterobilayers

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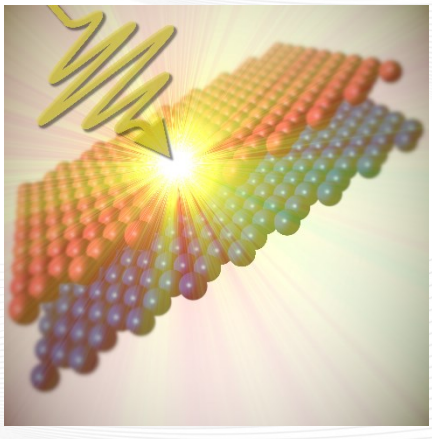
On our poster, we present the experimental and theoretical study on the hybridization among intralayer and interlayer moiré excitons in a $MoSe_2/WS_2$ heterostructure with antiparallel alignment. Using a dual-gate device and cryogenic white light reflectance and narrow-band laser modulation spectroscopy, we subject the moiré excitons in the $MoSe_2/WS_2$ heterostack to a perpendicular electric field, monitor the field-induced dispersion and hybridization of intralayer and interlayer moiré exciton states, and induce a cross-over from type I to type II band alignment.
Moreover, we employ perpendicular magnetic fields to map out the dependence of the corresponding exciton Landé *g*-factors on the electric field. Finally, we develop an effective theoretical model combining resonant and non-resonant contributions to moiré potentials to explain the observed phenomenology and highlight the relevance of interlayer coupling for structures with close energetic band alignment as in $MoSe_2/WS_2$. [1]



P75. Near-field characterization of deep sub-wavelength confinement in InP cavities

Frederik Schröder[1,3], Meng Xiong[1,3], Rasmus E. Christiansen[2,3], Yi Yu[1,3], Laura N. Casses[1,3], Elizaveta Semenova[1,3], Kresten Yvind[1,3], MartijnWubs[1,3], Ole Sigmund[2,3], Jesper Mørk[1,3] and Nicolas Stenger[1,3]

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Enhancing light-matter interaction has important applications in integrated photonics and quantum technology. Since light-matter interaction strength scales inversely with the mode volume, spatial confinement of light is of significant interest. Silicon dielectric nanocavities have been demonstrated to exhibit sub-wavelength confinement of light without being limited by absorption losses [1]. For integration with active materials, a direct bandgap semiconductor like indium phosphite is favorable.

We report sub-wavelength mode-confinement in an indium phosphide nanocavity [2]. The devices are designed exploiting topology optimization [3] and fabricated with electron-beam lithography and inductively coupled plasma etching. The experimental demonstration of sub-wavelength confinement is carried out by scattering-type scanning near-field optical microscopy with a pseudo-heterodyne detection scheme. Demodulation at higher harmonic orders of the tip tapping frequency enables retrieval of the scattered electric field with a nanoscale spatial resolution. Importantly, we show that the electric field is strongly confined with a mode volume of $0.26(\lambda/2n)^3$.

References

[1] M. Albrechtsen et al. Nature Communications, 13(1), p. 6281 (2022). DOI: 10.1038/s41467-022-33874-w
[2] M. Xiong et al. Optical Materials Express 14(2), p. 397 (2024). DOI: 10.1364/OME.513625
[3] R. E. Christiansen et al. Journal of the Optical Society of America B, 38(2), p. 510. DOI: 10.1364/josab.405955

P76. Ultrafast All-Optical Polarization Switching with q-BIC Resonance for Enhanced Second Harmonic Generation

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Second harmonic generation (SHG) is vital in various fields, such as integrated photonics, frequency conversion, self-referencing of frequency combs, nonlinear spectroscopy, and pulse characterization. The polarization state can encode information that necessitates ultrafast polarization switching for integrated photonics. However, existing electronic switching methods suffer from slow response times despite high conversion efficiency, while all-optical nonlinear devices offer high speed but limited modulation depth. State of the art methods yielded SHG signal strengths remaining in the femtowatt range. In this study, I propose an innovative solution involving all-optical polarization switching with nearly 100% modulation depth, coupled with a novel approach utilizing quasi-bound states in the continuum (q-BIC) resonance to augment SHG output power. A degenerated pump-probe setup with a nanostructure exhibiting q-BIC resonance at the fundamental frequency to enhance SHG was used. Leveraging 3R-MoS2, which exhibits monolayer-like behavior in bulk but offers increased material interaction, the findings demonstrate a modulation depth close to 100% and switching speeds limited only by the duration of the fundamental pulse.

Moreover, the SH signal strength reaches the picowatt range. Looking ahead, the tunability of the BIC resonance enables variable SH signal generation, including the possibility of multiple resonances. This approach, contingent upon D3h crystal symmetry considerations, holds promise for high-speed integrated frequency converters, broadband autocorrelators for ultrashort pulse characterization, and as a component in all-optical transistors.

P77. Investigating edge-functionalized graphene nanoribbons in the visible to NIR regime via scattering-type scanning near-field optical microscopy

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Edge-functionalizing has been found to fine-tune the opto-electronic and magnetic properties of graphene nanoribbons (GNRs). In this work, we characterize perylene imide attached GNRs (PMI-GNRs) in the visible to NIR range via scattering-type near-field optical microscopy and discuss the possibilities of observing plasmon resonances within the same.

Introduction

Plasmonics have found numerous applications in chemical detection, photovoltaics, nanoscale photometry, nonlinear optics etc. Controlling these collective excitations have been of prominent interest in recent years. The ultrahigh carrier mobilities of selected 2D materials, such as graphene, have made them candidates for tuneable plasmon excitations and biosensors with higher sensitivity than metallic ones have been realized [1].

Graphene nanoribbons (GNRs), which are graphene strips with widths up to a few 10s of nanometres, have garnered interest due to their interesting opto-electronic and magnetic properties. These are particularly interesting due to their non-zero band gap in comparison with graphene. GNR plasmons have greatly been explored in the mid-IR frequencies and although ways of pushing their plasma frequency towards the visible to NIR regime (e.g. via doping) have been theoretically predicted, to the best of our knowledge they have not yet been experimentally observed [2].

Edge functionalization of GNRs with functional groups such as anthraquinone (AQ), naphthalene imide (NMI) and perylene imide (PMI) have demonstrated the ability to fine tune the optoelectronic properties partly due to their supramolecular self-assembly[3]. The band gap in these functionalised GNRs hence has been demonstrated to lie in the visible range, with bandgap energies of ~2 eV. In this work, we investigate the plasmonic behaviour of these materials utilising scattering-type scanning near field optical microscopy (s-SNOM) in the visible and NIR range. We observe strong near-field amplitude and phase contrast as we move from visible to near infrared. As these properties relate to the dielectric function of the material (i.e. reflectivity and absorption), we calculate an approximate plasmon resonance frequency for varying edge functional groups and discuss the potential of increased absorption in this range due to plasmonic excitation. Achieving plasmonic resonances in visible-NIR ranges can have massive impacts on photonics and communication technologies.

Experimental details and results

A. Sample and experimental details

Edge-functionalized ribbons, PMI-GNRs were synthesized as per the previously reported procedure[3]. Briefly, polyphenylene precursor bearing one bromo group and one dodecyl chain per repeating unit was obtained through the AB-type Diels Alder polymerization of tetraphenylcyclopentadienone-based monomer. Bromo group on the precursor polymer was substituted with perylene monoimide through Suzuki coupling reaction to yield PMI functionalized polymer. The PMI polymer was subsequently converted into PMI-GNR through the oxidative cyclo-dehydrogenation using $FeCl_3$ in dichloromethane and nitromethane. Purified PMI-GNRs were dispersed into 1,2,4-trichlorobenzene and dilute solutions were drop casted on freshly peeled graphite surface to form self-assembled structures of straight and uniform nanoribbons[3], as shown in fig. 1.

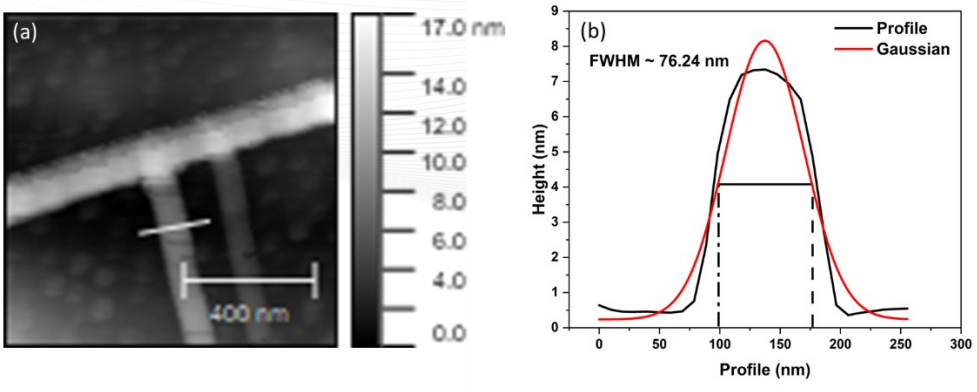

Fig. 1: (a) AFM image of PMI-GNR bundles. (b) Line profile across one bundle

The Vis-NIR s-SNOM in the CUSTOM facility at the University of Manchester consists of a Neaspec s-SNOM system integrated with 4 continuous wave lasers with wavelengths 633 nm, 785 nm, 1064 nm and 1550 nm. This is further coupled to the apex of an AFM tip, which is operated in tapping mode. The system works with a pseudo-heterodyne detection scheme enabling the extraction of the amplitude and phase independently of the scattered light. The scattered signal is demodulated at higher harmonics of tapping frequency of the tip to reduce far-field background noise and isolate the near field signal. By scanning the sample underneath the AFM tip in tapping mode, both the topography and the scattered near-field amplitude and phase can be mapped simultaneously.

B. Results

We observed a strong contrast in the near-field amplitude and phase images between sample and substrate as we move from 633 nm to 785 nm. But this decreased as we move onto 1550 nm, the contrasts are almost non-existent. As the phase of the near-field signal relates to absorption and the near-field amplitude relates to reflectivity, this suggests increased absorption around ~785nm. A quantitative estimate of these contrasts was obtained by obtaining a profile across the ribbon bundles and plotted against the wavelength as shown in fig. 2.

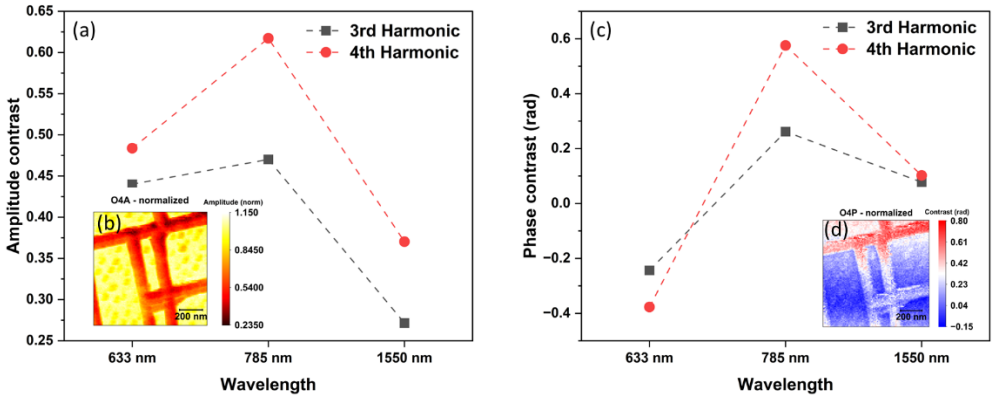

Fig. 2: (a) & (c) Amplitude and phase contrasts for PMI-GNRs across wavelengths. Insets (b) and (d) shows the amplitude and phase images at 785 nm

A rough approximation of the plasmon resonance frequency for our nanoribbon sample was theoretically predicted using the formula,

$$\hbar\omega_{GSp} = \sqrt{\frac{4\alpha}{\epsilon_1 + \epsilon_2} E_F \hbar c q} \qquad (1)$$

where E_F is the Fermi Energy (~ 1 eV), ħ is the reduced planck's constant, α is the fine structure constant given by 1/137, ω_{GSP} the plasmon resonance frequency, α is a constant given by 1/137, ϵ_1 (1) and ϵ_2 (2) are the dielectric constants at the two interfaces, c the speed of light and q the plasmon wavevector [45]. An excitation wavelength of approximately 890 nm was obtained for a ribbon width of 6 nm. This correlates with our experimental observations, as an increase in contrast is observed as we move towards 785 nm. We therefore expect this contrast to further increase up to ~890 nm, before reducing. In future studies, we will also investigate other NIR frequencies (e.g. 1 µm) beyond our calculated plasmon frequency to determine if we are observing a plasmon resonance in these materials.

Summary and future work

The opto-electronic behaviour of PMI-edge functionalized GNRs were characterized using s-SNOM in the visible to NIR regime. Strong amplitude and phase contrasts were observed at 633 nm and 785 nm, which almost vanished at a higher NIR wavelength. A theoretical approximation indicated the presence of plasmon resonance in the range considered. Future scope for this work would involve narrowband s-SNOM imaging of the sample near the predicted wavelength to visualize the plasmon polariton propagation in the ribbons. The exact fermi energy needs to be found out from conductivity measurements and hence the accuracy of the prediction can be improved.

References

[1] D. Rodrigo, O. Limaj, D. Janner, D. Etezadi, F.J. García De Abajo, V. Pruneri, and H. Altug, "Mid-infrared plasmonic biosensing with graphene," Science (1979) **349**(6244), 165–168 (2015).
[2] F.J.G. De Abajo, "Graphene plasmonics: Challenges and opportunities," ACS Photonics **1**(3), 133–152 (2014).
[3] A. Keerthi, B. Radha, D. Rizzo, H. Lu, V. Diez Cabanes, I.C.Y. Hou, D. Beljonne, J. Cornil, C. Casiraghi, M. Baumgarten, K. Müllen, and A. Narita, "Edge Functionalization of Structurally Defined Graphene Nanoribbons for Modulating the Self-Assembled Structures," J Am Chem Soc **139**(46), 16454–16457 (2017).
[4] S. Ergun, J.B. Yasinsky, and J.R. Townsend, TRANSVERSE AND LONGITUDINAL OPTICAL PROPERTIES OF GRAPHITE (Pergamon Press Ltd, 1967).
[5] D. Research, P. André, and D. Gonçalves, Springer Theses Recognizing Outstanding Ph Plasmonics and Light-Matter Interactions in Two-Dimensional Materials and in Metal Nanostructures Classical and Quantum Considerations (n.d.).

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P78. Nano-electrical characterization of moiré systems

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Moiré bilayers have emerged as established playgrounds for exploring various strongly correlated electronic and topological phenomena, such as unconventional superconductivity and Chern insulator phases. Characterizing the electrical properties of moiré systems at the nanoscale can greatly enhance the understanding of their diverse electronic features. By leveraging the versatility of correlative and cryogenic scanning probe microscopy (SPM), we demonstrate a comprehensive research process on layered graphene structures, spanning from the identification of regions of interest with Kelvin probe force microscopy (KPFM) to the revelation of their local electrical and electromechanical properties using conducting-tip atomic force microscopy (ct-AFM) and piezo-response force microscopy (PFM). We have achieved a lateral resolution of <10 nm in these moiré bilayers, which is remarkable for a dry-cryostat environment, and renders cryogenic SPM both suitable and user-friendly for studying moiré systems.

P79. Imaging and Spectroscopy of Novel TMD Lateral Heterostructures Grown by Chemical Vapor Deposition

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Semiconducting transition metal dichalcogenide (TMD) monolayers are known for their robust excitonic emission properties. The scope of these materials has been expanded further via the fabrication of heterostructures that combine different TMD monolayers [1]. Vertical heterostructures can be fabricated through mechanical exfoliation and stacking of layers. In addition to excitons within a layer, vertical heterostructures, such as $MoSe_2$-WSe_2, also host electron-hole complexes between the different layers, such as interlayer excitons. Lateral heterostructures (LHs), where the different monolayers are bonded covalently in the plane of the layers, are less trivial to fabricate. Here chemical vapor deposition (CVD) has proven to be a versatile technique that allows for the fabrication of LHs [2] and studying their excitonic properties [3]. In LHs charge transfer (CT) excitons can exist with the hole in WSe_2 and the electron in $MoSe_2$ [4]. The binding energy of these CT excitons in $MoSe_2$-WSe_2 LHs is smaller than the binding energy of the excitons in the individual materials. CT excitons have a large in-plane electric dipole moment making them attractive candidates for exciton-based optoelectronic devices. In our work, we investigate the properties of the CT excitons in LHs and compare them with theoretical predictions. We perform photoluminescence imaging, high-resolution micro-photoluminescence, and Raman spectroscopy at room temperature and 4K on CVD-grown LHs. We investigate exciton complexes and transport at the $MoSe_2$-WSe_2 interface.

References

[1] Malic, E., Perea-Causin, R., Rosati, R., Erkensten, D., Brem, S., Exciton transport in atomically thin semiconductors. *Nat Commun* **14**, 3430 (2023).
[2] Najafidehaghani, E., Gan, Z., George, A., Lehnert, T., Ngo, Q., G., Neumann, C., Bucher, T., Staude, I., Kaiser, D., Vogl, T., Hübner, U., Kaiser, U., Eilenberger, F., Turchanin, A., 1D p-n junction electronic and optoelectronic devices from transition metal dichalcogenide lateral heterostructures grown by one-pot chemical vapor deposition synthesis. *Adv. Funct. Mater.* **31**, 2101086 (2021).
[3] Beret, D., Paradisanos, I., Lamsaadi, H., Gan, Z., Najafidehaghani, E., George, A., Lehnert, T., Biskupek, J., Kaiser, U., Shree, S., Estrada-Real, A., Lagarde, D., Marie, X., Renucci, P., Watanabe, K., Taniguchi, T., Weber, S., Paillard, V., Lombez, L., Poumirol, J., Turchanin, A., Urbaszek, B., Exciton spectroscopy and unidirectional transport in $MoSe_2$-WSe_2 lateral heterostructures encapsulated in hexagonal boron nitride. *npj 2D Mater Appl* **6**, 84 (2022).
[4] Rosati, R., Paradisanos, I., Huang, L., Gan, Z., George, A., Watanabe, K., Taniguchi, T., Lombez, L., Renucci, P., Turchanin, A., Urbaszek, B., Malic, E., Interface engineering of charge-transfer excitons in 2D lateral heterostructures. *Nat Commun* **14**, 2438 (2023).

P80. Fingerprint of magneto-optical Faraday rotation in Raman spectra of MoS_2

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We perform Raman scanning microscopy on a MoS_2 flake at 2K and in varying magnetic field (*B*), for both parallel (VV) and perpendicular (VH) polarization configuration of polarizer and analyser. We observe suppression of the A_1' Raman signal of MoS_2 in *B*=9T in the VH configuration. Raman maps were recorded in different *B* for both VV and VH configurations, and the intensity ratio of Raman signals A_1' and E' was inferred from them. The observed changes in suppression of A_1' are in good agreement with previous literature data [2]. However, in another set of published data [3] this change could have only been detected at significantly higher *B*. Beside the influence of *B* on the oscillation modes of a crystal, one must also consider the impact of the magneto-optical Faraday effect. For this purpose, we recorded in addition a series of Raman spectra of the Si substrate as the function of *B* and polarization. The MoS_2 and Si peak ratios show approximately the same dependence on *B*, which indicates the dominant cause for the changes in the detected Raman signals being the Faraday effect. As the Faraday rotation angle is linear with *B*, it is straightforward to compensate it, which can even be automated in the cryogenic Raman microscope that we have developed.

P81. Light-matter interaction with bound states in the continuum in monolithic van der Waals metasurfaces

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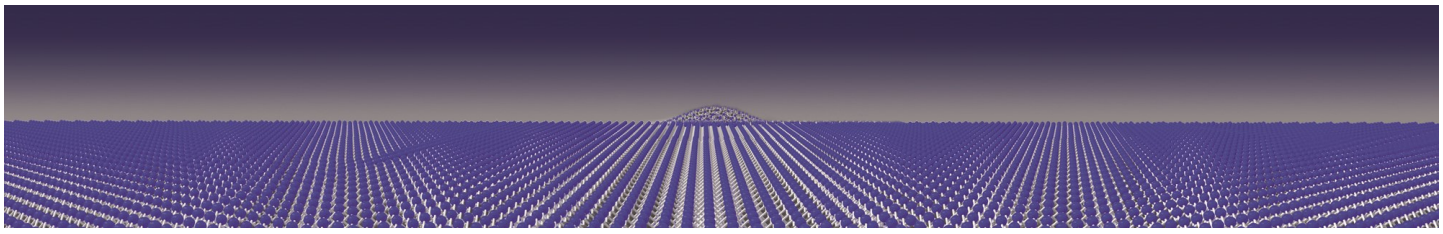
Van der Waals (vdW) materials, such as hexagonal boron nitride (hBN) and Transition Metal Dichalcogenides (TMDCs), exhibit remarkable optical properties. These include tightly bound excitons, optically active spin defects, substantial optical anisotropy, and high refractive indices, making them ideal for engineering novel nanophotonic applications. In our study, we exploit the concept of quasi-bound states in the continuum (qBIC) to create sharp optical resonances within dielectric metasurfaces made entirely of hBN or TMDCs. This monolithic approach achieves optical resonances with quality factors exceeding 100, towards increased light-matter interaction and cavity QED. Specifically, in hBN metasurfaces, we achieved spectral tuning across the whole visible spectrum [1] and weak-coupling of native spin defects [2]. Moreover, our approach shows great promise for achieving strong light-matter coupling regime, as demonstrated by the anti-crossing observed between qBIC resonances and intrinsic excitons in TMDC metasurfaces, leading to a Rabi splitting of 116 meV in ambient conditions [3]. These findings underscore the potential of integrating qBIC metasurfaces with vdW materials to design innovative nanophotonic platforms and room temperature polaritonic devices.

References

[1] L. Kühner, L. Sortino, *et al.* "High-Q Nanophotonics Over the Full Visible Spectrum Enabled by Hexagonal Boron Nitride Metasurfaces" *Advanced Materials* 35, 13 (2023)
[2] L. Sortino, *et al.* "Optically addressable spin defects coupled to bound states in the continuum metasurfaces" *Nature Communications* (2024)
[3] T. Weber, L. Kühner, L. Sortino, *et al.* "Intrinsic strong light-matter coupling with self-hybridized bound states in the continuum in van der Waals metasurfaces" *Nature Materials* (2023)



P82. Cascaded quantum system for on-demand heralded single-photon source at mid-infrared frequencies

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We propose a new method to generate single photons in the mid-infrared (MIR) using solid-state or molecular quantum emitters in the visible. We show that cavity QED effects can be used to selectively enhance Frank-Condon transitions, thereby deterministically preparing a single Fock state of a polar phonon mode. An antenna coupled to this polar phonon mode can convert the phonon into a single photon that propagates to the far-field with identical frequency. In this proposal, we combine macroscopic QED calculations with methods from open quantum system theory, and show that efficient generation of MIR photons can occur for modest light-matter coupling strengths, which are achievable with state-of-the-art technologies. The cascaded system that we propose provides a new quasi-deterministic source of heralded single photons in a region of the electromagnetic spectrum difficult to reach with solid-state quantum emitters.

P83 Investigating 2D van der Waals magnets with AI assisted nitrogen vacancy magnetometry

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Atomically thin van der Waals materials allow the design of functional devices comprised of stacked crystalline layers with individually vastly different material properties. This field of tailor-made materials has been recently enhanced by the discovery of stable 2D magnets such as CrSBr, enabling new applications in the field of spintronics.
We use widefield nitrogen vacancy (NV) vector magnetometry to measure the magnetic stray field from an hBN encapsulated 3L CrSBr flake in the temperature range from 85-150K.
While we observe the expected Curie-Weiss behavior with a T_N = 132K in the magnitude of the magnetization, we observe partial switching of the sample (no domains), pinned to a line defect in the hBN at approximately 20K below T_N. This partial switch successively extends with T throughout the sample.
We reconstruct the T-dependent magnetization employing a deep learning approach based on a convolutional neural network (CNN). Because CrSBr is an in-plane layered AFM, this inversion problem is mathematically ill-defined and therefore relies on numerical solutions constrained by physics defined boundary conditions. Specifically, we incorporate Maxwell's equations through micro magnetic simulations in the computation of the loss during the training phase of the network.

P84. Doping-control of excitons and magnetism in few-layer CrSBr

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In two-dimensional (2D) magnets, phenomena distinct from bulk magnetism have been revealed, such as sensitivity to charge doping and electric field in few-layer CrI3 [1]. Within the class of 2D magnets, air-stable CrSBr stands out as an antiferromagnetic semiconductor with a high Néel temperature, excitons coupled to the magnetic order [2], and exciton-magnon coupling [3]. In this talk, I will present our work on doping-control of excitons and magnetism in few-layer CrSBr [4]. We demonstrate that both exciton and magnetic transitions are sensitive to field-effect charging, exhibiting bound exciton-charge complexes and doping-induced metamagnetic transitions. We further visualize magnetic domain formation induced by magnetic field or charge-doping at the metamagnetic transition all-optically by raster-scan reflectance imaging. Our work identifies few-layer CrSBr as a rich platform for exploring collaborative effects of charge, optical excitations, and magnetism.

References

[1] S. Jiang et al., Nat. Nanotechnol. 13, 549 (2018).
[2] N. Wilson et al., Nat. Materials 20, 1657-1662 (2021).
[3] Y. J. Bae et al., Nature 609, 282 (2022).
[4] F. Tabataba-Vakili et al., arXiv:2312.11041 (2023).

P85. Unveiling the Mechanism of Phonon-Polariton Damping in α-MoO_3

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Phonon polaritons (PhPs) – light coupled to lattice vibrations – in the highly anisotropic polar van der Waals material molybdenum trioxide (a-MoO_3) have recently been a subject of intense research due to their extreme subwavelength field confinement[1], directional propagation[2,3] and unprecedented low losses[1,4]. However, most previous studies were focused on exploiting the squeezing and steering capabilities of a-MoO_3 PhPs for controlling light at the nanoscale, without inquiring much into the dominant microscopic mechanism that determines their long lifetimes, key for their implementation in nanophotonic applications. In this work we explore the fundamental mechanisms of PhP damping in a-MoO_3 by combining *ab initio* density functional perturbation theory (DFPT) calculations with experimental scattering-type scanning near-field optical microscopy (s-SNOM) and conventional Fourier-transform infrared (FTIR) spectroscopy measurements over a wide temperature range (8 – 300 K). The excellent agreement between the experiment and the theory in reproducing the polaritonic lifetime, achieved without involving any adjustable parameters, allows us to identify third-order anharmonic phonon-phonon scattering as the main damping mechanism of a-MoO_3 PhPs. These results thus unveil the fundamental limits of low-loss PhPs, critical for validating their implementation into nanophotonic devices.

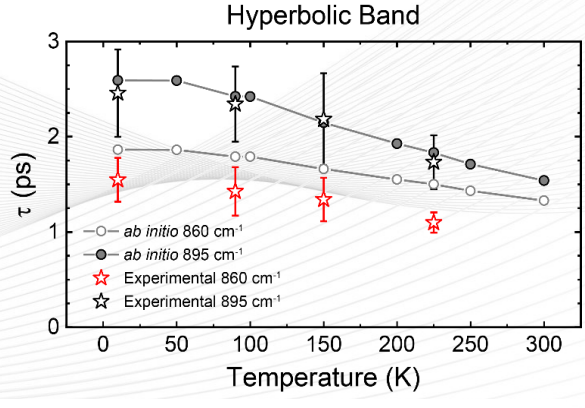

Figure 1. Temperature Dependence of the PhPs Lifetimes in α-MoO_3. Theoretical (circles) and experimental (star symbols) PhPs lifetimes for a 104nm-thick α-MoO_3 flake as a function of temperature for the hyperbolic RB (ω_0 = 860 cm^{-1} and ω_0 = 895 cm^{-1}). Gray straight lines are guides to the eye.

References

[1[Ma, W. *et al.* In-plane anisotropic and ultra-low-loss polaritons in a natural van der Waals crystal. *Nature* **562**, 557–562 (2018).

[2]Martín-Sánchez, J. *et al.* Focusing of in-plane hyperbolic polaritons in van der Waals crystals with tailored infrared nanoantennas. *Sci Adv* **7**, (2021).

[3] Duan, J. *et al.* Planar refraction and lensing of highly confined polaritons in anisotropic media. *Nature Communications 2021 12:1* **12**, 1–8 (2021).
[4] Taboada-Gutiérrez, J. *et al.* Broad spectral tuning of ultra-low-loss polaritons in a van der Waals crystal by intercalation. *Nat. Mater.* **19**, 964–968 (2020).

P86. Enhancing interlayer exciton dynamics by coupling with monolithic cavities via field-effect Stark tuning

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Optical microcavities represent an effective tool for controlling the photonic emission behavior of light-sensitive materials by light recirculation. Spatially-indirect interlayer excitons (IXs) can significantly alter their emission energy through the quantum-confined Stark effect. However, their electrical tunability in systems combined with cavities has not been utilized until now. In our study, we adjust the energy detuning between the cavity resonance and the IX emission within a monolithic Fabry-Perot cavity using a vertical electric field. We demonstrate a concurrent boost in both the emission intensity and the lifetime of weakly-coupled IXs when optimally coupled with the optical cavity, due to pronounced Purcell inhibition and cavity transparency effects. Additionally, we explore the adjustable momentum dispersion of coupled IXs using back-focal plane imaging and provide explanations based on the cavity interactions of IX transition dipoles, supported by theoretical models. Our findings mark a significant step in integrating highly interactive IXs within monolithic cavities, showcasing the potential of electrically-tunable IX cavity coupling for both fundamental research in exciton condensate manipulation and the development of excitonic devices.

P87. Observation of Exceptional Points in Metamaterials (MMs) and Polaritonic Cavities

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One of the most captivating features of coupled systems (which in quantum mechanics are described by non-Hermitian (Hamiltonians) is the presence of spectral branch-point singularities, known as exceptional points (EPs), where the real parts and imaginary parts of the coupled modes (eigenvalues) coalesce when varying parameters such as coupling strength as well as loss and gain.
In this work, we theoretically and experimentally demonstrate that EPs can be observed in a well-known system comprised of a metamaterial and a photonic cavity by tuning the coupling strength. Our system offers an opportunity to study systematically larger sensitivity enhancement near the EP..

P88. Anisotropic Exciton Polariton Propagation in $ZrSe_3$

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The optical properties of TMCs are dominated by excitons due to their large binding energies, with strong light-matter coupling between excitons and photons leading to the propagation of waveguided exciton polariton (EP) modes in bulk flakes. When probed via s-SNOM, the interference between tip-backscattered light and in-plane propagative modes scattered by the crystal edge causes the formation of EP fringes in near-field amplitude images. These fringes are deeply sensitive to crystal axis, excitation wavelength and crystal thickness, with observations of this fringe tuneability allowing for detailed mode analysis and derivation of the crystal dielectric tensor in higher-symmetry crystals. This poster reports on attempts to apply this methodology to identify the properties of waveguided modes in lower-symmetry crystals such as monoclinic $ZrSe_3$.

P89. Negative reflection of nanoscale-confined polaritons in a low-loss natural medium

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Negative reflection occurs when light is reflected toward the same side of the normal to the boundary from which it is incident. This exotic optical phenomenon is not only yet to be visualized in real space but also remains unexplored, both at the nanoscale and in natural media. Here [1], we directly visualize nanoscale-confined polaritons negatively reflecting on subwavelength mirrors fabricated in a low-loss van der Waals crystal. Our near-field nanoimaging results unveil an unconventional and broad tunability of both the polaritonic wavelength and direction of propagation upon negative reflection. On the basis of these findings, we introduce a device in nano-optics: a hyperbolic nanoresonator, in which hyperbolic polaritons with different momenta reflect back to a common point source, enhancing the intensity. These results pave way to realize nanophotonics in low-loss natural media, providing an efficient route to control nanolight, a key for future on-chip optical nanotechnologies.

References

[1] G. Álvarez-Pérez, J. Duan, et al. *Science Advances* 8, eabp8486 (2022).

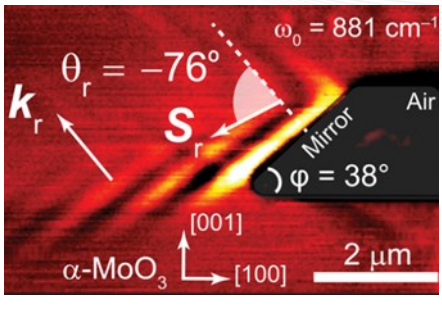

Figure 5: Visualization of negative reflection of nanoscale-confined polaritons in a natural medium.

P90. Cavity-enhanced photon indistinguishability at room temperature and telecom wavelengths

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Indistinguishable single photons in the telecom-bandwidth of optical fibers are indispensable for long-distance quantum communication. Solid-state single photon emitters have achieved excellent performance in key benchmarks, however, the demonstration of indistinguishability at room-temperature remains a major challenge. Here, we report room-temperature photon indistinguishability at telecom wavelengths from individual nanotube defects in a fiber-based microcavity operated in the regime of incoherent good cavity-coupling. The efficiency of the coupled system outperforms spectral or temporal filtering, and the photon indistinguishability is increased by more than two orders of magnitude compared to the free-space limit. Our results highlight a promising strategy to attain optimized non-classical light sources.

P91. Controlling magnetic domain evolution via strain in CrSBr

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Two-dimensional (2D) magnets are an emerging area of research with potential for the development of magnetic materials and device applications ranging from magnetic storage to spintronics [1,2]. In contrast to conventional magnets, the magnetic properties of these materials respond sensitively to external stimuli, such as strain or doping. Engineering van der Waals (vdW) heterostructures from such 2D magnets can yield complex magnetic ground states including skyrmion phases or other non-collinear magnetic configurations [3]. The 2D semiconductor CrSBr is an A-type antiferromagnet with remarkable stability under ambient conditions and a Néel temperature of T_N~132 K in the bulk [4]. Recently, a controllable and reversible strain-induced antiferromagnetic (AFM) to ferromagnetic (FM) phase transition was reported in CrSBr [5], suggesting the possibility of devices such as magnetoresistive switches that are actuated by strain or magnetic tunnel junctions that do not require an external applied field. The observed effect is attributed to changes in the magnetic exchange pathways that result in enhancement of the AFM interlayer interaction under compressive strain or decrease and eventually change of the AFM coupling to FM under tensile strain [5-6]. However, direct evidence of the influence of strain on the magnetic behavior and the effects of inhomogeneous strain in the material are not captured by the measurement techniques that have been used so far. In this talk, I will present nanometer-scale magnetic imaging experiments, using our recently developed scanning SQUID-on-lever probe [7], that shed light on how strain affects the local magnetic behavior of the flake. We measure exfoliated flakes of CrSBr, in which strain has been induced along the a-axis by bending. As a result, spatially dependent compressive and tensile strain of varying strengths is produced on the same flake [8]. I will present how this inhomogeneous strain affects the magnetic hysteresis and the magnetic switching of the material when we apply an external magnetic field along the easy axis (b-axis). By performing micromagnetic simulations, we are able to reproduce the magnetic evolution and gain further insight into the underlying magnetization configurations.

References

[1] C. Gong et al. Nature **546** (2017), 265–269.
[2] B. Huang et al. Nature **546** (2017), 270–273.
[3] Y. Xu et al. Nat. Nanotechnol. **17** (2022), 143–147.
[4] O. Göser et al. Journal of Magnetism and Magnetic Materials **92** (1990), 129-136.
[5] J. Cenker et al. Nat. Nanotechnol. **17** (2022), 256-261.
[6] X. Bo et al. New J. Phys. **25** (2023), 013026.
[7] Wyss et al, Phys. Rev. Applied **17** (2022), 034002
[8] M. Kapfer et al. Science **381** (2023), 677-681.

P92. Van der Waals materials for nanophotonics and laser devices

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Nanophotonic structures enable a range of applications including optical waveguiding, Purcell enhancement of light emission and low-threshold lasing. Many research fields and technologies have benefited from nano-scale resonators and waveguides realised by noble metals or dielectrics such as silicon, and III-V materials. While these offer a large range of opportunities for both research and technology, van der Waals (vdW) materials may expand the possibilities of nanophotonics in the visible and near-infrared due to high refractive indices (n>4), low absorption in visible wavelength range, and compatibility with a wide range of substrates due to their weak vdW attraction.
Here, we will present how to fabricate nanoantennas and metasurfaces in vdW materials in a variety of geometries and a range of photonic applications. We observed Mie resonances as well as strong coupling between the excitonic features and anapole modes in the vdW nanoantenna. Due to the weak vdW interactions of the nanoresonators and the substrate, we were able to use an atomic force microscopy cantilever in the repositioning of double-pillar nanoantennas to achieve ultra-small gaps of 10 nm [1]. By employing a monolayer of WS2 as the gain material, we observe room-temperature Purcell enhancement of emission as well as low-temperature formation of single photon emitters with enhanced quantum efficiencies [2,3]. More recently, we have also achieved bound states in the continuum ultra-low threshold lasing with these materials [4], highlighting the vdW materials as a promising platform for optoelectronic devices.

References

[1] “Transition Metal Dichalcogenide Dimer Nanoantennas for Tailored Light–Matter Interactions,” ACS Nano 16,4 (2022)
[2] “Van der Waals Materials for Applications in Nanophotonics”, Laser & Photonics Reviews, 2200957 (2023)
[3] “Van der Waals Nanoantennas on Gold as Hosts for Hybrid Mie-Plasmonic Resonances” arXiv preprint arXiv:2304.02537, under review.
[4] "Lasing from a 2D material enabled by a dual-resonance metasurface" accepted, ACS Nano (2024)

P93. Pump-probe spectroscopy of Rydberg excitons in TMDC monolayers

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Quantum photonic technologies rely on strong optical nonlinearities, such as those provided by Rydberg atoms. The solid-state analog to this are Rydberg excitons. Rydberg excitons in cuprous oxides with principal quantum numbers of up to n=25 show strong optical non- linearities, whose signatures could be detected by pump-probe spectroscopy [1]. In TMDC monolayers, which exhibit particularly strongly bound excitons, an increased nonlinearity could already be established for exciton-polaritons with n=2 [2].
Here, we report on the pump-probe spectroscopy of Rydberg states of excitons in TMDC monolayers at liquid helium temperatures. We use spectrally broad femtosecond probe pulses and a spectrometer to measure the transient differential reflectivity spectra. The degenerate pump-pulses are suppressed in a cross-polarized configuration such that the same Rydberg state is excited and probed. The doping of the monolayers is defined by electrical gating and kept neutral for the measurements.

References

[1] Heckötter, J., Walther, V., Scheel, S. et al., Nat Commun 12, 3556 (2021)
[2] Gu, J., Walther, V., Waldecker, L. et al., Nat Commun 12, 2269 (2021)

P94. Cryo-Magneto Near-Field Microscopy and Ultrabroadband Terahertz Nanospectroscopy of 2D Materials

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Infrared near-field spectroscopy provides unique capabilities for exploration of the nanoworld as it combines the information density of optical techniques with the spatial resolution of atomic force microscopy of ~10 nm. Due to technical challenges, infrared near-field microscopy is often limited to the mid-infrared range, with little access to lower photon energies. Also, it is usually not possible to apply magnetic fields in situ.

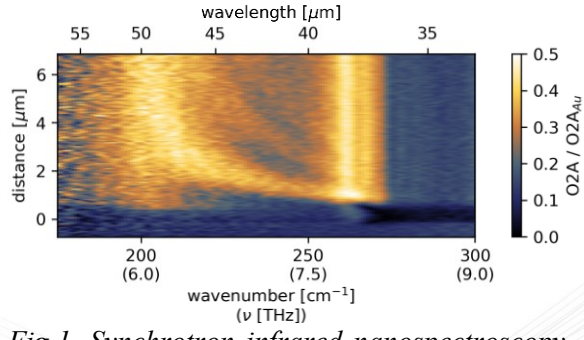

Fig.1. Synchrotron infrared nanospectroscopy enables broadband polariton interferometry of the hyperbolic phonon polaritons of GeS in the single-digit THz range [2].

At the National Synchrotron Light Source II (NSLS-II), we recently commissioned a new synchrotron-based infrared nanospectroscopy setup (NeaSnom by NeaSpec/Attocube). It is now available for general user proposals and enables ultrabroadband infrared nanospectroscopy in the single-digit THz spectral range, with a total spectral coverage from 5 to 150 THz (22 - 750 meV, 175 cm^{-1} – 6000 cm^{-1}) [1,2]. Fig. 1 showcases the THz hyperbolic phonon polaritons of GeS, an example of the setup's capabilities for nanospectroscopy of 2D and van der Waals materials. As a second technical breakthrough, we developed a near-field microscopy setup that operates at cryogenic temperatures and magnetic fields up to 7 T [3,4]. Fig. 2 illustrates how a magnetic field dramatically alters the optical properties of graphene due inter-Landau level transition. Work funded by U.S. Department of Energy under contracts DE-SC0012704 and DE-SC0019443.

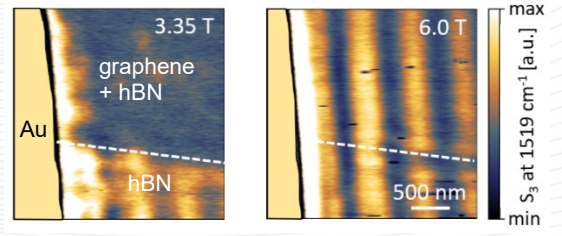

Fig.2.Magneto near-field microscopy explores the magnetic-field dependent optical properties of graphene [4].

References

[1] L. Wehmeier et al., under review (2024).
[2] L. Wehmeier et al., ACS Photonics 10, 4329 (2023).
[3] M. Dapolito et al., Nat. Nanotechnol. 18, 1409. (2023).
[4] L. Wehmeier et al., arXiv.2312.14093 (2023).

P95. THz-induced conversion of dark and bright interlayer excitons in $MoSe_2/WSe_2$ heterostructures

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Vertically stacked heterostructures of transition metal dichalcogenides (TMDCs) are a versatile platform to study electronic many-body phenomena. In these systems, the commonly encountered type-II band alignment and the presence of strong Coulomb interactions result in the formation of tightly-bound interlayer excitons (IXs). In view of their dipolar nature and rich interaction physics TMDC heterostructures offer an excellent platform for manipulation and engineering of optically active states. While forbidden for its monolayer constituents, the symmetry arguments in TMDC heterobilayers allow for the unique transition between spin dark and bright exciton states. This motivates the investigation of transitions between different excitonic species in heterostructures and even consider potential conversion pathways from inter- to intralayer excitons.Here, we address this topic by studying spectrally narrow IXs in the Moiré free limit of atomically reconstructed domains in hBN-encapsulated $MoSe_2/WSe_2$ heterobilayers, with well-defined dipolar selection rules and in absence of localization. We demonstrate the conversion of IX spin-triplet to spin-singlet states on ultrafast timescales of a few picoseconds by applying short THz pulses after optical excitation. Monitoring the time-resolved photoluminescence dynamics, a strong quenching of the triplet population induced by the THz radiation is observed, accompanied by a simultaneous increase of the singlet state emission. This allows us to study the subsequent formation dynamics of the triplet states in a controlled setting. Interestingly, upon THz arrival we also observe the reemergence of intralayer exciton signatures of $MoSe_2$ even several 100s of picoseconds after their initial decay. These results are intriguing from the perspective of many-body states coupled to low-frequency radiation and offer interesting possibilities towards ultrafast external control of spin states in van der Waals heterostructures.

P96. Magnetic tuning of quantum interference in excitonic three-level systems of WSe_2

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Monolayer semiconductors are emerging platforms for strong nonlinear light-matter interaction, due to their giant oscillator strength of tightly bound excitons formed by electron-hole pairs at the fundamental band edge. In monolayer WSe_2, unconventional high-energy excitons (HX) appear at around twice the energy of band-edge A-excitons.[1] The two species are tightly coupled through interaction with ultrafast laser pulses, effectively forming the analogue of a quantum-optical ladder-type three-level state system. Excitonic quantum interference emerges with coherence times beyond 100 fs in second-harmonic generation (SHG) in monolayers [2,3]. The phenomenon is also observed in bilayers, where the interlayer twist angle can be used to tune the energies of the exitonic states. The HX can be tuned over 235 meV, with a twist-angle susceptibility of 8.1 meV/°, an order of magnitude larger than that of the A-exciton [4,5].
Here, we study the valley-selective effect of magnetic fields normal to the TMDC plane on the high-lying excitonic species. In particular, we report on effective g-factors experienced by high-lying HX as determined from the shift of quantum interference conditions in second-harmonic generation with magnetic field.

References

[1] K.-Q. Lin *et al.*, Nat. Commun. **12**, 5500 (2021).
[2] K.-Q. Lin *et al.*, Nat. Phys. **15**, 242 (2019).
[3] J. M. Bauer et al., Nat. Photon. **16**, 777 (2022).
[4] K.-Q. Lin et al., Nat. Commun. **12**, 1553 (2021).
[5] K.-Q. Lin et al., Nat. Nanotechnol. **19**, 196 (2024).

P97. Measuring Phonon Dispersion and Electron-Phason Coupling in Twisted Bilayer Graphene using the Cryogenic Quantum Twisting Microscope

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The interaction between electrons and lattice vibrations - phonons - is ubiquitous in solids. Yet few techniques are able to quantitatively image electron-phonon coupling. Here we have built the first cryogenic quantum twisting microscope (cryo-QTM). We use its momentum-resolved capabilities combined with inelastic tunnelling spectroscopy to image the phonon dispersion of graphite and twisted bilayer graphene (TBG). Furthermore, we demonstrate that it is a quantitative technique that allows us to measure the strength of the electron-phonon coupling for each phonon mode in the twisted bilayer systems. Surprisingly, by continuously scanning the twist-angle, we observe a diverging coupling for the low-energy acoustic modes as the twist-angle decreases toward 6°. Our theory analysis allows us to disentangle the contributions from intralayer (single-layer graphene) and interlayer (twisted bilayer) phonons, revealing the importance of the Phason mode in modifying the interlayer coupling in TBG.

P98. In-Plane Electric-Field-Induced Orbital Hybridization of Excitonic States

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The giant exciton binding energy and the richness of degrees of freedom make monolayer transition metal dichalcogenide an unprecedented playground for exploring exciton physics in 2D systems. Thanks to the well-energetically separated excitonic states, the response of the discrete excitonic states to the electric field could be precisely examined. Here we utilize the photocurrent spectroscopy to probe excitonic states under a static in-plane electric field. Combined with numerical simulation, we demonstrate that the in-plane electric field leads to a significant orbital hybridization of Rydberg excitonic states with different angular momentum (especially orbital hybridization of 2s and 2p) and, consequently, optically actives 2p-state exciton. [1] Besides, the electric-field controlled mixing of the high lying exciton state and continuum band enhances the oscillator strength of the discrete excited exciton states. This electric field modulation of the excitonic states in monolayer TMDs provides a paradigm of the manipulation of 2D excitons for potential applications of the electro-optical modulation in 2D semiconductors.

References

[1] B. Zhu#, K. Xiao#, S. Yang, K. Watanabe, T. Taniguchi, X. Cui*, Phys. Rev. Lett. **131 (3)**, 036901

P99. Exploring nanoconfinement effects using van der Waals nanocapillaries

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Two-dimensional (2D) materials can be re-assembled into designer structures layer-by-atomic-layer in a precisely chosen sequence using van der Waals (vdW) technology. Applying this method, we have demonstrated the creation of two-dimensional capillaries by assembling 2D crystals. It can be viewed as if individual atomic planes were pulled out of a bulk layered crystal leaving an atomically thin void behind. This technology offers the smallest possible spatial confinement that can vary from just a few angstroms in height up to tens of nanometres, on demand. On this basis, we investigated the process of capillary condensation inside such capillaries by monitoring their elastic deformation using atomic force microscopy while changing relative humidity. We found that the classical description of capillary condensation – the Kelvin equation - could still qualitatively explain our experimental results at the atomic scale. Such nanocapillaries represent an ideal platform to study the nanoconfinement effects and light-matter interaction at the nanoscale.

P100. Strain activation of localized states in WSe_2

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We explore strain-activated emission centers formed by atomic force microscopy (AFM) indentation in monolayer WSe2 on a flexible polymer substrate. In the indented areas, we observe sharp new photoluminescence (PL) peaks characterized by sublinear power dependence in the spectral regions 1.62 − 1.66 eV and 1.70 − 1.73 eV. After lowtemperature thermal annealing (< 120 ◦C), WSe2 experiences strain relaxation, leading to a blue shift of the peaks' spectral position and their ultimate disappearance. Our analysis of peaks' position vs. strain allows drawing multiple conclusions regarding the nature of these emission centers. We elucidate the roles of excitonic confinement and hybridization between free excitons and defect-related states, a process activated by the level of strain. Overall, our approach suggests that the energy of localized emitters may be controlled via strain engineering.

P101. Epitaxial growth and in situ optical spectroscopies of 2D materials

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In contrast to the widely studied graphene and transition metal dichalcogenide (TMDC) family of 2D semiconductors, the group-III monochalcogenides (III-MCs) $M_{III}X$ (M_{III}∈{In,Ga} and X∈{S,Se,Te}) are much less investigated. III-MCs are layered semiconductors having thickness-dependent chemical, electronic, optical and vibrionic properties, such as a bandgap that can be tuned over the ultra-violet to the infrared spectral range as well as from indirect to direct as the thickness increases from a single tetramer to a few layers. Here, we present our UHV cluster tool that can be used to synthesize novel 2D materials and their heterostructures. It consists of a molecular beam epitaxy (MBE) chamber for the growth of ultrapure 2D group-III-MCs/nitrides, TMDCs and group-IV chalcogenides, connected via an UHV transfer channel to an analytical chamber capable of in-situ optical confocal spectroscopy (photoluminescence and Raman) at lattice temperatures of 300K to ~6K. As proof of principle, we show the optimization of the growth of 2D-GaSe by careful in-situ feedback of the crystalline phase and structural quality via reflection-high-energy electron diffraction and Raman spectroscopy. Finally, we show a complementary tool that will help evaluate the performance and reliability of the MBE-grown 2D materials by studying the main trap characteristics through electrical and optical deep-level transient spectroscopy.

P102. Excitons in reconstructed moiré heterostructures

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Layered transition metal dichalcogenides represent elementary building blocks of van der Waals semiconductor heterostructures. Vertical stacks of monolayers give rise to physical properties that depend sensitively on the choice of materials, the rotation angle between the individual layers, and the emergent band structure. Here, we discuss exciton phenomena in the presence of atomic lattice reconstruction in $MoSe_2$-WSe_2 heterobilayer systems obtained by exfoliation stacking [1] and chemical vapor deposition [2]. In particular, our experimental studies suggest lattice transformation from ideal moiré periodicity to mesoscopically reconstructed domains for heterostacks near both parallel and antiparallel alignment. We provide a unifying perspective on the origin of the diverse excitonic features associated with mesoscopic lattice reconstruction, and substantiate our findings by one-to-one correlations between observations in optical spectroscopy and secondary electron imaging of the heterostack morphology.

References

[1] S. Zhao et al., Nat. Nanotechnol. 18, 572-579 (2023).
[2] Z. Li et al., Nano Lett. 23, 4160-4166 (2023).

P103. Steering and cloaking of hyperbolic polaritons at deep-subwavelength scales

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The pursuit of light propagation at extreme subwavelength scales has been a prominent subject within nanophotonics. Achieving control over this phenomenon is pivotal for the realization of photonic circuits and on-chip devices. Polaritons in natural materials, which are hybrid light-matter modes, offer a powerful framework for light control with field confinement far below the diffraction limit. Polaritons have emerged as effective carriers of light, electrical signals, and even heat at the nanoscale within on-chip circuits. Here, we implement nanoscale polaritonic in-plane steering and cloaking in a low-loss atomically layered van der Waals insulator, α-MoO_3, comprising building blocks of customizable stacked and assembled structures. Each block, providing high quality factors and low interface losses, contributes specific characteristics that allow us to steer polaritons along the desired trajectories. This approach allows us to guide polaritons along any desired paths, leading to the demonstration of in-plane cloaking devices at deep subwavelength scales. From a scientific perspective, our results introduce a natural materials-based approach for the comprehensive manipulation of nanoscale optical fields.This breakthrough opens up a wealth of possibilities for advances in transformation polaritonics and represents a solid step in the quest towards achieving the ultimate optical manipulation goal through a meticulous organization of atomically thin interfaces.