From Fundamentals to the Future: Advancing Functionalities of Two-Dimensional Quantum Materials

Taiwanese-German WE-Heraeus-Seminar

14 - 18 July 2024

at the

Evangelische Akademie, Tutzing, Germany

WILHELM UND ELSE
HERAEUS-STIFTUNG

Introduction

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

Aims and scope of the Taiwanese-German WE-Heraeus-Seminar:

This Binational WE-Heraeus-Seminar will bring together distinguished researchers, mainly from Germany and Taiwan, to explore cutting-edge topics in low-dimensional materials, correlated systems, and quantum technologies, spanning both theory and experiment. The multifaceted electronic, optical, topological, and mechanical properties of low-dimensional quantum materials and atomic lattices and their exceptional variability and tunability make them promising candidates for new and improved (quantum) technologies.

In this four-day workshop, we invite experienced colleagues and, in particular, young researchers to share their latest work on the physics of low-dimensional materials regarding the fundamentals of novel quantum properties and potential future applications. We will build and foster scientific connections between Germany and Taiwan, theory and experiment, fundamental science and applications, and between current academic research and the semiconductor industry.

Introduction

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Introduction

Venue:

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Registration:

Marion Reisinger (WE Heraeus Foundation)
at the reception office
Sunday (16:00 h – 20:00 h) and Monday morning

Program

Program

Sunday, 14 July 2024

16:00 – 20:00	Registration	
From 18:00	*DINNER*	
19:45 – 20:45	Lain-Jong (Lance) Li	**Two-dimensional semiconductors for advanced electronics**
From 21:00		**UEFA EURO 2024, Final (Musiksaal)**

Monday, 15 July 2024

08:00 – 08:45	*BREAKFAST*	
09:30 – 09:45	Scientific organizers	**Opening and Welcome**
09:45 – 10:00	Stefan Jorda	**About the Wilhelm and Else Heraeus Foundation**
10:00 – 11:00	Klaus Ensslin	**Quantum devices in twisted graphene layers**
11:00 – 11:30	*COFFEE BREAK*	
11:30 – 12:10	Mario Hofmann	**Emergent optoelectronic properties of graphene-based junctions**
12:10 – 12:30	Lina Bockhorn	**Topological phenomena of folded graphene in magnetotransport properties**
12:30 – 14:00	*LUNCH*	
14:00 – 14:40	Christian Volk	**Radio-frequency charge detection on gate-defined bilayer graphene quantum dots**
14:40 – 15:20	Annika Kurzmann	**Electrostatically defined graphene quantum dots**
15:20 – 16:00	*COFFEE BREAK*	

Program

Monday, 15 July 2024

16:00 – 16:40	Joel I-Jan Wang	**Hybrid superconducting quantum circuits with van der Waals heterostructures**
16:40 – 17:20	Ming-Wen Chu	**Probing the plasmon dispersions in three- and two-dimensional quantum matters by momentum-dependent electron energy loss spectroscopy**
17:20 – 18:00	Carolin Gold	**Engineering and imaging microscopic properties in graphene heterostructures**
18:00 – 20:00	DINNER	
20:00 – 20:40	Christian Koitzsch	**Project introduction ESMC (online talk)**
21:00 – 22:00		**POSTER SESSION I (Musiksaal)**

Program

Tuesday, 16 July 2024

08:00 – 08:45	*BREAKFAST*	
09:00 – 10:00	Tay-Rong Chang	**Electronic structure of topological materials**
10:00 – 11:00	Dmitri Efetov	**Thermodynamic measurements of correlated states in magic angle twisted bilayer graphene**
11:00 – 11:30	*COFFEE BREAK*	
11:30 – 12:10	Denis Kochan	**Magnetoelectric phenomena of non-centrosymmetric superconductors**
12:10 – 12:30	Aitor Garcia-Ruiz	**Moire materials under magnetic fields: a world of butterflies**
12:30 – 14:00	*LUNCH*	
14:00 – 14:40	Ruoming Peng	**Scanning quantum microscopy for emergent phases of matter**
14:40 – 15:20	Klaus Zollner	**Proximity-induced phenomena in twisted van der Waals heterostructures**
15:20 – 16:00	*COFFEE BREAK*	
16:00 – 16:40	Cosimo Gorini	**3D topological insulator nanowires: quantum magneto-transport in (negatively) curved space**
16:40 – 17:20	Ya-Ping Chiu	**Atomic-scale moiré topology in twisted transition metal dichalcogenide bilayers**
17:20 – 18:00	Markus Huber	**Ultrafast nanoscopy of charge carrier dynamics in quantum materials**
18:00 – 20:00	*DINNER*	
20:00 – 21:00		**POSTER SESSION II (Musiksaal)**

Program

Wednesday, 17 July 2024

08:00 – 08:45	*BREAKFAST*	
09:00 – 10:00	Roser Valenti	**Modelling correlated electrons in two-dimensional van der Waals platforms**
10:00 – 11:00	Ying-Jer Kao	**Chern dartboard insulator: sub-Brillouin zone topology and skyrmion multipoles**
11:00 – 11:30	*COFFEE BREAK*	
11:30 – 12:10	Laura Classen	**Field control of many-body phases in frustrated moiré bilayers**
12:10 – 12:30	Hsinzon Tsai	**Visualizing dynamic molecular manipulation on a graphene field effect transistor**
12:30 – 14:00	*LUNCH*	
14:00 – 14:40	Chung-Hou Chung	**Revealing the mystery of strange metal states in correlated electron systems**
14:40 – 15:20	Tim Wehling	**Electron correlations in graphene multi-layers**
15:20 – 16:00	*COFFEE BREAK*	
16:00	EXCURISION	**BUS LEAVING 16:00** **ANDECHS VIA HERRSCHING**
18:30 – 20:45	*DINNER ANDECHS*	
21:00	BUS RETURN	

Program

THURSDAY, 18 July 2024

08:00 – 08:45	*BREAKFAST*	
09:00 – 10:00	Yann-Wen Lan	**Twisted light interacted with materials for boosting low dimensional transistors**
10:00 – 11:00	Alexey Chernikov	**Excitons in 2D monolayer and heterobilayer semiconductors**
11:00 – 11:30	*COFFEE BREAK*	
11:30 – 12:10	Ting-Hua Lu	**Angular momentum of light for applications in two-dimensional quantum materials**
12:10 – 12:30	Cheng-Maw Cheng	**Topological phase transition in Sn single layer from stanene to Beta-Sn**
12:30 – 14:00	*LUNCH*	
14:00 – 14:40	Chaw-Keong Yong	**Optically tunable many-body exciton-phonon quantum interference**
14:40 – 15:20	Nadine Leisgang	**Interlayer excitons in gated two-dimensional semiconductors**
15:20 – 16:00	*COFFEE BREAK/ FAREWELL*	

End of the seminar and departure – BUS TO REGENSBURG LEAVING 16:00

Posters

Poster Session I, Monday 15 July 2024, 21:00 h

Kuo-En Chang	**Unusual quantum hall state in near 30°-twisted bilayer graphene**
Olfa Dani	**Measuring spin-flip rates of single spins in coupled quantum dots**
David Alexander Darek Emmerich	**Ultra-steep slope cryogenic FETs based on bilayer graphene**
Marta García Olmos	**Topology and disorder in a 2D semi-Dirac material**
Jonas Gerber	**Spin-orbit coupling in bilayer graphene/transition-metal dichalcogenide quantum devices**
Maximilian Graml	**Excitons in nanostructures from the Bethe-Salpeter equation**
Jianping Guo	**Current-induced switching in van der Waals WTe_2/Fe_3GeTe_2 heterostructures**
Marcel Hild	**THZ-induced linear and circular ratchets in patterned-gated graphene**
Wolfgang Hogger	**Interference effects in high-harmonic generation from Dirac materials**
Yu-Chiang Hsieh	**Possible signature of frustrated magnetism in kagome-strained graphene**
Che-Pin Hsu	**Fabry-P´erot interference in gate-controlled graphene superlattice**
Tzu-Chao Hung	**Understanding single molecule fluorescence by means of scanning tunneling microscopy-induced luminescence**
Andreas Hüttel	**MoS_2 nanotubes as intrinsic 1d superconductors?**

Poster Session I, Monday 15 July 2024, 21:00 h

Wun-Hao Kang	**Transverse magnetic focusing of the radial rashba spin-orbit coupling in proximitized graphene**
Jhen-Dong Lin	**Unveiling the importance of finite-momentum dark excitons to energy transfer in monolayer transition-metal dichalcogenides**
Yen Ting Liu	**Hybrid superconductor-quantum dot devices utilizing magic-angle twisted bilayer graphene**
Alina Mrenca-Kolasinska	**Modeling transverse magnetic focusing in circular cavity**
Florian Schöppl	**Magneto transport in bilayer graphene cavities**

Poster Session II, Tuesday 16 July 2024, 20:00 h

Julia Amann	**Anisotropic transport in 1D (bilayer) graphene superlattices**
Maximilian Fürst	**Transport of massless Dirac electrons on curved surfaces**
Ping-Yuan Lo	**Full-zone valley polarization landscape of finite-momentum excitons in transition-metal dichalcogenide monolayers**
Arkajyoti Maity	**Breaking symmetries with light: Novel non-linear responses in optically pumped centrosymmetric Dirac systems**
Stepan Marek	**Exciton spectra from first principles density matrix time propagation**
Magdalena Marganska	**Superconductivity from electronic interactions on a fragmented Fermi surface**
Sebastian Matschy	**Characterization of a THz near-field microscope**
Roop Kumar Mech	**Nanoscale imaging of moiré patterns using time-domain Electro-Mechanical technique**
Erwin Mönch	**Cyclotron resonance overtones and near-field magnetoabsorption via terahertz Bernstein modes in graphene**
Nhat Quyen Nguyen	**Ultrafast dynamics in quasi-2D CDW systems $LaTe_3$ and $LaSeTe_2$**
Alexander Riedel	**Coherent suppression of high-harmonic generation from Dirac-materials**
Robin Schock	**Transfer and contact optimization of MoS_2 nanotubes**
Christoph Setescak	**The coarse geometric origin of topological phases**

Poster Session II, Tuesday 16 July 2024, 20:00 h

Bálint Szentpéteri	**Tuning the proximity induced spin-orbit coupling in bilayer graphene based heterostructures**
Isabell Weimer	**Gate screening of coulomb interactions in bernal bilayer graphene**
Patrick Wittig	**Effects of spin-orbit coupling in a valley chiral kagomé network**
Tsuei-Shin Wu	**Magnetic force microscopy perspective of the anomalous phase in a kagome magnet with out-of-plane easy-axis anisotropy**
Yueh-Ting Yao	**Atomic Scale Quantum Anomalous Hall Effect in Monolayer Graphene/MnBi2Te4 Heterostructure**

Abstracts of Lectures

(in alphabetical order)

Topological Phenomena of Folded Graphene in Magnetotransport Properties

L. Bockhorn[1], S. J. Hong[2], B. Zheng[1], J. C. Rode[1], and R. J. Haug[1]

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The stacking- and folding angle of 2D materials has emerged as an important, novel tuning parameter for the tailoring of physical properties. Especially, folded graphene layers show astonishing electronic and magnetic properties. In these samples, not only the typical electronic properties of twisted graphene layers are observed, but also phenomena due to the folded region, e. g. snake states and zero line modes.

One approach to achieve folded graphene samples is based on atomic force microscopy (AFM) technique [1, 2, 3]. Therefore, we use an AFM tip to cut into a graphene layer to initiate a self-assembly process that involves the folding of the graphene layer and the subsequent growth of a twisted graphene bilayer. From our observations, we conclude that during the growth process, these self-assembled structures move not only forward, but also appear to rotate and lock in at specific commensurate twist angles. These rotations and the assignment of twist angles to commensurate configurations suggest a conservation of energy by finding efficient configurations.

In our transport measurements of folded graphene samples, we observe e.g. an additional peak next to the charge neutrality peak, which is independent of the magnetic field. This peak at a certain charge carrier density is attributed to the compressive strain due the folded edge [4, 5]. As a result of the connection of the upper and lower graphene layers via the fold edge, there is a unique situation where an applied magnetic or electric field points in opposite directions in the individual layers. In the region of the folded edge transitions to chiral edge states transport can be observed in a very narrow area.

References

[1] J. C. Rode et al., Ann. Phys. 529, 1700025 (2017)
[2] J. C. Rode et al., 2D Mater. 6, 015021 (2018)
[3] L. Bockhorn et al., Appl. Phys. Lett. 118, 173101 (2021)
[4] S. J. Hong et al., 2D Materials, 8, 045009 (2021)
[5] S . J. Hong et al., Phys. Rev . B, 105, 205404 (2022)

Electronic structure of topological materials

Tay-Rong Chang[1,2,3]

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Topological phases in condensed matter physics have garnered significant global attention in the past decade, as they transcend Landau's traditional paradigm of spontaneous symmetry breaking. The initial phase of research in this field delved into topological insulators (TIs). Distinguishing themselves from conventional band insulators, three-dimensional (3D) TIs exhibit a bulk energy gap due to spin-orbit coupling effects, alongside gapless surface states protected by time-reversal symmetry. More recently, the spotlight has shifted towards topological semimetals (TSMs), encompassing three identified types: Dirac, Weyl, and nodal-line semimetals. Dirac and Weyl semimetals resemble 3D analogs of graphene, featuring linear dispersion of bulk band structures from nodal points across all three momentum directions, while nodal-line semimetals exhibit 1D nodal loops within the 3D Brillouin zone. Beyond the conventional graphene-type (type-I) TSMs, there has been extensive exploration into novel type-II TSMs, characterized by strong violations of Lorentz symmetry in band dispersion. In contrast to their nonmagnetic counterparts, magnetic topological materials have recently garnered intensive research interest. These materials offer a unique array of topological states, including antiferromagnetic TIs, axion insulators, magnetic Weyl/Dirac/nodal-line semimetals, and Chern insulators, while also serving as a promising platform for investigating the intricate interplay between symmetry, magnetism, and correlations. In this presentation, I will review a spectrum of material predictions within both nonmagnetic and magnetic topological realms, employing first-principles calculations, and delve into various exotic phenomena observed experimentally within these compounds.

Topological Phase Transition in Sn Single Layer from Stanene to Beta-Sn

Cheng-Maw Cheng[1,2,3], Ye-Shun Lan[4], Chia-Ju Chen[4], Shu-Hua Kuo[1], Yen-Hui Lin[4], Angus Huang[4,5,6], Jing-Yue Huang[1], Pin-Jui Hsu[4,7], and Horng-Tay Jeng[4,6,8]

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Two-dimensional topological insulators (2D TIs) are prized for unique electronic properties, especially in spintronics. These materials feature spin-polarized, disorder-resistant edge states. In contrast, topologi-cal nodal line semimetals (TNLSM) exhibit a distinct one-dimensional ring of degeneracy protected by topology, resilient to disorder. However, 2D TNLSMs lack protected boundary modes, posing experi-mental challenges. β-Sn, a metallic allotrope with a superconducting temperature of 3.72 K, emerges as a potential topological superconductor for hosting Majorana fermions in quantum computing. In this work, we successfully prepared single layers of α-Sn(111) and β-Sn(001) on a Cu(111) substrate, employing scanning tunneling microscopy (STM), angle-resolved photoemission spectroscopy (ARPES), and Density Functional Theory (DFT) calculations. The electronic structure of β-Sn(001) undergoes a topological tran-sition from 2D topological insulator α-Sn to 2D topological nodal line semimetal β-Sn, presenting two co-existing nodal lines. This realization in a single 2D material is unprecedented. Additionally, unexpected freestanding-like electronic structures of β-Sn/Cu(111) were observed, highlighting ultrathin β-Sn(001) films' potential for exploring the electronic properties of 2D topological nodal line semimetals and topo-logical superconductors in the 2D limit, such as few-layer superconducting β-Sn in lateral contact with topological nodal line single-layer β-Sn.

Excitons in 2D monolayer and heterobilayer semiconductors

Prof. Alexey Chernikov
Institute of Applied Physics and Würzburg-Dresden Cluster of Excellence ct.qmat,
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Optical properties of two-dimensional van der Waals semiconductors are dominated by Coulomb-bound electron-hole pair states known as excitons. In this class of materials, the excitons are primary carriers of energy and information, while also featuring a rich variety of multi-particle complexes. In heterostructures, ground state excitons are often of dipolar nature with major consequences for their interactions with light and with each other. They offer an excellent platform to study linear and non-linear dynamics, combined with external tunability by electric and magnetic fields as well as by the materials' environment. In addition, excitonic complexes are known to be mobile both in monolayers and heterostructures, with the transport of optical excitations playing a central role from both fundamental and technological perspectives.

The first part of the talk will be focused on the exciton physics of monolayer van der Waals semiconductors, impact of free carrier doping, and use of intense THz pulses to transiently modify light-emission of the exciton-electron ensembles. Both static and dynamics changes of the optical properties in the presence of dilute and dense Fermi gases will be discussed. In the second part, I will present linear and non-linear propagation of interlayer excitons in both monolayer and atomically reconstructed heterobilayers for an extended density range up to the Mott transition. Key results include demonstration of rapid exciton diffusion in absence of disorder- and Moiré-induced localization, role of the exciton-exciton interactions, and effectively negative diffusivity in the regime of dissociated excitons and dense electron-hole plasma.

Atomic-scale moiré topology in twisted transition metal dichalcogenide bilayers

Hung-Chang Hsu, Yi-Han Lee, Ya-Ping Chiu*

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The intricate interactions and stacking structures of twisted bilayers (twBL) transition metal dichalcogenides (TMDs) play a crucial role in the field of twistronic research. The stacking structure that accompanies the moire will determine the unique physical properties of electrons intertwined in the twBL. Despite the importance of stacking structures, direct experimental elucidation of the corresponding atomic details within the twBL is still lacking. In this study, we first applied *in situ* scanning tunneling microscopy/spectroscopy and non-contact atomic force microscopy to dissect the atomic structure of each sublayer in twBL transition metal double cations on HOPG substrates. The electronic results show the expected rhombic stacked moiré pattern. In addition, atomic structure measurements reveal unexpected stacking structures in which the moire predominantly induces lattice displacements affecting mainly one sublayer in the twBL.

Probing the Plasmon Dispersions in Three- and Two-Dimensional Quantum Matters by Momentum-Dependent Electron Energy Loss Spectroscopy

I-Ta Wang[1], Ta-Lei Chou[1], Chien-Ting Wu[2], Chin Shan Lue[3], Hung Chung Hsueh[4], Cheng Hsuan Chen[1], and Ming-Wen Chu[1]

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Plasmons (ω_p) are the quanta of collective oscillations of charges in solids and their dispersions in momentum (q) space have been established as the function of the electronic dimensionality, with $\omega_p \sim q^2$ in three-dimensional (3D) and $\omega_p \sim \sqrt{q}$ in two-dimensional (2D) limits [1,2]. The derivation of these conventional wisdoms is based on classical electron systems with parabolic band dispersions. Quantum materials with linearly-dispersing bands and/or a monolayer (ML) character offer emergent opportunities for revisiting this classical notion on plasmon dispersions [3]. Using q-dependent electron energy loss spectroscopy (q-EELS), we tackle the plasmon dispersions in 3D semimetal CuTe and 2D ML MoS_2. The CuTe manifests linearly-dispersing bands across the Fermi level and the plasmon excitation of these electrons that disperse like 2D graphene remarkably complies with $\omega_p \sim q^2$ in the classical 3D picture. Moreover, the plasmon displays a blueshift at reduced temperatures, at odds with the conventional physics of redshifts by the quenched thermal excitation of carriers across the Fermi level at cryogenic temperatures. Our recently developed q-EELS methodology for the effective mass and Fermi velocity of carriers unravels that the distinct blueshift in CuTe arises from the anomalous mass reduction and velocity acceleration of the linearly-dispersing electrons by the growing charge-density-wave (CDW) order at low temperatures. Such a CDW-induced phenomenon is unexplored in the past. In the otherwise q-EELS study of ML MoS_2, we observe the acoustic dispersion of $\omega_p \sim q$ in the long-wavelength limit and its bridging to $\omega_p \sim \sqrt{q}$ at large q's, noticeably different from the monotonic $\omega_p \sim \sqrt{q}$ in the classical 2D context. The grand detail on the plasmon dispersions in CuTe and ML MoS_2 will be elucidated in this work.

References

[1] P. M. Platzman and P. A. Wolff, Waves and Interactions in Solid State Plasmas (Academy Press, New York and London, 1973)
[2] F. Stern, Phys. Rev. Lett. **18**, 546 (1967)
[3] S. Das Sarma and E. H. Hwang, Phys. Rev. Lett. **102**, 206412 (2009)

Revealing the mystery of strange metal states in correlated electron systems

C. Chung[1,2]

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A major mystery in strongly interacting quantum systems is the microscopic origin of the “strange metal” phenomenology, with unconventional metallic behavior that defies Landau’s Fermi liquid framework for ordinary metals. This state is found across a wide range of correlated quantum materials, including rare-earth intermetallic compounds and unconventional superconductors at finite temperatures (T) near a magnetic quantum phase transition. It shows a quasi-linear-in-temperature resistivity and a logarithmic-in-temperature specific heat coefficient. In this talk, I will present two theoretical studies to reveal the mystery of strange metal state in $CePd_{1-x}Ni_xAl$ [1, 2], a geometrically frustrated Kondo lattice compound, as well as in $Ce_{1-x}Nd_xCoIn_5$ [3], a heavy-electron quantum critical superconductor. A generic theoretical framework is proposed based on the competition between magnetically short-ranged-ordered fermionic spin-liquid state and the Kondo correlations near Kondo breakdown quantum phase transition of 2D Kondo lattice model. We find the strange metal behaviors observed in the above two systems are well described within this framework in the context of quantum critical Kondo fluctuations coupled to a fermionic spin-liquid. Our studies pave the way for the understanding of the strange metal state observed in high-Tc cuprate superconductors.

References

[1] J. Wang, Y-Y Chang, and C.-H. Chung*, A mechanism for for the strange metal phase in rare-earth intermetallic compounds, PNAS **119**, e2116980119 (2022).

[2] H. Zhao *et al.*, *Nat. Phys.* **15**, 1261–1266 (2019).

[3] Yung-Yeh Chang, Hechang Lei, Cedomir Petrovic*, Chung-Hou Chung*, The scaled-invariant Planckian metal and quantum criticality in $Ce_{1-x}Nd_xCoIn_5$, Nature Communications **14** (581) (2023).

Field control of many-body phases in frustrated moiré bilayers

L. Del Re[1] and L. Classen1,[2]

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We determine the ground states and excitation spectra of the paradigmatic four-flavour Heisenberg model with nearest- and next-nearest-neighbor exchange couplings on the triangular lattice in a field controlling the population imbalance of flavor pairs. Such a system arises in the strongly correlated limit of moiré bilayers of transition metal dichalcogenides in an electric displacement field or in-plane magnetic field, and can be simulated via ultracold alkaline-earth atoms. We argue that the field tunes between effective SU(4) and SU(2) symmetries in the balanced and fully polarised limits and employ a combination of mean-field calculations, flavour-wave theory, and exact diagonalisation to analyse the intermediate, imbalanced regime. We find different symmetry-broken phases with simultaneous spin and excitonic order depending on the field and next-nearest-neighbor coupling. Furthermore, we demonstrate that there is a strongly fluctuating regime without long-range order that connects candidate spin liquids of the SU(2) and SU(4) limit. The strong fluctuations are facilitated by an extensive classical degeneracy of the model, and we argue that they are also responsible for a strong polarisability at 1/3 polarisation that survives from the mean-field level to the exact spectrum.

Thermodynamic measurements of correlated states in Magic Angle Twisted Bilayer Graphene

Dmitri K. Efetov

LMU Munich, Munich, Germany

It has been recently postulated, that the strongly correlated flat bands of magic-angle twisted bilayer graphene (MATBG) can host coexisting heavy and light carriers. While transport and spectroscopic measurements have shown hints of this behavior, a more direct experimental proof is still lacking. Here, we explore the thermoelectric response of MATBG through the photo-thermoelectric (PTE) effect in gate-defined MATBG pn-junctions. At low temperatures, we observe sign-preserving, filling dependent oscillations of the Seebeck coefficient at non-zero integer fillings of the moiré lattice, which suggest the preponderance of one carrier type despite tuning the Fermi level from hole to electron doping of the correlated insulator. Furthermore, we use the ultra-low carrier concentration in MATBG to engineer ultra-sensitive single photon detectors for near-IR photons.

Quantum Devices in Twisted graphene layers

Alexandra Mestre Tora, Marta Perego, Giulia Zheng, Elias Portoles, Clara Galante, Shuichi Iwakiri, Artem Denisov, Thomas Ihn, and Klaus Ensslin

Physics Department, ETH Zurich, Switzerland

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Magic-angle twisted bilayer graphene (MATBG) can host an intriguing variety of gate-tunable correlated states, including superconducting and correlated insulator states. Junction-based superconducting devices, such as Josephson junctions and SQUIDs, have been introduced recently and enable the exploration of the charge, spin, and orbital nature of superconductivity and the coherence of moiré electrons in MATBG.
Here we demonstrate high quality Josephson junction in bilayer [1] and quadruple layer [unpublished] graphene as well as operation of a SQUID [2] and observation of Little-Parks oscillations in a gate-defined ring geometry [3]. First steps towards carrier confinement in moiré systems have been taken. [4]

References

[1] F. K. de Vries, E. Portoles, G. Zheng, T. Taniguchi, K. Watanabe, T. Ihn, K. Ensslin, and P. Rickhaus, Nature Nano **16**, 760 (2021)

[2] Elías Portolés, Shuichi Iwakiri, Giulia Zheng, Peter Rickhaus, Takashi Taniguchi, Kenji Watanabe, Thomas Ihn, Klaus Ensslin, and Folkert K. de Vries, Nature Nano 17, 1159 (2022)

[3] Shuichi Iwakiri, Alexandra Mestre-Torà, Elías Portolés, Marieke Visscher, Marta Perego, Giulia Zheng, Takashi Taniguchi, Kenji Watanabe, Manfred Sigrist, Thomas Ihn, Klaus Ensslin Nature Com. 15, 390 (2024)

[4] Giulia Zheng, Elías Portolés, Alexandra Mestre-Torá, Marta Perego, Takashi Taniguchi, Kenji Watanabe, Peter Rickhaus, Folkert K. de Vries, Thomas Ihn, Klaus Ensslin, Shuichi Iwakiri, arXiv:2312.11698

Moire materials under magnetic fields: a world of butterflies

A. Garcia-Ruiz (艾飛宇)[1], D. Renjun (杜人君)[2] and L. Ming-Hao (劉明豪)[1]

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During the last two decades, moire materials have emerged as a unique platform to explore the physics of condensed matter. These are composed of several layered materials with their crystallographic axes intentionally misaligned, where the misalignment angle serves as a degree of freedom that adds tunability to the system. Experiments have shown that moire materials feature a rich phase diagram, where different orders, such as superconductivity or correlated insulator [1], can coexist.

In this talk, I will present the effects of external magnetic fields on theelectronic properties of monolayer-twisted-trilayer graphene [see Fig. 1(a)]. In particular, I will explain how the interplay between the nanometer-scale potential and the nanometer-scale magnetic length gives rise to the Hofstadter's butterfly spectrum [2], a self-similar fractal band structure. Alongside with the theoretical methodology, I will also show the experimental signatures of this type of spectrum: the Brown-Zak oscillations.

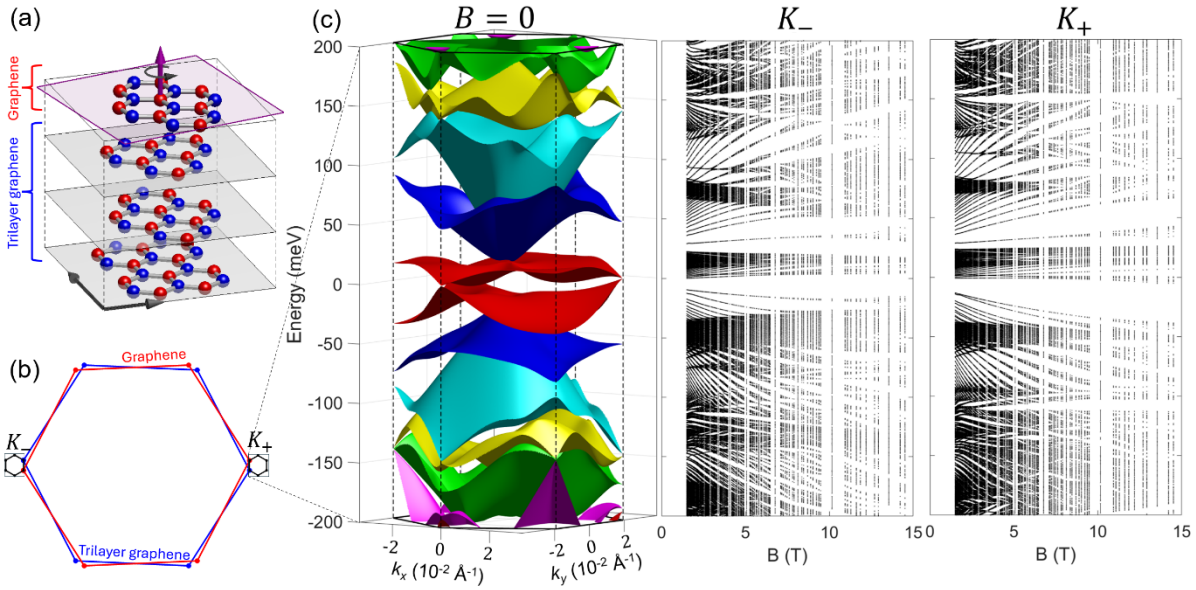

Figure 1: (a) Sketch of monolayer-twisted bilayer graphene and (b) the Brillouin zone. (c) Non-magnetic miniband structure of this system and the miniband widths as a function of magnetic field (Hofstadter's spectrum) around the two corners of graphene's Brillouin zone.

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Engineering and imaging microscopic properties in graphene heterostructures

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The last century has seen a plethora of technological advances that have shaped our everyday life into the form we know today. As we push the boundaries of materials and technologies underpinning these innovations, it becomes more important than ever to understand the intricate interplay of the microscopic properties of a material or device with the emergent quantum phenomena that manifest at larger scales. Despite decades of intensive theoretical and experimental endeavors, bridging these two length scales has remained a notable challenge, leaving numerous questions unanswered. The distinctive properties and exceptional tunability of van der Waals (moiré) materials render them an unparalleled and versatile platform in this quest.

In this talk, we utilize atomic force microscopy techniques not only to (i) study (quantum) electronic states at multiple different scales, but also to (ii) control and engineer the interplay of microscopic and macroscopic properties in van der Waals materials on a local scale. Bending narrow van der Waals ribbons with an atomic force microscopy tip, we realize (moiré) van der Waals heterostructures with varying twist angle and strain [1]. Imaging these heterostructures with conductive atomic force microscopy (CAFM) at temperatures ranging from room temperature down to 1.5K, we find that this technique offers a robust platform to image the resultant moiré interference patterns arising from the interaction between two slightly lattice mismatched, misaligned or rotated van der Waals materials. Furthermore, it provides insights into the unique properties of the material such as e.g. the interplay of different (quantum) electronic states on a local scale. This not only opens exciting avenues for studying the interplay between microscopic and macroscopic length scales within these materials but also presents unique prospects for locally controlling and engineering their microscopic properties.

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3D topological insulator nanowires: quantum magneto-transport in (negatively) curved space

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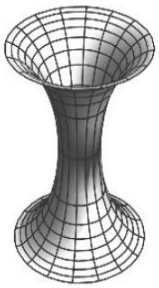
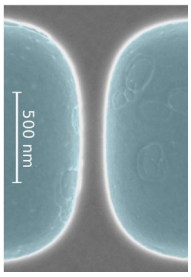
In 3D topological insulator nanostructures low-temperature phase-coherent transport takes place on a 2D Dirac metal wrapped around an insulating 3D bulk. These conditions are established in particular in high-quality HgTe nanowires [1], where transport is thus uniquely due to Dirac electrons propagating on a non-planar surface. The latter can be pierced by an applied magnetic field in selected regions, causing magneto-transport to strongly depend on a peculiar conjunction of structural (real space) and spectral (reciprocal space) geometrical properties. Qualitatively different transport regimes – sensitive to the nanowire shape -- become available by simply reorienting in space a field in the Tesla range [2, 3], allowing in fact to study quantum Hall physics in (negatively) curved space [4].





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Emergent optoelectronic properties of graphene-based junctions

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2D materials junctions exhibit unique properties that arise from the strong light-matter interaction in their constituents and the intimate junction interface. In the simplest case of a 2D junction, a two-dimensional material is laterally surrounded by an air gap. We have demonstrated the efficient transduction of light into current in such as structure. Unlike traditional photosensors or solar cells, conversion proceeds through direct rectification of the light's electric field as evidenced by clear polarization control and wavelength-dependent photovoltage [1]. Graphene-junction based rectennas showed a tenfold increase in photon-electron coupling over existing optical rectennas. The high efficiency and straightforward realization of 2D junction-based optoelectronics permit their extension to large networks of junctions. We have devised a simulation tool that can capture the complex carrier transport mechanism in such 2D junction assemblies and which predicts the occurrence of emergence – collective behavior that is not observed in individual members [2]. Such emergence is experimentally confirmed in lateral 2D all-carbon junction networks and enables wearable and ubiquitous sensors with unprecedented optoelectronic performance. Finally, a novel electrochemical deposition process is observed in graphene/graphene junctions and applied towards high-resolution decoration processes and neuromorphic devices.

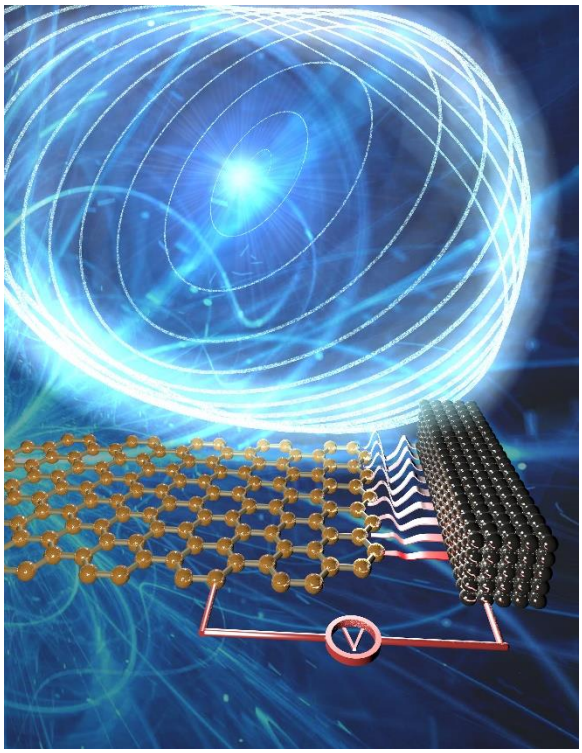

Figure 1. Artistic rendition of 2D material junction-based rectenna

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Ultrafast nanoscopy of charge carrier dynamics in quantum materials

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A key prerequisite to establish a causal link between nanoscopic elementary dynamics and macroscopic functionalities of matter has been the improvement of optical microscopy to the shortest length- and timescales. Here, I will show two recent breakthroughs in tracing ultrafast nanoscale charge carrier dynamics in condensed matter systems.

First, I will discuss how ultrafast terahertz near-field microscopy disentangles the interplay between single-grain structure, composition, and carrier dynamics in lead halide perovskite films [1] – a candidate for future solar cell devices. Phonon fingerprinting allows us to discern nano-grains of different crystallographic phase and chemical composition directly from our experimental data. Tracing the carrier dynamics following photoexcitation with an optical pump pulse, we push the technique to extreme temporal resolution. We develop an approach to access the out-of-plane charge carrier diffusion, which is a key quantity for solar cell performance, by accessing deep-subcycle shifts of the detected terahertz near-field waveforms. On the nanoscale, a surprising robustness of diffusion against structural and chemical variations is found, possibly shedding light on the origin of the remarkable performance of perovskite-based photovoltaic devices. Our approach could help resolve further unanswered questions, including the impact of hot carrier effects or the details of the charge collection process at the extraction layers.

Secondly, I will present a fundamentally new approach to bring all-optical microscopy to the atomic scale while simultaneously retaining subcycle temporal resolution for the first time [2]. We demonstrate the unique capabilities of this new “Near-field Optical Tunnelling Emission” (NOTE) microscope by imaging packing defects on the surface of gold and tracing the subcycle flow of electrons between the scanning tip and a semiconducting van der Waals trilayer in real-time. A specialty of NOTE microscopy is that it is not only compatible with insulating samples, where no time-averaged currents flow, but also yields all-optical subcycle spectroscopic information with atomic resolution. Hence, NOTE provides direct access to atomic scale light-matter interaction and quantum dynamics on their intrinsic length and timescales.

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Chern dartboard insulator: sub-Brillouin zone topology and skyrmion multipoles

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Topology plays a crucial role in many physical systems, leading to interesting states at the surface. A paradigmatic example is the Chern number defined in the Brillouin zone that leads to robust gapless edge states. Here we introduce the reduced Chern number, defined in the subregions of Brillouin zone, and construct a family of Chern dartboard insulators with quantized reduced Chern numbers but with trivial bulk topology. Chern dartboard insulators are protected by the mirror symmetries and exhibit distinct pseudospin textures, including (anti)skyrmions, inside the sub-Brillouin zone. These Chern dartboard insulators host exotic gapless edge states, such as Möbius fermions and midgap corner states, and can be realized in the photonic crystals. Our work opens up new possibilities for exploring sub-Brillouin zone topology and nontrivial surface responses in topological systems.

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Magnetoelectric phenomena of non-centrosymmetric superconductors

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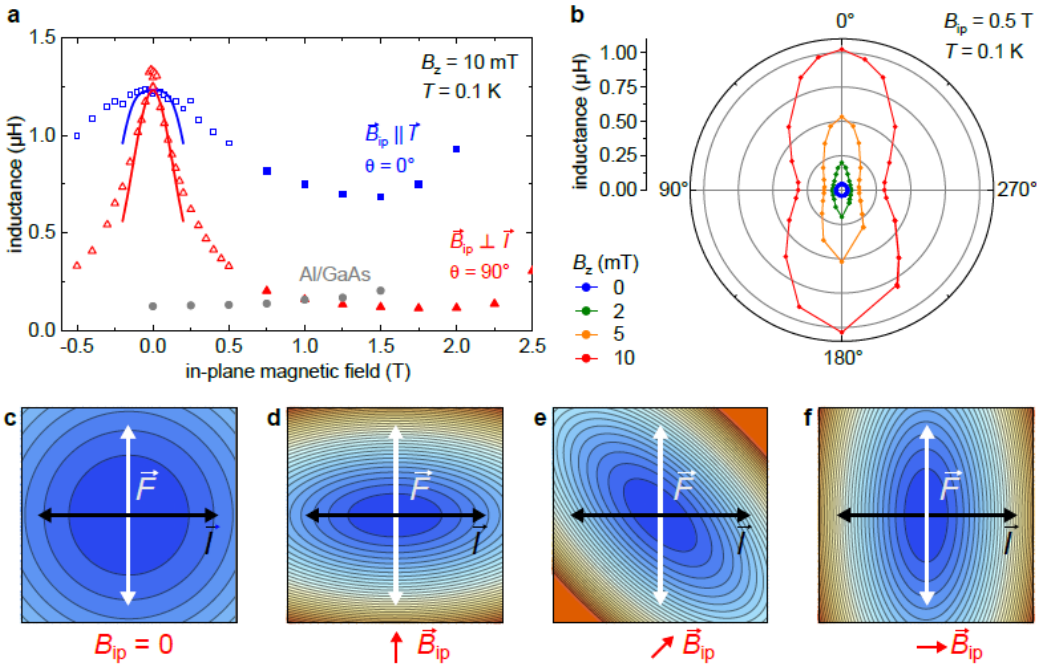
Abstract

Superconductivity in materials with broken inversion symmetry has been a subject of theoretical and experimental studies from the early 90's. It was understood that unlike symmetric spin-orbit coupling found in centrosymmetric metals, spin-orbit coupling in non-centrosymmetric materials has a spectacular influence on the electronic bands through a specific spin splitting of the quasiparticle states. Superconductivity as a Fermi-surface instability towards pairing of electrons with opposite momenta and spins is naturally influenced by such a modification of the electronic states. The removal of inversion symmetry and also of time-reversal, e.g. by an applied external magnetic field, promotes a novel form of electron pairing–the so-called helical phase, in which Cooper pairs acquire a finite center of mass momentum. The latter gives rise to several interesting magneto-electric or magneto-chiral effects, like the enhancement of T_c in the presence of magnetic fields, the supercurrent diode effect, magneto-chiral inductance anisotropy, zero-pi-like transitions, the anomalous Josephson effect, as well as, unusual vortex squeezing and engendered London physics in the Meissner state. The last decade witnessed a renewed interest in superconductors with broken inversion symmetry by using the so-called synthetic superconductors, e.g. 2DEG with a strong Rashba spin-orbit-coupling in a proximity of conventional superconductors, in a pursuit to find or engineer topologically non-trivial superconducting states with non-Abelian (Majorana) excitations.

In the talk I will discuss general properties of the non-centrosymmetric superconductors summarizing the main theoretical and phenomenological concepts standing behind. Apart of that, I will present exciting experimental evidences showing the emergence of i) *supercurrent diode effect* and *Josephson inductance anisotropy* [1] in the synthetic Josephson junctions incorporating proximitized 2DEG formed in InAs-quantum wells that possess strong Rashba coupling and large g-factor, ii) *zero-pi-like transitions* and *anomalous Josephson effect* [2] in such non-centrosymmetric systems, and, last but not least, also iii) an *unexpected enhancement of pinning and squeezing* of Abrikosov vortices when probed in such Rashba-based superconductors in a Meissner phase [3]. I will elucidate these phenomena from the microscopic point of view, but as well as, phenomenologically–as a direct manifestation of the Lifshitz invariant that is allowed in the Ginzburg-Landau free energy when the underlying Cooper pairs acquire a finite center of mass momentum.



Optional Figure 1. a, Sample inductance of Rashba superconductor as a function of in-plane magnetic field for different orientations of the driving current (red and blue symbols). The controlled measurement (grey symbols) corresponds to a centrosymmetric (i.e. non-Rashba) superconductor. b, Polar plot showing the angle dependence of the vortex inductance for selected values of out-of-plane magnetic field. c, The color plot schematically represents the modulus of the order parameter, $|\psi\ (x,y)|^2$, near the core of a pinned vortex, in the absence of in-plane field. The horizontal black arrow represents the direction of a current bias, while the white arrow indicates the direction at which a Lorentz force acts on a pinned vortex. The measured vortex inductance is rotation symmetric and inversely proportional to the curvature of $|\psi\ (x,y)|^2$ along the force direction. d-f, When a finite in-plane field is applied the vortex core is squeezed as a consequence of the Rashba spin-orbit interaction, reflecting the measured change in vortex inductance. The curvature is always probed along the white axis, rotating the in-plane magnetic field the vortex rotates keeping its small elliptic axis parallel with the direction of in-plane field. This allows one to extract from the vortex inductance the spatial profile –order parameter tomography--of $|\psi\ (x,y)|^2$.

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Electrostatically defined graphene quantum dots

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Graphene is a promising candidate for future nano-electronic devices including building blocks for quantum information processing. Reasons are the expected long spin lifetimes and high carrier mobility. The improvements in fabrication technologies for graphene nanostructures, namely, the encapsulation between boron nitride, edge-contacting, graphite back-gates and the use of electrostatic gating of bilayer graphene, have leveraged the quality of quantum dots to such an extent, that few-electron or -hole quantum dots have been realized that are comparable to the best devices in gallium arsenide [1].

We confine charge carriers laterally by applying strong displacement fields forcing charge carriers to flow through a narrow channel. In transport direction, charge carriers are confined by pn-junctions forming natural tunnel barriers, thus creating a p-type quantum dot coupled to n-type leads, or vice versa. The tunnel barriers can be tuned using additional gates, providing a high degree of control through gate voltage over the quantum dots' charge, spin, and valley degrees of freedom.

Our experimental findings yield a notably clear level scheme for two-particle spectra. Intriguingly, the single-dot two-carrier ground state of bilayer graphene quantum dots is not a paired spin-singlet, but a spin-triplet [2]. This discovery holds significant implications for the design of typical two-carrier singlet-triplet qubits. Through the implementation of charge detection, we have successfully performed Elzerman read-out [3] and measured single-spin relaxation times (T_1) up to 50ms. Recent observations indicate extended valley T_1 relaxation times, approaching 1s, between the spin (valley) (1,1) triplet and (0,2) singlet states in a double quantum dot [4].

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Twisted Light interacted with materials for boosting low dimensional transistors

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Light with orbital angular momentum (OAM), also called twisted light, carries a well-defined OAM of $\ell\hbar$ per photon, where its topological charge ℓ can take thousands of possible integer values or states. Twisted light carrying different OAM have been employed in varying the levels of light-generated electron signals in GaAs, which was attributed to the electrons that are excited through the OAM-of-light-enhanced quadrupole transitions. In this talk, we will present the recent researches [1-5] that are relevant to OAM induced optical, magnetic and electrical responses in both layered materials and nanomaterials-based transistor. The results show many interesting phenomena, revealing a field that needs to widely explore.

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3. Twisted Light Induced Magnetic Anisotropy Changes in an Interlayer exchange Coupling System. (**Nanoscale Horizons** 2021, 6, 462-467)
4. Twisted Light-Enhanced Photovoltaic Effect. (**ACS Nano** 2021 15, 14822-14829)
5. Twisted Light-induced photocurrent in SiNW FET **(ACS Nano** 2022 16, 6, 9297-9303**)**

Interlayer excitons in gated two-dimensional semiconductors

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Two-dimensional heterostructures provide a highly tunable platform for many-body interactions and strongly correlated phenomena, including Mott insulators, generalized Wigner crystals and excitonic insulators. Of particular interest are atomically thin transition metal dichalcogenides (TMDs), such as MoS_2, $MoSe_2$ and WSe_2. They strongly interact with light to form excitons – electrons and holes bound by Coulomb attraction – which remain stable up to room temperature. The reduced dimensionality together with the relatively large effective mass and low kinetic energy of the charge carriers yield strong interactions between the individual electrons and excitons in the system. In addition, new excitonic species can be formed when combining two or more TMD monolayers, where the electrons and holes are separated between the individual layers – so-called interlayer excitons. The ability to engineer and control the properties of the thin semiconductors by external means makes these systems a versatile platform for rich exciton and electron physics and unique opto-electronic applications.

We use optical spectroscopy and electroluminescence experiments to study interlayer excitons in homobilayer and heterobilayer systems in the presence of an underlying Fermi sea. By tuning various experimental parameters, such as carrier density, external electric and magnetic fields, dielectric environment and temperature, we investigate the coupling between excitons and the correlation of electrons in those systems.

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Two-Dimensional Semiconductors for Advanced Electronics

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With the scaling of dimensions, the control of transistor gates weakens due to increased source-drain tunneling. Therefore, reducing the thickness of the transistor body is necessary to ensure effective electrostatic control. The utilization of new materials such as "ultra-thin" 2D semiconducting materials has garnered attention. In this presentation, I aim to provide an analysis and rationale regarding the potential for scaling device dimensions, potentially down to the 1nm technology node, utilizing 2D transition metal dichalcogenides (TMD) semiconductors. From a circuit perspective, I will share our insights on benchmarking 2D-based circuits against state-of-the-art Si FinFETs, using SRAM circuits as a case study to highlight the advantages of employing 2D materials over Si FinFET (or GAA) in technology nodes ranging from N16 down to N1.

There exist numerous challenges in device fabrication that warrant discussion. I will delve into some key bottlenecks and recent advancements accomplished by our team and collaborators. Firstly, our findings indicate that hydroxide vapor phase epitaxy facilitates the growth of WS2 monolayers with significantly reduced structural defects, thereby enhancing electron mobility to approximately ~200 cm2/Vs. This method also benefits other materials like MoS2 and WSe2. Secondly, I will revisit the mechanism of wafer-scale growth for 2D materials. Thirdly, I will highlight the application of ultrahigh-k dielectrics on short-channel (<30 nm) 2D monolayer transistors, which can substantially reduce the subthreshold swing (down to 70 mV dec-1) while achieving an ON/OFF current ratio of up to 107. Lastly, I will discuss the feasibility of using semimetal as a contact metal for TMD monolayers.

Angular momentum of light for applications in two-dimensional quantum materials

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Circularly polarized light, with its spin angular momentum (SAM) of $\pm\hbar$ per photon, and optical vortex beams, known as twisted light, which carry orbital angular momentum (OAM) of $\ell\hbar$ per photon, find diverse applications in fields like communication, optical manipulation, quantum entanglement, and enhanced imaging. Twisted light introduces an extra degree of freedom (DOF) through its quantum number ℓ, making it relevant in spintronics and enabling exploration of complex phenomena. Interactions between light endowed with both SAM and OAM and materials like layered transition metal dichalcogenides (TMDs) may induce additional DOF within the material. Recent studies into controlling valley polarization in TMDs have attracted attention for valleytronics applications, showcasing their adjustable properties. Monolayer molybdenum disulfide (MoS_2) stands out for its optical bandgap and modulatable valley degree of freedom. While methods like circularly polarized light or strain engineering influence valley freedom in MoS_2, precise control over its spin behavior remains a challenge. Innovative techniques such as magnetic fields or hybridization with other materials are being explored to address this challenge. Our study delves into the interaction between light possessing both SAM and OAM and layered MoS_2, utilizing advanced techniques for comprehensive measurement of optical and electrical properties [1, 2]. Insights from this research could revolutionize spin-based optoelectronics, enhancing our ability to manipulate spin properties in TMD materials.

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Scanning Quantum Microscopy for Emergent phases of matter

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Visualization of nanoscale magnetic response in condensed matter systems provides a pathway to unravel the underlying mechanisms of spin interactions. The two-dimensional (2D) materials provide controlled and versatile platforms for exploring exotic correlated and topological states [1]. In the initial segment of our study, I will present a recent breakthrough involving the twisted double bilayer CrI_3. Our investigation brings to light the softening of magnetic anisotropy and the heightened magnetic competition at a small twisted angle. This magnetic competition manifests as a spontaneous periodic magnetic texture with a distinctive period, setting it apart from the Moire periodicity associated with the given twisted angle. Transitioning to the second part of my exploration, I will extend the inquiry into the realm of 2D superconducting systems. I will share insights into the dynamics of vortices in a few nm thin exfoliated 2H-$NbSe_2$. A noteworthy observation is the melting of vortex solids near the critical temperature, facilitating the re-arrangement of vortices and unconventional magnetic noise in different cool-down cycles.

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Visualizing Dynamic Molecular Manipulation on a Graphene Field Effect Transistor

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Harnessing electric fields at the nanoscale to manipulate molecular motion unlocks new prospects for nanotechnology. By coordinating molecular movements, we can build novel nanostructures, promote mass movement, and alter device characteristics. As we scale down electronic devices to nanometers, their interactions with nearby electric fields and currents grow crucial. To fully grasp these tiny-scale dynamics, we need advanced microscopy methods capable of capturing individual adsorbate movements while also analyzing the local electronic structure. In my presentation, I'll introduce an innovative approach aimed at manipulating the charge and spatial distribution of individual molecular adsorbates on a graphene field-effect transistor (FET) observed through a scanning tunneling microscope. Once the molecules get charged, they behave like ions on the surface which can be controlled by the surface electrochemical potential [1]. Activating a gate electric field causes F4TCNQ molecules on the device's surface to switch between a charge-neutral self-organized solid phase and a negatively-charged correlated liquid phase [2]. This shift in molecular arrangement on the surface also impacts the device's conductivity, demonstrating Fermi level-pinning by molecular orbitals. Furthermore, we created stop-motion footage of the molecular distribution changes by sending brief current pulses through the graphene FET. This allows us to track the diffusion and electromigration of single molecules as well as non-equilibrium phase transition dynamics. These observations offer insights into controlling nanoscale molecular movements with external electric fields and understanding the scattering momentum transfer between electrons and adsorbates in the dynamical equilibrium.

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Modelling correlated electrons in two-dimensional van der Waals platforms

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In recent years a plethora of new correlated states have been observed by stacking and twisting two dimensional van der Waals materials of different kind. Some prominent examples are twisted bilayer graphene, bilayer heterostructures of graphene with the spin-orbit assisted Mott insulator α-RuCl3 -a candidate for Kitaev spin physics-, or bilayer heterostructures of the Mott insulator 1T-TaS2 with the metal 1H-TaS2. Unique to these bilayer structures is the possible emergence of phases not foreseable from the single layers alone, such as heavy fermions, quantum spin liquids, correlated metals, or topological superconductivity.

In this talk I will discuss the microscopic modelling of such heterostructures by a combination of first-principles calculations, effective-model considerations and many-body techniques and will present results on the emerging correlated electronic and magnetic properties in 1T-TaS2/1H-TaS2 bilayers [1] and α-RuCl3 /graphene [2,3] that we compare with available experiments.

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Radio-Frequency Charge Detection on Gate-Defined Bilayer Graphene Quantum Dots

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Quantum dots (QDs) in bilayer graphene (BLG) are promising hosts for spin or valley qubits. The small, voltage controllable band gap in BLG allows the realization of electron-hole double quantum dots (DQDs) that exhibit near-perfect particle-hole symmetry. The particle-hole symmetric spin and valley texture leads to a protected single-particle spin-valley blockade which can be exploited for spin-to-charge and valley-to-charge conversion [1]. This promises a high-fidelity readout scheme for spin and valley states, which is essential for qubit operations. This blockade mechanism has so far only been studied by DC transport.

Here, we present high-bandwidth charge detection of an electron-hole DQD using a capacitively coupled quantum point contact (QPC). An optimized device design reduces screening effects and increases the sensitivity of the charge detector. The use of radio-frequency (RF) reflectometry techniques allows for a distinction of the charge states with a signal-to-noise ratio (SNR) of up to 160 and a bandwidth of up to 7 MHz. Finally, we demonstrate time-resolved detection of individual tunneling events across the (0h,0e) - (1h,1e) charge transition. These findings mark an important step in realizing a qubit in the electron-hole BLG QD system.

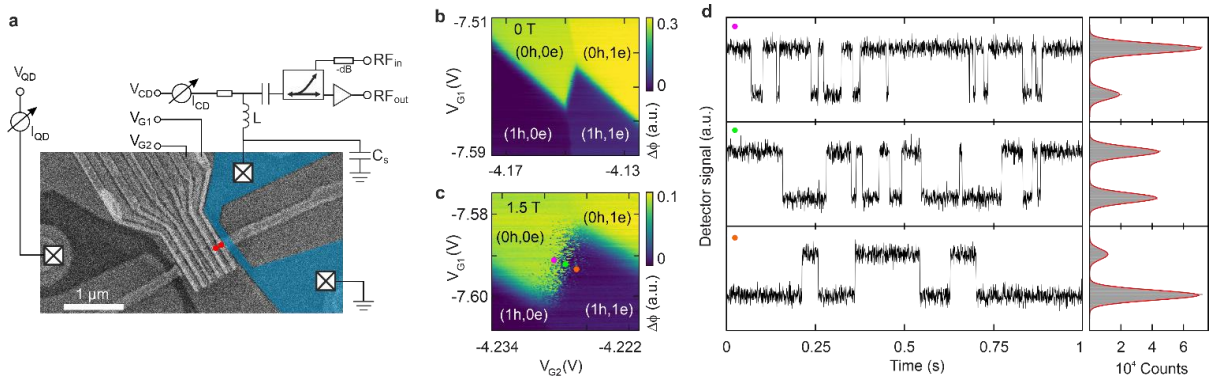

Fig. 1. (a) Scanning electron microscope image together with a schematic of the RF readout circuit. QDs (red) are formed under the finger gates and couple capacitively to a QPC formed in the channel (blue). The RF signal reflected of an LC resonant circuit connected to that channel is measured. (b, c) Charge stability diagrams in the single-electron single-hole regime measured at B = 0T and at B = 1.5T. (d) Time-resolved detection of (0h,0e) - (1h,1e) charge transitions together with their histograms.

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Hybrid Superconducting Quantum Circuits with van der Waals Heterostructures

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Van der Waals materials constitute a diverse array of layered substances, spanning semi-metals, insulators, semiconductors, ferromagnetic materials, superconductors, and topological insulators. These materials can be intricately assembled to form van der Waals heterostructures, holding significant promise for constructing key components for emerging solid-state quantum computing platforms. Conversely, superconducting circuits and circuit quantum electrodynamics (cQED) techniques offer a distinctive and potent toolkit for investigating novel quantum materials, complementing traditional quantum transport measurements.

In this presentation, I will explore superconducting quantum circuits constructed using van der Waals heterostructures, which play a central role in advancing and enhancing existing quantum technologies. Moreover, I will share insights from our recent studies concerning the kinetic inductance and pairing symmetries of 2D superconductors, such as $NbSe_2$ and the magic-angle twisted bilayer graphene (MATBG). By utilizing superconducting circuits and cQED techniques, our research endeavors to deepen understanding and harness the potential of these materials for quantum technologies.

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Electron correlations in graphene multi-layers

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Controlling and understanding electron correlations in quantum matter is an outstanding goal in materials science. In recent years, a wealth of new correlated states has been found by carefully stacking and twisting two-dimensional van der Waals materials. Unique to these stacked structures is the emergence of correlated phases not foreseeable from the single layers alone. In this talk, we contrast correlations, spin, valley and superconducting order in twisted and non-twisted graphene multilayers. In all cases, hybridization of Dirac cones leads to (partially) flat bands with non-trivial quantum geometry, which prevents interaction-driven Mott Hubbard localization of electrons. Distinct correlated electron states arise depending on whether a moiré superlattice is present or not. In the moiré case, exemplified by twisted bilayer graphene, topological heavy fermion physics emerges where local moment formation, Kondo physics and isospin order compete [1,2]. In moiré-less graphene multilayers, instead of local moments, long-range charge, valley, and spin fluctuations control the formation of isospin order and superconductivity..

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Optically tunable many-body exciton-phonon quantum interference

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The Fano effects are ubiquitous in spectroscopy study of atoms, semiconductor nanostructures, photonics, and strongly correlated systems. It arises when quantum interference takes place between two competing optical pathways linking the discrete and continuum states. Fano resonance plays a crucial role in defining optical transitions, scattering, transport and heat dissipation in low-dimensional systems. Most studies of Fano interference predominantly framed within the classical atomic Fano theory, focusing on tuning the optical transitions of the coupled quantum states with closely matched excitation energies. An exciting prospect emerges if Fano quantum interference can be optically driven and manipulated even when the discrete states are energetically remote from the continuum band, going beyond the conventional Fano paradigm. This scenario would enable unambiguous tuning of Fano resonance across a broad energy range on an ultrafast timescale. We introduce a novel paradigm for achieving widely tunable many-body Fano quantum interference in low-dimensional systems, beyond the conventional requirement of closely matched energy levels between discrete and continuum states observed in atomic Fano systems. Leveraging Floquet engineering, we demonstrate remarkable tunability of Fano lineshapes, even when the original discrete and continuum states are separated by over 1 eV. Specifically, by controlling the quantum pathways of discrete phonon Raman scattering using femtosecond laser pulses, we tune the Raman intermediate states across the excitonic Floquet band. This manipulation yields continuous transitions of Fano lineshapes from antiresonance to dispersive and to symmetric Lorentzian profiles, accompanied by significant variations in Fano parameter q and intensities of Raman scattering spanning two orders of magnitude. A subtle shift in the excitonic Floquet resonance profoundly modifies quantum interference strength from destructive to constructive interference. This work opens new avenues for coherent control of quantum interference in low-dimensional systems.

Proximity-induced phenomena in twisted van der Waals heterostructures

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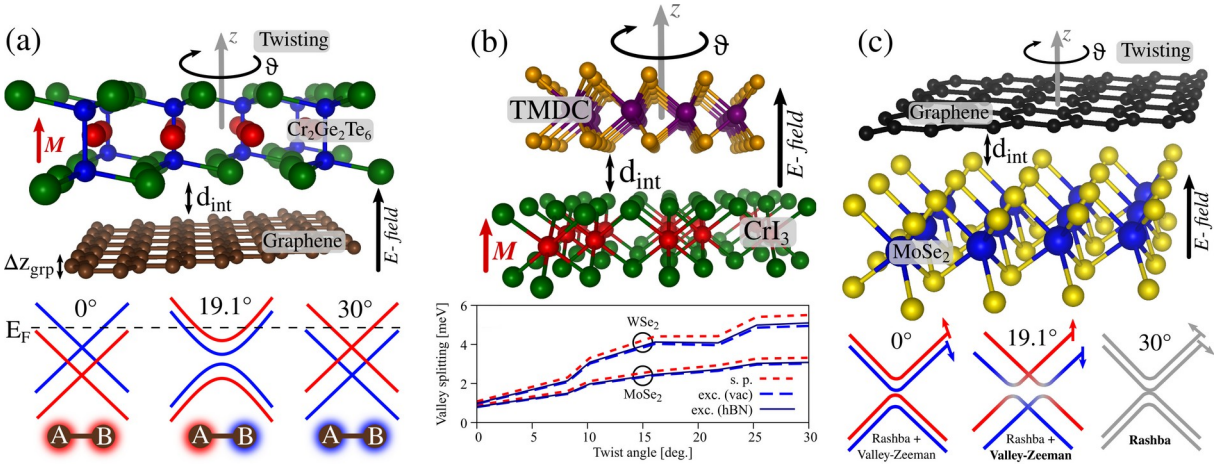
Proximity-induced phenomena in van der Waals heterostructures have emerged as a platform to tailor the electronic, spin, optical, and topological properties in two dimensional materials. A crucial degree of freedom, which has only recently been recognized, is the relative twist angle between the monolayers. We present comprehensive DFT-based results on twist- and gate-tunable proximity spin-orbit and exchange coupling in various 2D material heterostructures. Remarkably, in graphene/Cr2Ge2Te6, the proximity exchange splitting of Dirac states can be reversed upon twisting, from 4meV to -4meV, while keeping the magnetization of Cr2Ge2Te6 fixed [1]. In WSe2/CrI3, the valley splitting shows a gigantic tunability, from 0 to 12meV (about 60 Tesla external field), combining twisting and gating [2]. In graphene/transition-metal-dichalcogenide bilayers, the spin-orbit coupling of proximitized Dirac bands can be tailored by several means [3]. Finally, we consider more complex twisted multilayer structures and demonstrate the emergence of purely radial spin-orbit fields, stemming from the interference of opposing Rashba fields. We also relate our findings to experimentally verifiable fingerprints of proximity-induced spin interactions.



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Abstracts of Posters

(in alphabetical order)

Unusual quantum Hall state in near 30°-twisted bilayer graphene

Kuo-En Chang[1], Sheng-Chin Ho[1], Ta-Lei Chou[2], Yu-Chiang Hsieh[1], Chiu-Hua Huang[1], Ching-Hua Kao[1], Kenji Watanabe[3], Takashi Taniguchi[4], Ming-Wen Chu[2], Tse-Ming Chen[1,5]

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The moiré pattern achieved by twisting and assembling two sheets of 2D materials at a magic angle or small angle exhibits intriguing phenomena like superconductivity, Mott insulator behavior, and ferroelectricity due to strong interaction effects [1, 2]. At a precisely 30° twist, a quasicrystal pattern emerges. Although it lacks the translational symmetry, a twelve-fold rotational symmetry comes out. Moreover, the existence of strong interlayer coupling, caused by the mirrored Dirac cones at high energy level, has been suggested [3, 4]. However, the observation of such coupling effects in electrical transport measurement still remains elusive. Here, we fabricate devices with a small deviation from 30° twist angles. The diffraction and high resolution patterns captured from transmission electron microscopy (TEM) confirm the twisted angle of the devices. For the transport measurement at low temperature, we observe an unusual degeneracy of plateaus in quantum Hall effect (QHE) which evolves into a twelve-fold degeneracy when increasing the temperature to 60K. More strikingly, the quantum oscillation in longitudinal resistance exhibits unconventional behavior as a function of carrier density and displacement fields. These quasicrystal-like phenomena suggest the significance of interlayer coupling and open a new door for investigating the quasicrystal in twisted angle bilayer graphene.

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Measuring Spin-flip rates of single spins in coupled quantum dots

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Spin relaxation is a limiting factor for spin-based information processing. Here, we investigate electron transport through asymmetrically coupled InAs double quantum dots, using a spin blockade mechanism for single electrons occupying the devices to determine spin relaxation rates directly from the measurement.
Due to the difference in sizes of the two dots, their g factors are different and therefore the Zeeman splitting becomes inhomogeneous so that two spin channels are never resonant simultaneously. This leads to a spin-dependent blockade mechanism for single electrons [1,2]. An electron entering the first dot may be trapped in the off-resonant channel and block transport. This blockade can be resolved by a spin flip bringing the electron to the resonant channel.
We analyzed this blockade in terms of spin flips for different magnetic fields and temperatures and we were able to determine the spin-flip rates directly from the measured resonant tunnel currents [1]. Our results are in good agreement with a quantum master equation that combines the dot-lead couplings with ohmic dissipation, identifying spin-flip cotunneling as the dominating decoherence mechanism.

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Ultra-steep slope cryogenic FETs based on bilayer graphene

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Cryogenic field-effect transistors (FETs) offer great potential for a wide range of applications, the most notable example being classical control electronics for quantum information processors [1].

In the latter context, on-chip FETs with low power consumption are a crucial requirement. This in turn requires millivolt operating voltages, which can only be achieved in devices with ultra-steep subthreshold slopes. However, in conventional cryogenic metal-oxide-semiconductor (MOS)FETs based on bulk material, the experimentally achieved inverse subthreshold slopes saturate at around a few mV/dec due to disorder and charged defects at the MOS interface [2]. FETs based on two-dimensional materials offer a promising alternative.

Here, we show that FETs based on Bernal stacked bilayer graphene encapsulated in hexagonal boron nitride and graphite gates exhibit inverse subthreshold slopes of down to 250 µV/dec at 0.1 K, approaching the Boltzmann limit. This result indicates an effective suppression of band tailing in van-der-Waals heterostructures without bulk interfaces, leading to superior device performance at cryogenic temperatures.

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Topology and disorder in a 2D semi-Dirac material

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Semi-Dirac materials in 2D present an anisotropic dispersion relation, linear along one direction and quadratic along the perpendicular one. This study explore the topological properties and the influence of disorder in a 2D semi-Dirac Hamiltonian. Topological protection of edge states is anisotropic an occurs only in one direction and can be rigorously founded on the Zak phase of the one-dimensional reduction of the semi-Dirac Hamiltonian, parametrically depending on one of the momenta. We explore the dependence on the disorder of the edge states and the robustness of the topological protection in these materials.

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Spin-orbit coupling in bilayer graphene/transition-metal dichalcogenide quantum devices

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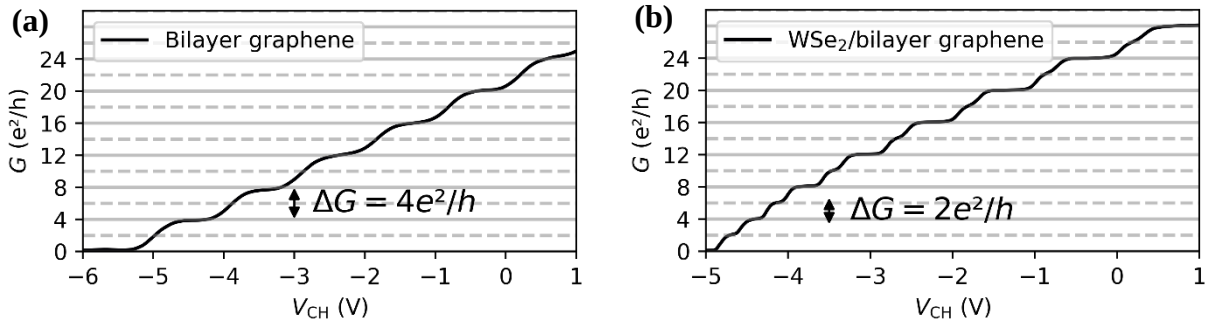
We characterize quantum point contacts and quantum dots in a bilayer graphene/WSe_2 heterostructure. In contrast to pristine bilayer graphene, where the intrinsic spin-orbit coupling (SOC) ranges typically from 40-80 µeV [1,2], we measure enhanced values of up to 1.4 meV by adding WSe_2 to the bilayer graphene. Moreover, we demonstrate the tunability of the SOC strength from its maximal value to complete suppression through manipulation of the perpendicular electric field.

This increased SOC strength combined with its tunability holds great potential for future quantum computing and spintronics applications.



Conductance G versus channel gate voltage (V_{CH}) of a quantum point contact in (a) bilayer graphene and (b) WSe_2/bilayer graphene. In WSe_2/bilayer graphene, the increased SOC lifts the fourfold degeneracy, resulting in a conductance step height of $\Delta G = 2e^2/h$.

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Excitons in nanostructures from the Bethe-Salpeter equation

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Electronic structure calculations are a well-established tool for the identification of candidate materials for technological applications, e.g., in photocatalysis, photovoltaics and energy storage. However, the widely used density functional theory (DFT) encounters fundamental problems regarding the description of optical properties of semiconductors. For the quantitative description of these optical excitations, many-body perturbation theory within the GW approximation and the Bethe-Salpeter equation (BSE) on top of GW is the state-of-the-art method [1].

We implemented the BSE in the highly scalable open-source package cp2k [2] for treating excitations of molecules in the gas phase and verified its results against the existing implementation in the FHI aims package [3]. Further, we applied our BSE implementation to study electronic excitations in nanographenes to highlight its scalability.

In the future, we aim for the ab-initio description of optical properties of two-dimensional materials, where we want to investigate spatially large excitons in heterostructures of transition-metal dichalcogenides (TMDC). To this end, we are working on a low-scaling implementation of the periodic BSE, taking advantage of the available low-scaling GW methods [4] and paving the way to the quantitative description of extended excitons in twisted TMDC heterostructures.

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Current-induced switching in van der Waals WTe_2/Fe_3GeTe_2 heterostructures

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The layered transition metal dichalcogenide WTe_2 has emerged as a fascinating material for exploring spin-orbit phenomena and current-driven magnetization dynamics. Owing to its strong spin-orbit coupling, broken inversion symmetry, and tunable electronic properties, WTe_2 exhibits unique spin-orbit torque behavior when interfaced with ferromagnetic layers. Here, we investigate spin-orbit torques using ferromagnetic resonance (FMR) in WTe_2/Py. Additionally, we study the spin-orbit torque-induced perpendicular magnetization switching behaviors in WTe2/FGT heterostructures. These experiments demonstrate that the out-of-plane spin polarization, induced by symmetry breaking in WTe_2, plays a crucial role.

THZ-induced linear and circular ratchets in patterned-gated graphene

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We have measured the terahertz-induced ratchet effect in graphene-based two-dimensional (2D) metamaterials consisting of a graphite gate patterned with an array of triangular antidots placed under a graphene monolayer. The ratchet current is generated by the combined action of a spatially periodic in-plane electrostatic potential and a periodically modulated radiation electric field caused by near-field diffraction. The magnitude and direction of the ratchet current are shown to be sensitive to the polarization state and are controlled by voltages applied to both the back and patterned gates, which vary the lateral asymmetry, carrier type, and density

Fig2.pdf

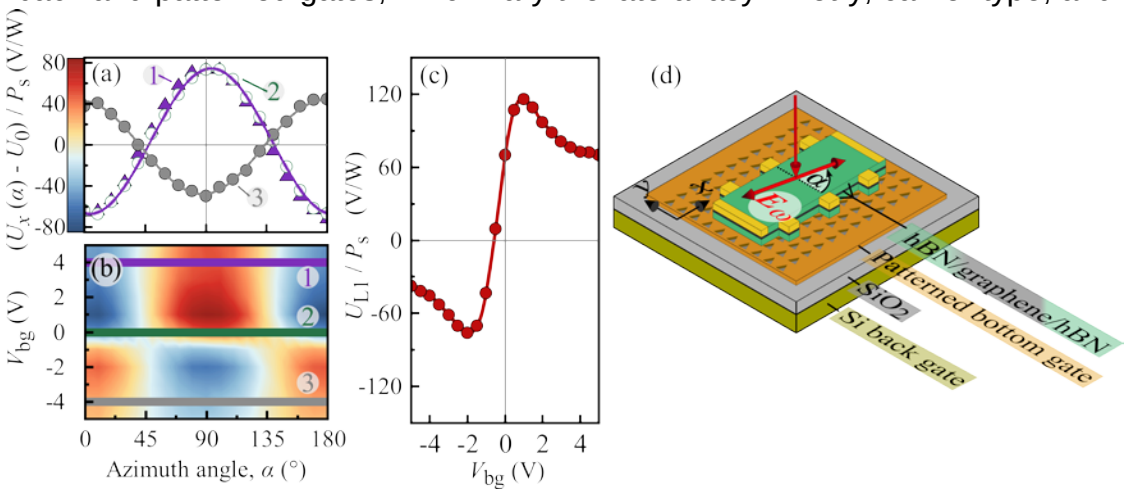

FIG. 1: (a) and (b): Polarization dependencies of the normalized photosignal measured along the source-drain contacts ($U_x(\alpha) - U_0)/P_s$ (contacts 5-1), for zero patterned gate and various back gate voltages. Panel (c): Amplitude of the dominating cosine contribution versus back gate voltage. Panel (d): sketch of the sample and the experimental configuration.

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Interference effects in high-harmonic generation from Dirac materials

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The study of high-harmonic generation (HHG) in solids by virtue of intense laser pulses provides a fascinating platform to study ultra-fast electron dynamics as well as material properties. We theoretically investigate HHG on the basis of massive Dirac Fermions, serving as a prototypical model for topologically non-trivial matter and other systems with pseudo-relativistic dispersion[1]. The harmonic emission is calculated using the well-established framework of the Semiconductor-Bloch equations. We found a potentially generic phenomenon of Dirac-like systems, which is a strong interference between inter- and intraband contributions. This interference qualitatively changes the observed spectrum and we investigate its dependence on dimensionless parameters[2] governing the transition dynamics of the system.

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Possible signature of frustrated magnetism in kagome-strained graphene

Yu-Chiang Hsieh[1], Kuan-Yu Chou[1], Sheng-Zhu Ho[1], Ru-Long Gou[1], Ching-Hua Kao[1], Kenji Watanabe[2], Takashi Taniguchi[3], Tse-Ming Chen[1,4]

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Strain engineering in two-dimensional materials offers numerous benefits and has significantly modified the intrinsic properties of these materials, creating an exciting research field known as straintronics. Recently, a versatile strain engineering technique that relies on lithography and atomic etching of hexagonal boron nitride (hBN) substrate has been developed, allowing us to use various artificial surface nanostructures and patterns to create high-quality strain. This approach has been used to created corrugated strain profile, which enabled the observation of two nontrivial Hall effects in bilayer graphene [1] and enhancing the interlayer exciton at room temperature in molybdenum disulfide [2]. Here, we create kagome lattice arranged pseudo-gauge field in graphene using this strain engineering technique and observe spin-ice-like quantum phenomena. At low temperatures, the kagome-strained graphene exhibits a distinct insulating state characterized by a Coulomb gap as a result of electron interactions. Additionally, it displays signatures of geometrically frustrated magnetism, including idiosyncratic hysteresis features [3] and time-dependent magnetic relaxation [4], which may be related to the geometrical frustration arrangement of the pseudo-gauge field. The distinct insulating state and the frustrated magnetism are robust to variations in carrier density, distinct from the typical flat-band scenario in twist engineering [5], but exhibit a pronounced sensitivity to the drive current. This is similar to those observed in a Luttinger liquid [6], suggesting the significance of electron interactions in our system.

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Fabry-Pérot interference in gate-controlled graphene superlattice

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Fabry-Pérot interference in gate-defined cavities is a useful tool in the scope of electron optics in graphene. Its weak magnetic field dependence reveals the emergence of the Berry phase embraced by the interfering electron trajectories [1] and can also become very different in the presence of a periodic potential that turns the conic structure of graphene's low energy bands into minibands [2]. Here, we consider gate-controllable graphene superlattice using periodically patterned substrate [3], whose transverse magnetic focusing spectra have been theoretically studied very recently [4]. Our simulation results provide new insights into this highly tunable superlattice miniband structure, with more complex observations of Fabry-Pérot interference fringes due to multiple extra Dirac points and under varying levels of external magnetic fields.

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Understanding single molecule fluorescence by means of scanning tunneling microscopy-induced luminescence

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Understanding the fundamental mechanisms of optoelectronic excitation and relaxation pathways on the single molecule level has only recently been started by combining scanning tunneling microscopy (STM) and spectroscopy (STS) with STM-induced luminescence (STML). To rationalize the photon emitting process from single molecules, we investigate transient charged state fluorescence and resonant energy transfer of individual metal phthalocyanine (MPc) molecules adsorbed on ultrathin NaCl films on Ag(111) by using STML.

First, we show the evidence for both cationic and anionic fluorescence of individual ZnPc which depends on the polarity of the tip-sample bias. By carefully mapping the molecular frontier orbitals over a wide energy range, correlating them with threshold voltages for light emission, and comparing with results from density functional theory calculation, we propose an alternative many-body picture to describe the charging and electroluminescence mechanism.

Second, we demonstrate successful activation of fluorescence from individual open-shell 3*d* complexes, NiPc molecules, by matching resonant energy transfer from other MPcs (M = Zn, Pd, Pt) at low temperature. Luminescence of open-shell 3*d* metal complexes is often quenched due to ultrafast intersystem crossing (ISC) and cooling into a dark metal-centered excited state. Combining our STML experiments as well as time-dependent density functional theory, we provide evidence that there is an activation barrier for the ISC. However, when an MPc molecule is placed close to NiPc by means of STM atomic manipulation, resonant energy transfer can excite NiPc without overcoming the ISC activation barrier, leading to Q-band fluorescence.

In our studies, we provide fundamental insights regarding the role of transiently charged states of emitter molecules within organic light-emitting diode devices as well as the use of luminophores based on more abundant transition metal complexes by restricting vibration-induced ISC.

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MoS_2 nanotubes as intrinsic 1d superconductors?

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Planar, monolayer MoS_2 is known to become superconducting at large ionic n-doping; it displays the typical "dome" of critical temperature as function of charge density and is a clear Ising superconductor [1]. Published works have addressed, e.g., the impact of band occupation [2], the superfluid response [3], or tunneling spectroscopy [4]. Theoretical works predict at strong hole doping topological superconductivity [5].
Separately, intrinsic superconductivity at ionic n-doping has also been shown in WS_2 nanotubes, with chirality-induced non-reciprocal superconductivity, diameter-dependent effects and indications of Little-Parks-Oscillations [6].

Clean and defect-free MoS_2 nanotubes, as grown via chemical transport reaction [7], should provide an even better test bed for the interplay of a tubular geometry and Ising superconductivity. In addition, with ionic doping mostly affecting the outermost shell of a multi-wall nanotube, the material system lends itself intrinsically for core-shell semiconductor/superconductor hybrid structures at strong spin-orbin interaction. Here, we present our ongoing work towards this objective [8,9].

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Transverse Magnetic Focusing of the Radial Rashba Spin-Orbit Coupling in Proximitized Graphene

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Graphene-based van der Waals heterostructures take advantage of tailoring spin-orbit coupling (SOC) in the graphene layer by proximity effect[1-4]. Taking such effective models, we perform realistic large-scale transverse magnetic focusing calculations and show that there are unique qualitative and quantitative features allowing for an unbiased experimental disentanglement of the conventional Rashba SOC from its novel radial counterpart, called here the radial Rashba SOC. Along with that, we propose a scheme for a direct estimation of the Rashba angle by exploring the magneto-response symmetries when swapping an in-plane magnetic field.

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Unveiling the Importance of Finite-Momentum Dark Excitons to Energy Transfer in Monolayer Transition-Metal Dichalcogenides

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This study delves into the theoretical exploration of exciton-mediated Förster resonant energy transfers (FRET) from photoexcited quantum dots (QD's) to monolayer transition-metal dichalcogenides (TMD-ML's) inspired by recent experiments, which have evidenced the FRET's of TMD-ML's to be extraordinarily fast and show near unity transfer efficiencies [1-4]. Later, another experiment shows that carrier dynamics in such systems are also critical issues in developing future optoelectronic devices [5]. Here, by employing the quantum theory of FRET-based on first-principles-calculated exciton fine structures, we unveil the remarkable potential of atomically thin TMD-ML's as an exceptional platform for FRET, leveraging their enhanced electron-hole (*e-h*) Coulomb interactions and superior excitonic properties [6]. We demonstrate that the energy-transfer responses of TMD-ML's are primarily governed by finite-momentum dark excitons, differing from the conventional understanding of bright excitons. Specifically, we highlight the essential role played by longitudinal dark exciton states, arising from *e-h* exchange interaction resulting in light-like linear band dispersion, in enhancing the efficiency of FRET in TMD-ML's against the inhomogeneity of QD-donor ensembles. With the essential role of dark excitons, the FRET in TMD-ML's no longer follows the distance power law as classically predicted and, notably, cannot manifest the dimensionality of the donor-acceptor system.

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Hybrid superconductor-quantum dot devices utilizing magic-angle twisted bilayer graphene

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Utilizing quantum dots as weak links to form a strongly coupled superconductor/quantum dot (non-superconducting)/superconductor structure offers an intriguing laboratory for exploring unusual physical phenomena and functionalities. For example, the superconducting current within this structure can exhibit phase variations of both 0 and π, depending on the number of electrons in the quantum dot [1]. Such gate-tunable π junctions have potential applications in Josephson current switches [2] or certain superconducting quantum circuits.

In realizing such a hybrid system, having an ultra-clean interface between superconductors and quantum dots is crucial. Hence, employing a singular two-dimensional material with gate-tunable superconductivity becomes an ideal candidate for this purpose. Here, we report the use of magic-angle twisted bilayer graphene [3] as the sole material for this hybrid system. This approach effectively mitigates the influence of differing materials at the interface. In this poster presentation, we will focus on our device fabrication and the transport results we have obtained so far.

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Full-Zone Valley Polarization Landscape of Finite-Momentum Excitons in Transition-Metal Dichalcogenide Monolayers

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Transition metal dichalcogenide monolayers (TMD-MLs) have attracted broad interest because of its spin-valley coupled characteristics in the electronic and excitonic structures [1]. However, it is known that the valley polarization of optically excited excitons are very likely to be degraded due to the intrinsic electron-hole (e-h) exchange interaction. Moreover, the momentum-forbidden dark excitons (MFDXs) are also highly involved in the excitonic dynamics and various optical phenomena [3]. Therefore, a comprehensive theoretical understanding of the MFDXs in TMD-MLs over the extended momentum space is demanded.

In this study [5], we present a theoretical investigation of the full-zone landscape of finite-momentum dark excitons in WSe_2-MLs by solving the density-functional theory (DFT)-based Bethe-Salpeter equation (BSE) under the guidance of symmetry analysis. The studies reveal the comprehensive valley-depolarization landscape of finite-momentum exciton of WSe_2 monolayer. Dictated by the crystal symmetry, the valley pseudospin texture over the extended exciton-momentum $\mathbf{k}_{ex}$ space exhibits rich structures, featured by the inherently full valley polarizations in the excitonic $\mathbf{K}_{ex}$, $\mathbf{K}'_{ex}$ and $\mathbf{Q}_{ex}$ valleys and also by the contrasted valley depolarization for the exciton states lying in the $\mathbf{\Gamma}_{ex}\mathbf{M}_{ex}$ paths. Attractively, the superior valley polarizations of the intervalley dark excitons in WSe_2-MLs are shown almost fully transferrable to the optical polarization in the phonon-assisted photoluminescences because of the native suppression of exchange-induced depolarization in the second-order optical processes. The analysis of phonon-assisted photoluminescences accounts for the recently observed brightness, high degree of optical polarization, and long lifetime of the intervalley dark exciton states in tungsten-based TMD-MLs.

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Breaking symmetries with light: Novel non-linear responses in optically pumped centrosymmetric Dirac systems

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We theoretically investigate the effects of non-adiabatic dynamics induced in centrosymmetric Dirac systems like monolayer graphene, pumped by intense sub-cycle laser pulses. The tailored pump creates electronic distributions which spontaneously break the symmetries of the Hamiltonian, giving rise to forbidden valley specific non-linear Hall responses and beyond, aided by the band Berry curvature dipole. We show how these responses can be experimentally tuned, all optically, in a pump-probe setup.

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Exciton Spectra from First Principles Density Matrix Time Propagation

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Description of excitation spectra of molecules and materials is challenging, due to the size of the accessible Fock space. While for ground state calculations, we can restrict our treatment of the many-body problem to the effective single particle description provided by DFT[1], same approximation cannot be used for excited state phenomena[2]. We implement the many-body perturbation theory based approximation to the self-energy operator, so called Coulomb-hole + screened exchange approximation[3], in an equation of motion method for the single particle reduced density. We discuss possible observables and their relation to other established methods, namely BSE and TDDFT[4].

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Superconductivity from electronic interactions on a fragmented Fermi surface

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The alternative mechanisms for the superconducting pairing have been explored for a long time – starting from the Kohn-Luttinger proposal in 1965, through the physics of high-Tc superconductors, up to the recent studies of superconducting pairing in the van der Waals material $NbSe_2$ [1,2]. The common feature of many of these works is that the superconducting correlations between the members of a Cooper pair don't have to arise from an effective attraction, but can be the result of two or more competing repulsions.

The Fermi surface in $NbSe_2$ is split into three pockets, around the Γ, K and K' points. The presence of different pockets divides the Coulomb scattering processes into subsets with different scattering ranges. The competing repulsion events at different ranges can result in the formation of Cooper pairs, provided that the short-range repulsion is stronger than the long-range one. Depending on which of the interaction types is dominant, we find that the material can support several superconducting gaps with different symmetries, both in the *s* and in the *f* pairing channel. We analyze the dI/dV characteristics of recently performed STM experiments on $NbSe_2$ [3] and find that while they are consistent with both one and two gaps, the agreement is better when two gaps are considered.

In order to gauge the strength of the interaction at different ranges we have calculated the screened Coulomb potential in this material, using the tight-binding model and the RPA approximation. We find that while the gaps at K/K' points can form in the absence of the Γ pocket, once it is included it can be a powerful player, even to the point of changing the symmetry of the gaps in the K/K' valleys.

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Characterization of a THz near-field microscope

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Since its first demonstration in 1990, THz time-domain spectroscopy has been established as a powerful tool to analyze the electrical-, plasmonic-, phononic- and vibrational characteristics of materials. With its photon energy in the low meV-range it provides a destruction- and contact-free measurement setup to access the free carrier response in a large variety of samples.
In my contribution I would like to present the recently done characterization of an apertureless THz near-field microscope (cf. [1]). The microscope uses a thin electro-optic crystal to determine the transmission spectra of two-dimensional samples. By limiting the thickness of the electro-optic crystal the microscope is effectively operating in the near-field regime thus increasing the resolution below the wavelength limit. The microscope is shown to have a resolution in the 50 µm range (one order of magnitude below the focusing limit) and a diffraction based simulation is used to determine the influence of the adjustable parameters on the resolution. The setup will serve as the basis of my recently started work as a PhD-student, in which the microscope will be used to analyze the plasmonic response in patterned graphene samples as well as in other two-dimensional samples such as exfoliated black phosphorous and semiconductor based 2DEGs. If the measurements work as planned they would be the first direct observation of the plasmonic field within a graphene sample with both temporal and spatial resolution.

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Nanoscale imaging of moiré patterns using time-domain Electro-Mechanical technique

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The moiré superlattices in van der Waals materials holds a fascinating realm of emergent electronic phenomena where the interplay between atomic structure and electronic correlations have been observed. The interesting properties exhibited by electrons in moiré superlattices have unveiled intriguing phenomena such as topology[1], superconductivity[2], strange metals[2], and other strongly correlated effects. Nevertheless, as the interest in the local properties of moiré superlattices continues to grow, further advancements in fabrication and characterization techniques are essential to motivate progress in this field.

In this study, we present a polymer-based approach utilizing Polyvinyl Chloride (PVC) for fabricating flipped twisted bilayer graphene devices that are compatible with scanning probe techniques. We used an advanced technique known as Electrostatic heterodyne force microscopy [3] (E-HFM) probing moiré electromechanical properties at mega-hertz frequency in multiple twisted graphene devices. By using the high-frequency and heterodyne detection scheme, E-HFM allows for significant reduction of spurious contributions from both electrostatic force and electrochemical strain, unravelling a unique contrast in twisted materials.

We believe that the dry-flip technique can be extended to the full range of moiré heterostructures, thereby opening new avenues for probing emergent phenomena in moiré materials using local scanning probe techniques.

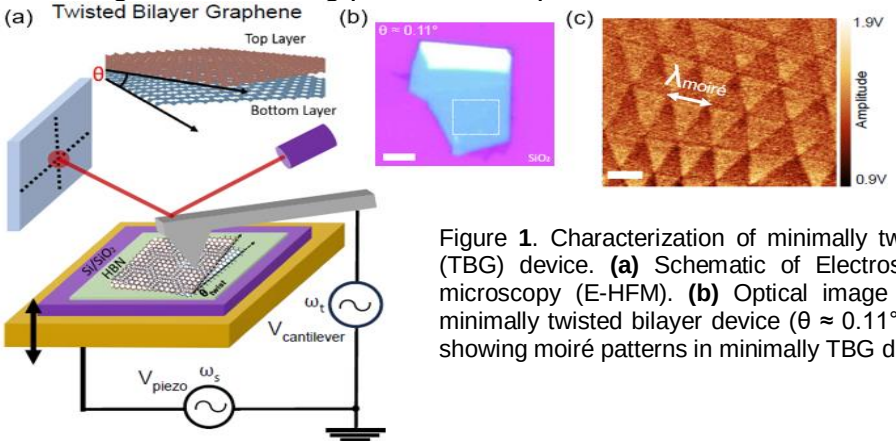

Figure **1**. Characterization of minimally twisted bilayer graphene (TBG) device. **(a)** Schematic of Electrostatic heterodyne force microscopy (E-HFM). **(b)** Optical image of a dry- flip stacked minimally twisted bilayer device (θ ≈ 0.11°). **(c)** E-HFM amplitude showing moiré patterns in minimally TBG device.

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Cyclotron resonance overtones and near-field magnetoabsorption via terahertz Bernstein modes in graphene

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Two-dimensional electron systems subjected to a perpendicular magnetic field absorb electromagnetic radiation via the cyclotron resonance (CR). Here we report a qualitative breach of this well-known behaviour in graphene [1]. Our study of the terahertz photoresponse reveals a resonant burst at the main overtone of the CR drastically exceeding the signal detected at the position of the ordinary CR. In accordance with the developed theory and extensive studies regarding frequency, polarisation and temperature, the photoresponse dependencies on the magnetic field, doping level, and sample geometry suggest that the origin of this anomaly lies in the near-field magnetoabsorption facilitated by the Bernstein modes [2], magnetoplasmon excitations reshaped by nonlocal electron dynamics. Close to the CR harmonics, these modes are characterized by the diverging plasmonic density of states that strongly amplifies terahertz absorption which, in turn, causes the photoresistance and photovoltage enhancement.

Our results have several profound consequences for further research on nonlocal light-matter interaction at the nanoscale and revisit the role of nonlocal conductivity in light-matter interaction that was previously believed to hamper field compression and slowing of light [3]. Our study refutes this perspective by revealing highly-confined ultra-slow plasmon modes enabled by nonlocality. Besides fundamental interest, our experimental results and developed theory show that the radiation absorption via nonlocal collective modes can facilitate strong photoresponse, a behaviour potentially useful for infrared and terahertz technology.

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Modeling transverse magnetic focusing in circular cavity

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Transverse magnetic focusing (TMF) has been used extensively for investigating various material properties, including probing the Fermi surface in metals and semiconductors, [1, 2], minibands in moire superlattices [3, 4], spin-orbit coupling strength [5], and Andreev reflection [6]. A typical system for studying TMF consists of a rectangular region with narrow probes at one of its edges. Here, we perform theoretical study of magnetic focusing in a distinct geometry, with circular shaped cavity, and injector and collector probes oriented radially with variable relative angle. To this end, we perform calculations using the Landauer-Buttiker formalism as well as semiclassical equations for electron movement, and observe focusing peaks corresponding to counterintuitive carrier trajectories. Our work provides insight into carrier dynamics in graphene and other 2D materials, and flexible computational approach for general scattering geometries.

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Ultrafast dynamics in quasi-2D CDW systems $LaTe_3$ and $LaSeTe_2$

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Charge density waves (CDW) involved with electronic and phononic subsystems simultaneously are a common quantum state in solid-state physics, especially in low-dimensional materials. This study presents a detailed analysis of time-resolved spectra on $LaTe_3$ and $LaSeTe_2$, quasi-two-dimensional paradigmatic CDW systems. Numerous coherent (Raman active) modes appear upon the phase transition into the CDW state. Using the time-dependent Ginzburg-Landau model, we examine the temperature dependence of mode frequencies, their damping times, and their oscillator strengths. These low-temperature modes originate from the linear coupling between the normal-state phonons at the CDW wave vector and the modulation of the conduction electron density induced by Fermi surface nesting. Furthermore, we can identify the nature of excitation of these coupled modes. The softening mode was discovered to be an overdamped mode, which is primarily electronic in nature. The experimental observation and theoretical understanding of ultrafast dynamics may offer insight into other general principles behind nonequilibrium phase transitions in many-body systems.

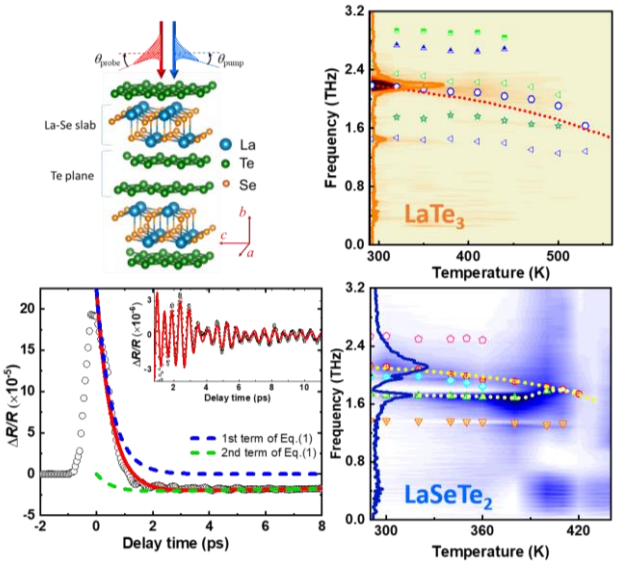

Figure 1. Ultrafast dynamics at various temperatures on the *ac*-plane of $LaTe_3$ and $LaSeTe_2$ single crystals.

Keywords: time-resolved ultrafast spectroscopy, charge density wave

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Transfer and contact optimization of MoS_2 nanotubes

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Transitional metal dichalcogenide (TMDC) based 2D materials and their optical and electronical properties are at the center of nanotechnology research efforts. However, the fabrication of quantum dots (Qds) in TMDCs still remains challenging, since the large effective electron mass in the conduction band requires minuscule devices sizes at the lithographic limit. We can overcome this limitation by utilizing MoS_2 nanotubes, effectively constraining charges by one more dimension with the macro-molecular geometry [1].

Extensive research efforts have been made to develop new transfer techniques, devices assemblies, and contact methods for 2D TMDCs. Previously, we could demonstrate that the semi-metal bismuth can be used to create transparent contacts to MoS_2 nanotubes and nanoribbons. Here, we present our current investigations into different contact materials and the impact of state-of-the-art dry and deterministic transfer techniques adapted from 2D materials[2].

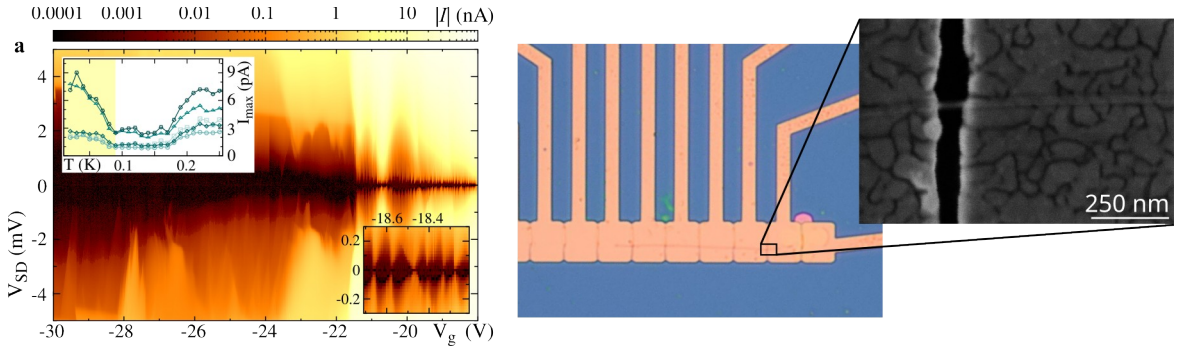

Figure: Left: low-temperature transport spectroscopy of a MoS2 nanoribbon. Right: MoS2 nanotube transferred with anthracene on gold contacts.

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Magneto transport in bilayer graphene cavities

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The remarkable sample quality of bilayer graphene in combination with the unprecedented electronic control of the band-structure makes bilayer graphene an excellent platform for electron optics. While the purity of the system allows for ballistic transport on the micrometer scales [1,2], the trigonal warping of the band structure close to each K points induces a valley dependent selection of momenta leading to unique transport and scattering properties [3,4]. Interested in the interplay of symmetry breaking induced by a variety of all-electronic gate confinements and the trigonal warping, we implement various quantum mechanical tight binding models and deploy them to investigate magneto transport through bilayer graphene cavities.

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The Coarse Geometric Origin of Topological Phases

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Topological phases of matter rely on the concept that the ensemble of occupied bulk energy bands of a translationally invariant Hamiltonian can be classified by topological invariants by making use of internal electronic symmetries. Non-trivial invariants give rise to exceptional electronic states at the boundary [1]. This approach falls short when dealing with disorder induced by prevalent crystal defects. We propose that one should work in a coarse geometric framework, where the invariant can be defined in the presence of disorder [2]. This construction is physically motivated, provides a natural setting for the bulk-boundary correspondence and furthermore provides a numerical efficient way to calculate the invariants [3]. We apply this approach to a low energy tight-binding model of a three-dimensional topological insulator with time reversal symmetry and the two-dimensional Kane-Mele model. We discuss the phase diagram in the disorder-free case and analyse the evolution of the topological phase upon the introduction of disorder.

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Tuning the proximity induced spin-orbit coupling in bilayer graphene based heterostructures

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To probe the interlayer interactions in van der Waals heterostructures, the pressure is an ideal tool, as it changes the interlayer distance and thus the interlayer tunneling.

Here, we show how the proximity induced spin-orbit coupling (SOC) is changed with the applied pressure in graphene and transition-metal dichalcogenide based devices. In monolayer graphene based heterostructure it was shown with weak anti-localization measurements that the pressure increases the SOC strength [1]. To demonstrate this, we measured bilayer graphene (BLG) and WSe2 based heterostructures. From magnetotransport measurements we extracted Landau level crossings, which can be used to obtain the strength of the SOC [2]. On the other hand, we performed Shubnikov-de Haas measurements to obtain the strength of the Rashba type SOC.

Furthermore, we measured WSe2/BLG/WSe2 heterostructures where we used the closing of the inverted phase to extract the SOC strength [3]. This phase occurs when the sign of the induced SOC is opposite for the top and bottom graphene layers.

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Gate screening of Coulomb interactions in Bernal bilayer graphene

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Measurements on dual gated, hexagonal Boron Nitride (hBN) encapsulated Bernal bilayer graphene samples, have revealed a complex phase space for Bernal bilayer graphene, including numerous Stoner metals, a correlated insulator consistent with a Wigner-Hall crystal [1] and superconducting behaviour [2].

We have investigated the influence of the gate induced Coulomb interaction screening [3] on the appearance of previously reported correlated phases in gated Bernal bilayer graphene devices, using the thickness of the dielectric hBN spacing layers as variable parameter. In direct comparison with the data of Seiler et. al. we observed behaviour, which is supportive of an effectively lowered magnitude of Coulomb interactions in a sample using thinner hBN layers. Additionally, three features in the transport data were identified, which could potentially be indicative of phases, not reported in [1] and [2].

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Effects of spin-orbit coupling in a valley chiral kagomé network

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Recently, scattering networks have gained a lot of attention, because they can model two-dimensional Dirac systems that are dominated by valley chiral modes. Here, we study the kagomé scattering network that has been proposed in double-aligned graphene-hexagonal boron nitride [1] and periodically strained graphene [2]. By combining scattering matrices, we transform the kagomé network to a triangular network with an energy-dependent scattering matrix and perform magnetotransport calculations. Additionally, due to the recent interest in proximity-induced spin-orbit effects in graphene, we include spin-orbit coupling in the scattering network model.

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Magnetic Force Microscopy Perspective of the Anomalous Phase in a Kagome Magnet with out-of-Plane Easy-Axis Anisotropy

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$Co_3Sn_2S_2$ is a halfmetallic magnetic Weyl semimetal where the time-reversal symmetry is broken by the ferromagnetic order from Co atoms in the Kagome lattice. The magnetism is still under debate to describe the anomalous behaviors at around 130K revealed from various experiment schemes. The coexisting ferromagnetic and antiferromagnetic order model is generally accepted now, but the exchanged bias and seemingly spin glass phenomena remain to be explained. Here we provide the viewpoint from the low-temperature magnetic force microscopy (LT-MFM) with comparable conditions to be compared by the results from other methods. We found the stronger out-of-plane ferromagnetic ordering history either by lowering the temperature or field-cooled with larger magnetic fields would induce larger domains and slower moment rotation evolutions when sweeping the magnetic field or increasing the temperature. Our data suggested that the exchange bias might be tunable by the strength of out-of-plane ferromagnetic ordering.

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Atomic Scale Quantum Anomalous Hall Effect in Monolayer Graphene/$MnBi_2Te_4$ Heterostructure

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The two-dimensional quantum anomalous Hall (QAH) effect is direct evidence of non-trivial Berry curvature topology in condensed matter physics[1]. So far, the QAH effect has exclusively been observed in magnetic topological materials. Searching for QAH in 2D materials with the advantage of thinner thickness and easier fabrication emerges as a crucial challenge in future applications. In this work, we propose the QAH effect in graphene/MnBi2Te4(MBT) heterostructure based on density-functional theory[2]. The monolayer MBT introduces intrinsic spin-orbital coupling, Kekulé-O distortion, and exchange Zeeman field on graphene, resulting in a Chern insulating phase with C=1 in covered monolayer graphene. Our effective Hamiltonian further presents a fruitful phase diagram that has never been studied previously. Our work provides a new and practical way to explore the QAH effect in monolayer graphene and the magnetic topological phases by the flexibility of MBT family materials.

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