HL 40: 2D Semiconductors and van der Waals Heterostructures IV

The session covers the magnetic and topological properties of 2D semiconductors and van der Waals heterostructures.

Time: Wednesday 15:30–19:00 Location: H15

HL 40.1 Wed 15:30 H15

Dielectric tensor of the layered magnetic semiconductor CrSBr — •Pierre-Maurice Piel[1], Sebastian Schaper[1], Marie-Christin Heissenbüttel[1], Aleksandra Lopion[1], Zdenek Sofer[2], and Ursula Wurstbauer[1] — [1]Institute of Physics, Muenster University, Germany — [2]Department of Inorganic Chemistry, University of Chemistry and Technology Prague, Prague, Czech Republic

Two-dimensional materials exhibit unique properties due to their atomically thin structure and weak van der Waals (vdW) coupling between layers resulting in layer dependent properties. As in the case of the layered magnetic semiconductor CrSBr, individual layers are ferromagnetically ordered below the Neel temperature (TN= 132K), while adjacent layers are coupled antiferromagnetically. Due to the highly anisotropic electronic bands in CrSBr, electronic and excitonic states at the fundamental band-gap behave quasi-one-dimensional [1]. To develop a better understanding of the extraordinary light-matter interaction in CrSBr, we access the materials dielectric tensor in the paramagnetic phase by spectroscopic imaging ellipsometry that is hard to access by alternative approaches such as reflectance measurements due to the strong anisotropy. In agreement with theory, we extract highly anisotropic dielectric functions along the crystallographic main axes with strong excitonic resonances particularly in the plane. [1] J. Klein et al. ACS Nano, 17, 6, 5316-5328 (2023).

HL 40.2 Wed 15:45 H15

Raman Polarization Switching in CrSBr — •Priyanka Mondal[1], Daria I. Markina[1], Lennard Hopf[1], Lukas Krelle[1], Sai Shradha[1], Julian Klein[2], Mikhail M. Glazov[3], Iann Gerber[4], Kevin Hagmann[1], Regine v. Klitzing[1], Kseniia Mosina[5], Zdenek Sofer[5], and Bernhard Urbaszek[1] — [1]TU Darmstadt, Darmstadt, Germany — [2]Massachusetts Institute of Technology, Cambridge, United States — [3]St. Petersburg, Russia — [4]Université de Toulouse,Toulouse, France — [5]University of Chemistry and Technology, Prague,Czech Republic

Semiconducting CrSBr is a layered A-type antiferromagnet, with individual layers antiferromagnetically coupled along the stacking direction. Due to its unique orthorhombic crystal structure, CrSBr exhibits highly anisotropic mechanical and optoelectronic properties acting itself as a quasi-1D material. CrSBr demonstrates complex coupling phenomena involving phonons, excitons, magnons, and polaritons. Here we show through polarization-resolved resonant Raman scattering the intricate interaction between the vibrational and electronic properties of CrSBr. For samples spanning from few-layer to bulk thickness, we observe that the polarization of the A_g^2 Raman mode can be rotated by 90 degrees, shifting from alignment with the crystallographic *a* (intermediate magnetic) axis to the *b* (easy magnetic) axis, depending on the excitation energy. In contrast, the A_g^1 and A_g^3 modes consistently remain polarized along the *b* axis, regardless of the laser energy used. We access real and imaginary parts of the Raman tensor in our analysis, uncovering resonant electron-phonon coupling.

HL 40.3 Wed 16:00 H15

Resonant Inelastic Light Scattering on CrSBr — •Jan-Hendrik Larusch[1], Pierre-Maurice Piel[1], Nicolai-Leonid Bathen[1], Zdenek Sofer[2], and Ursula Wurstbauer[1] — [1]Institute of Physics, University of Münster, Germany — [2]Department of Inorganic Chemistry, University of Chemistry and Technology Prague, Prague, Czech Republic

The van der Waals material CrSBr is an optically active semiconductor and an air-stable 2D magnet with ferromagnetic (FM) ordering within each layer and antiferromagnetic (AFM) coupling between adjacent layers, alongside triaxial magnetic anisotropy. Additionally, CrSBr has a highly anisotropic electronic band structure, rendering it a quasi-one-dimensional electronic system, resulting in linearly polarized excitons that are strongly bound [1]. Distinct differences in excitonic emission signatures arise depending on the transition in magnetic ordering from AFM to FM states [2]. To study the coupling between excitons and collective excitations, we employ magnetic field-dependent resonant inelastic light scattering (RILS) experiments at temperatures well below the Néel temperature (~4K). While first-order phonon modes in Raman spectra remain mostly unaffected by magnetic ordering, RILS reveals resonantly enhanced as well as additional, magnetic field-dependent modes. The later are interpreted as spin-density excitations aka magnon modes. The combined PL and RILS study reveal strong interactions between electronic, excitonic, lattice and spin degrees of freedom. [1] J. Klein et al. ACS Nano, 17, 5316-5328 (2023) [2] M.C. Heißenbüttel et al. (2024). arXiv:2403.20174.

HL 40.4 Wed 16:15 H15

Disentangling three anisotropic resistivities of the topological insulator α-Bi_4Br_4 — •Jonathan K. Hofmann[1,2], Serhii Kovalchuk[1,3], Yuqi Zhang[4,5,6], Vasily Cherepanov[1], Timofey Balashov[1], Zhiwei Wang[4,5,6], Yugui Yao[4,5,6], Irek Morawski[3], F. Stefan Tautz[1,2], Felix Lüpke[1,7], and Bert Voigtländer[1,2] — [1]Peter Grünberg Institut, Forschungszentrum Jülich, Germany — [2]Lehrstuhl für Experimentalphysik IV A, RWTH Aachen University, Germany — [3]Institute of Experimental Physics, University of Wrocław, Poland — [4]Key Laboratory of Advanced Optoelectronic Quantum Architecture and Measurement, Ministry of Education, School of Physics, Beijing Institute of Technology, China — [5]Beijing Key Lab of Nanophotonics and Ultrafine Optoelectronic Systems, Beijing Institute of Technology, China — [6]International Center for Quantum Materials, Beijing Institute of Technology, China — [7]II. Physikalisches Institut, Universität zu Köln, Germany

The higher-order topological insulator α-Bi_4Br_4 is a promising, highly anisotropic quasi one-dimensional van der Waals material. Using a four-tip scanning tunneling microscope, we combine four-point resistance measurements in the square geometry on a bulk sample of α-Bi_4Br_4 with four-point resistance measurements on thin flakes in a linear configuration to disentangle the anisotropic resistivity tensor at room temperature (RT) and at 77 K: At RT, the resistivity along the chain direction is 6.4 times smaller than the resistivity perpendicular to the chains. At 77 K, this anisotropy reduces to 5.0. The vertical anisotropies are ~ 1300 and ~ 6500, at RT and 77 K, respectively.

15 min. break

HL 40.5 Wed 16:45 H15

Spin Hall effect in van-der-Waals ferromagnet — •Tomoharu Ohta[1,2], Nan Jiang[3,4,5], Yasuhiro Niimi[3,4,5], Kohei Yamagami[6], Yoshinori Okadada[6], Yoshichika Otani[7,8], and Kouta Kondou[4,8] — [1]Walter Schottky Institute and Physics Department, Technical University of Munich, Garching, Germany — [2]Munich Center for Quantum Science and Technology (MCQST), München, Germany — [3]Depertment of Physics, Osaka University, Osaka, Japan — [4]Institute for Open and Transdisciplinary Research Initiatives (OTRI), Osaka, Japan — [5]Center for Spintronics Research Network (CSRN), Osaka, Japan — [6]Okinawa Institute of Science and Technology, Graduate University, Okinawa, Japan — [7]Institute for Solid State Physics, The University of Tokyo Chiba, Japan — [8]RIKEN Center for Emergent Matter Science (CEMS), Saitama, Japan

We investigated the spin Hall effect (SHE) in a vdW ferromagnet Fe5GeTe2 (FGT) with a TC of 310 K utilizing the spin torque ferromagnetic resonance method. In synchronization with the emergence of the ferromagnetic phase resulting in the anomalous Hall effect (AHE), a noticeable enhancement in the SHE was observed below TC. On the other hand, the SHE shows a different temperature dependence from the AHE below 120 K: the effective spin Hall conductivity clearly enhanced below TC unlike the anomalous Hall conductivity, might be reflecting variation of band-structure accompanied by the complicated magnetic ordering of the FGT. The results provide a deep understanding of the SHE in magnetic materials to open a new route for novel functionalities in vdW materials-based spintronic devices.

HL 40.6 Wed 17:00 H15

Pseudo-magnetotransport simulations in strained graphene — •Alina Mrenca-Kolasinska[1] and Ming-Hao Liu[2] — [1]AGH University, Krakow, Poland — [2]National Cheng Kung University, Tainan, Taiwan

Graphene, a 2D material consisting of carbon atoms, despite its simple structure and composition can host intriguing phenomena. Application of inhomogeneous strain can lead to pseudomagnetic field (PMF), predicted to have opposite sign in the K and K 0 valley. Special strain profiles have been designed to generate uniform pseudomagnetic field in graphene [1, 2].

In this work we consider transport in pseudo magnetic field in these strain configurations. By deforming the sheet we can control the PMF, and design geometries which allow us to demonstrate interesting transport phenomena. These include electron focusing and snake states observed without external magnetic field present. For efficient modeling of quantum transport within these scenarios in large-scale systems close to realistic size devices, we extend the scalable tight-binding model [3] to accurately capture the effect of displacement field in the Hamiltonian. Our investigations open new possibilities for control over the valley degree of freedom.

[1] F. Guinea, et al., Phys. Rev. B 81, 035408 (2010).
[2] F. Guinea, M. I. Katsnelson, and A. K. Geim, Nat. Phys. 6, 30 (2010).
[3] M.-H. Liu, et al., Phys. Rev. Lett. 114, 036601 (2015).

HL 40.7 Wed 17:15 H15

Strong magnetic proximity effect in van der Waals heterostructures driven by direct hybridization — •Claudia Cardoso[1], Antomio T. Costa[2], Allan H. McDonald[3], and Joaquin Fernandez-Rossier[2] — [1]S3 Centre, Istituto Nanoscienze, CNR, Via Campi 213/a, 41125 Modena, Italy — [2]International Iberian Nanotechnology Laboratory, 4715-330 Braga, Portugal — [3]Physics Department, University of Texas at Austin, Austin, Texas 78712, USA

Proximity effects may induce an electronic property of a material, to an adjacent material in which that property is not present. Here we propose a class of magnetic proximity effects based on the spin-dependent hybridisation. We consider the hybridisation between the electronic states at the Fermi energy in a nonmagnetic conductor and the narrow spin-split bands of a ferromagnetic insulator.

Unlike conventional exchange proximity, this proximity effect has a strong impact on the nonmagnetic layer and can be further modulated by application of an electric field.

Using density functional theory calculations, we illustrate this effect in graphene placed next to a monolayer of CrI_3, a ferromagnetic insulator. The calculations show a strong hybridisation of the graphene bands with the narrow conduction band of CrI_3 in one spin channel only. Furthermore, the results confirm that the hybridisation strength can be modulated by an out-of-plane electric field, paving the way for applications.

HL 40.8 Wed 17:30 H15

Magnetotransport in heterostructures of MBE-grown BS/BSTS and graphene — •Marina Marocko[1], Matthias Kronseder[1], Tobias Rockinger[1], Takashi Taniguchi[2], Kenji Watanabe[2], Dieter Weiss[1], and Jonathan Eroms[1] — [1]Institute of Experimental and Applied Physics, University of Regensburg, 93040 Regensburg, Germany — [2]NIMS, 1-1 Namiki, Tsukuba, Ibaraki 305-0044, Japan

A number of novel phenomena have been observed or predicted in heterostructures of topological insulators and graphene. Similar to transition metal dichalcogenides, topological insulators are expected to dramatically increase the intrinsically very low spin-orbit coupling (SOC) in graphene due to the proximity effect. This opens the way for a range of potential applications, including a spin transistor based on the spin-orbit valve effect.

In our recent experiments, we used a thin MBE-grown film of BS/BSTS topological insulator to induce SOC in graphene. This material has the advantage of adjustable stoichiometry and thus increased possibilities of band structure engineering. The SrTiO3 substrate used for the MBE growth of BS/BSTS also serves as a gate dielectric.

Magnetotransport measurements at 1.7K show a very distinct and narrow weak antilocalization peak around zero magnetic field, which is a sign of induced SOC in graphene. The fitting procedure yields approximate values of the Rashba and valley-Zeeman spin-orbit coupling. We discuss how the extracted SOC values compare with theoretical predictions.

HL 40.9 Wed 17:45 H15

Exploring the valley splitting and valley dynamics of WSe_2 proximity-exchange coupled to CrI_3 — •Natalie Kuhn[1], Marc Schütte[1], Jo Henri Bertram[1], Frank Volmer[1], K. Watanabe[2], T. Taniguchi[3], Christoph Stampfer[1,4], Lutz Waldecker[1], and Bernd Beschoten[1] — [1]2nd Institute of Physics and JARA-FIT, RWTH Aachen University, 52074 Aachen, Germany — [2]Research Centre for Functional Materials, National Institute for Materials Science, 1-1 Namiki, Tsukuba 305-0044, Japan — [3]International Center for Materials Nanoarchitectonics, National Institute for Materials Science, 1-1 Namiki, Tsukuba 305-0044, Japan — [4]Peter Grünberg Institute (PGI-9), Forschungszentrum Jülich, 52425 Jülich, Germany

Proximity exchange coupling between 2D magnets and monolayers of transition metal dichalcogenides (TMDs) can lift valley degeneracy of the TMD. This is promising for the field valleytronics, as valley splitting is expected to increase valley lifetimes.

In this study, we investigate the proximity exchange coupling in van der Waals heterostructures made of monolayer WSe_2 and few-layer CrI_3, a 2D antiferromagnet. The proximity-induced valley splitting of WSe_2 is spatially probed by reflection contrast measurements of WSe_2 excitons. We observe distinctly different regions in WSe_2 identified by their reversed valley splitting. Their origin is explored by their magnetic field dependent reversals, i.e. hysteresis curves that are induced by reversing the magnetization of the interface layer of CrI_3. Using time-resolved Kerr rotation measurements we find a strong enhancement of WSe_2 valley lifetimes of the spin split valence bands.

HL 40.10 Wed 18:00 H15

Excitonic traps in freely suspended 2D membranes — •Alexander Musta[1,3], Leonard Geilen[1,3], Lukas Schleicher[2,3], Benedict Brouwer[1,3], Petricia Sara Peter[2,3], Anne Rodriguez[2,3], Eva Weig[2,3], and Alexander Holleitner[1,3] — [1]Walter Schottky Institute, TU Munich, Germany — [2]Chair of Nano and Quantum Sensors, TU Munich, Germany — [3]Munich Center for Quantum Science and Technology (MCQST), Munich, Germany

We present studies on the strain profile of large-area suspended transition-metal-dichalcogenides monolayers by photoluminescence measurements. Variations in the strain profile lead to band bending, which results in a redshift of the excitonic spectrum. Additionally, we observe an increase in intensity at the center of the suspended structures. We correlate the excitonic luminescence profiles with mechanical characterizations of the membranes, including AFM measurements and spatial mode mapping.

HL 40.11 Wed 18:15 H15

Rabi Splitting in Quantum Wells and TMDCs: Influence of Many-Particle Coulomb Correlations — •Henry Mittenzwey[1], Felix Schäfer[2], Markus Stein[2], Oliver Voigt[1], Lara Greten[1], Daniel Anders[2], Isabel Müller[2], Florian Dobener[2], Marzia Cuccu[3], Christian Fuchs[4], Kenji Watanabe[5], Takashi Taniguchi[5], Alexey Chernikov[3], Kerstin Volz[4], Sangam Chatterjee[2], and Andreas Knorr[1] — [1]ITP, Technische Universität Berlin, D-10623 — [2]LaMa, Justus-Liebig-University Giessen, D-35392 — [3]IAPP and ct.qmat, Technische Universität Dresden, D-01062 — [4]WZMW, Philipps-University Marburg, D-35032 — [5]NIMS, Namiki 1-1, Tsukuba, Ibaraki 305-0044, Japan

In this joint theory-experiment collaboration, we study the Rabi splitting of excitons under simultaneous strong light-matter and Coulomb interaction on ultrafast timescales.

It turns out, that in a setting, where Coulomb and optical interaction are comparable (MQW), the Rabi splitting almost linearly follows the optical field amplitude similar to an ideal two-level system. On the other hand, in a setting with dominating Coulomb interaction ($MoSe_2$), the Rabi splitting depends sublinearly on the optical field strength and it significantly deviates from an ideal two-level system. Within the developed theoretical approach based on Heisenberg equations of motion and a correlation expansion of many-body interactions, we identify the origin of this sublinear trend due to six-particle exciton-to-biexciton transitions.

HL 40.12 Wed 18:30 H15

Inhomogeneous Broadening of Dark Rydberg Excitons in TMDC Monolayers Probed by Ultrafast Frequency-Resolved Autocorrelation Spectroscopy — •Katem Mitkong, Tom Jehle, Daniel C. Lünemann, Lukas Lackner, Juanmei Duan, Christian Schneider, and Christoph Lienau — Institute of Physics, Carl von Ossietzky University, Oldenburg, Germany

Monolayers of Transition Metal Dichalcogenides (TMDCs), as two-dimensional materials, exhibit unique optical properties influenced by their dielectric environment. The reduced dimensionality enhances the exciton binding energy, enabling the formation of Rydberg exciton series even at room temperature. In this study, broadband nonlinear Interferometric Frequency-Resolved Autocorrelation (IFRAC) spectroscopy with few-cycle time resolution is used to probe the optically dark 2p exciton state in WS2 monolayers. The result readily distinguishes coherent second harmonic generation (SHG) from incoherent two-photon photoluminescence emission (TPPLE) without requiring polarization control. We observe the 2p dark exciton state at 2.20 eV, with TPPLE linewidths that depend on excitation power. Comparison with Lindblad Master equation solutions shows significant inhomogeneous broadening of the 2p resonance, about three times greater than that of 1s excitons. This broadening, attributed to the extended spatial wavefunction of 2p excitons relative to 1s excitons, underscores their increased sensitivity to inhomogeneities such as local strain and dielectric fluctuations. This finding suggests potential applications in nanoscale sensing technologies.

HL 40.13 Wed 18:45 H15

Expanding the lithography toolbox - 2D devices and beyond
— •Vasilis Theofylaktopoulos — Heidelberg Instruments Nano AG, Bändliweg 30, 8048 Zurich, Switzerland

Lithography is used in 2D devices to contact them with precisely placed electrodes, shape the building blocks or to control other properties such as doping or strain. Thermal scanning probe lithography is an up and coming method that can assist in all of the above.[1] In this talk the working principle of tSPL will be introduced and examples of its application will be given in the field of 2D electronics, photonics and metasurfaces.[2,3,4]

The NanoFrazor is a tSPL tool offering complimentary features to established lithography techniques such as photolithography, ebeam and focused ion beam. It uses a heated cantilever to write features with sizes bellow 15nm. At the same time grayscale patterning is possible with a resolution of 2nm. A reader is integrated at the tip allowing for parallel imaging to the patterning enabling markerless overlay. This simplifies the placement of features on 2D materials which are easily imaged under the resist. A laser can be used with the same resist stacks to create larger features >500nm such as contact pads. Finally, the process patterning the resist through sublimating it can yield devices with better electronics properties compared to ebeam.[5]

[1] S. T. Howell, A. Grushina, F. Holzner, and J. Brugger, Thermal scanning probe lithography - a review, Microsyst. Nanoeng., vol. 6, no. 1, p. 21, Apr. 2020, doi: 10.1038/s41378-019-0124-8.

[2] X. Liu et al., Thermomechanical Nanostraining of Two-Dimensional Materials, Nano Lett., vol. 20, no. 11, pp. 8250-8257, Nov. 2020, doi: 10.1021/acs.nanolett.0c03358.

[3] M. C. Giordano, G. Zambito, M. Gardella, and F. Buatier De Mongeot, Deterministic Thermal Sculpting of Large Scale 2D Semiconductor Nanocircuits, Adv. Mater. Interfaces, vol. 10, no. 5, p. 2201408, Feb. 2023, doi: 10.1002/admi.202201408.

[4] N. Marcucci, M. C. Giordano, G. Zambito, A. Troia, F. Buatier De Mongeot, and E. Descrovi, Spectral tuning of Bloch Surface Wave resonances by light-controlled optical anisotropy, Nanophotonics, vol. 12, no. 6, pp. 1091-1104, Mar. 2023, doi: 10.1515/nanoph-2022-0609.

[5] A. Conde-Rubio, X. Liu, G. Boero, and J. Brugger, Edge-Contact MoS2 Transistors Fabricated Using Thermal Scanning Probe Lithography, ACS Appl. Mater. Interfaces, vol. 14, no. 37, pp. 42328-42336, Sep. 2022, doi: 10.1021/acsami.2c10150.