HL 17: 2D Semiconductors and van der Waals Heterostructures III

The session covers electronic and optoelectronic phenomena in two-dimensional semiconductors and van der Waals heterostructures.

Time: Tuesday 9:30–13:00 Location: H15

HL 17.1 Tue 9:30 H15

Size-Dependent Electrical Transport in Quasi-1D $ZrSe_3$-Stripes — •Davin Höllmann[1], Lars Thole[1], Sonja Locmelis[2], and Rolf J. Haug[1,3] — [1]Institut für Festkörperphysik, Leibniz Universität Hannover, 30167 Hannover, Germany — [2]Institut für Anorganische Chemie, Leibniz Universität Hannover, 30167 Hannover, Germany — [3]Laboratorium für Nano- und Quantenengineering, Leibniz Universität Hannover, 30167 Hannover, Germany

The anisotropy in form of quasi one-dimensional (1D) chains in transition metal trichalcogenides (TMTCs) makes them stand out compared to other more conventional two-dimensional (2D) materials [1]. Building on previous work [2], we investigated the electrical properties of thin stripes of the TMTC $ZrSe_3$ particularly regarding their width and thickness. The bulk material used was fabricated by a chemical vapor transport method and then exfoliated to achieve thin stripes.

We determined band gap energies for samples with varying heights. Those are shown to increase linearly from 0.37 eV to 0.63 eV as the thickness of the material decreases from 35 nm to 14 nm. Furthermore, we compared narrow samples with wider samples where both have comparably similar length and thickness and found that the conductivity happens dominantly in the outer selenium atoms i.e. across the chains.

[1] J. O. Island et al., 2D Materials 4, 0220033 (2017)
[2] L. Thole et al., ACS Omega 7, 39913-39916 (2022)

HL 17.2 Tue 9:45 H15

MOCVD Growth of two-dimensional, high-mobility InSe — •Robin Günkel[1], Milan Solanki[1], Daniel Anders[2], Markus Stein[2], Badrosadat Ojaghi Dogahe[1], Oliver Massmeyer[1], Max Bergmann[1], Nils Langlotz[1], Jürgen Belz[1], Sangam Chatterjee[2], and Kerstin Volz[1] — [1]Department of Physics and Material Sciences Center, Philipps-University Marburg, Germany — [2]Institute of Experimental Physics I and Center for Materials Research (ZfM/LaMa), Justus-Liebig-University Giessen, Germany

To advance Moore's Law, transistors must shrink while maintaining performance, but 3D semiconductor-based gates face limitations as their thickness approaches the nanometer scale due to surface scattering effects. 2D materials, such as graphene, offer a promising alternative that combines miniaturization with high field effect mobility. Among these, layered indium selenide (InSe) is a focus for logic devices due to its high mobility. However, the complex phase diagram of InSe poses challenges, often resulting in undesired phases. This study uses metal-organic chemical vapor deposition (MOCVD) to grow homogeneous, single-phase InSe on 2" sapphire by tuning the precursor ratio of DiPSe and TMIn. Growth starts with small nuclei forming a continuous layer, with subsequent layers growing as InSe triangles. Atomic force microscopy, Raman spectroscopy, STEM, and XRD provide insight into the growth behavior and the role of surface chemistry. Terahertz spectroscopy confirms carrier mobilities in the order of 1000 cm^2/(Vs). Ongoing efforts focus on heterostructures with other van der Waals materials to further tailor properties.

HL 17.3 Tue 10:00 H15

Transparent and reproducible contacts to MoS_2 nanotube quantum dots — •Robin T. K. Schock[1], Stefan B. Obloh[1], Korbinian Fink[1], Matthias Kronseder[1], Matjaž Malok[2], Maja Remškar[2], and Andreas K. Hüttel[1] — [1]Institute for Experimental and Applied Physics, University of Regensburg, 93040 Regensburg, Germany — [2]Solid State Physics Department, Jožef Stefan Institute, 1000 Ljubljana, Slovenia

MoS_2, a leading material among transition metal dichalcogenides, exhibits remarkable optical and electronic properties. However, its high effective electron mass necessitates narrow confinement potentials to achieve single quantum level transport.

Nanotubes offer a compelling solution by naturally confining electrons in two dimensions. Our previous work demonstrated single level transport in nanotube QDs confined to the active device area, using the classical Scotch tape method.[1] Despite this, a major challenge remains in fabricating reliable electrical contacts, as devices still exhibit large resistance variations. We attribute this to the curved geometry of the nanotube surface, leading e.g. to nanogaps between the contact material on the tube and the chip surface.[2]

Here we introduce a contact deposition technique that addresses these challenges, achieving highly improved contact yield and reproducibility. This advancement enables the fabrication of more complex device architectures, as e.g., nanotube QDs on top of 2D material heterostacks. - [1] R. T. K. Schock et al., Adv. Mat. 35, 2209333 (2023); [2] R. T. K. Schock et al., PSSb, 2400366 (2024)

HL 17.4 Tue 10:15 H15

Defect engineering in two-dimensional materials for resistive switching — •Manoj Dey, Matthias Scheffler, and Wahib Aggoune — The NOMAD Laboratory at the FHI of the Max-Planck-Gesellschaft, Berlin, Germany

Non-volatile resistive switching (RS) in memristors has attracted significant attention for advancing in-memory technologies. Recently, exceptional RS has been observed in defected two-dimensional (2D) materials, called atomristors. Adsorption/desorption of metal atoms from the electrodes onto vacancy sites is experimentally observed and proposed as its origin [1,2]. Here, we explore the characteristics of defects and demonstrate their relationship with the observed RS. Using hybrid density functional theory with many body van der Waals corrections, we reveal that the defective monolayers are semiconducting (*i.e.*, high resistivity), whereas adsorption of metal atoms leads to a metallic character (*i.e.*, low resistivity). Interestingly, the adsorption energy of metal is found to be exothermic, with magnitude varying depending on the host materials. This indicates the feasible adsorption and switching in experiments. To bridge with experiments we also consider both the effects of the electrode (*e.g.* Au(111)) and finite-temperature vibrations. While vibrational effects are negligible, electrode screening induces band gap renormalization and slightly stabilizes metal adsorption compared to free-standing monolayers. These insights will guide the exploration of novel 2D materials for RS applications.

[1] Ruijing Ge *et al.*, *Adv. Mater.*, **33**, 2007792 (2021).
[2] Saban M. Hus *et al.*, *Nat. Nanotechnol.*, **16**, 58 (2021).

HL 17.5 Tue 10:30 H15

Anisotropic supercurrent suppression and revivals in a graphene-based Josephson junction under in-plane magnetic fields — •Katarina Stanojević[1,5], Philipp Schmidt[1,2], Kenji Watanabe[3], Takashi Taniguchi[4], Bernd Beschoten[1], Vincent Mourik[5], and Christoph Stampfer[1,2] — [1]JARA-FIT and 2nd Institute of Physics, RWTH Aachen University, Germany — [2]Peter Grünberg Institute (PGI-9), Forschungszentrum Jülich, Germany — [3]Research Center for Electronic and Optical Materials, National Institute for Materials Science, Japan — [4]International Center for Materials Nanoarchitectonics, National Institute for Materials Science, Japan — [5]JARA Institute for Quantum Information (PGI-11), Forschungszentrum Jülich, Germany

Graphene-based Josephson junctions represent a promising platform for hybrid quantum devices due to their unique electronic properties. The absence of Schottky barriers enables highly transparent interfaces, while graphene's ability to host proximity-induced superconductivity make it an interesting candidate for realizing tunable weak links. A key step towards harnessing graphene Josephson junctions for topological quantum applications is understanding the influence of in-plane magnetic fields, which tune the Zeeman energy and might enable the formation of topologically protected states. Here, we report on a tunable bilayer graphene Josephson junction encapsulated in WSe_2. We investigate the behavior of the supercurrent under applied in-plane magnetic fields, revealing a pronounced anisotropy in the magnetic field induced decay and revival of the supercurrent for varying in-plane field angles.

HL 17.6 Tue 10:45 H15

Electric field control of the proximity-induced spin-orbit gap in bilayer graphene/WSe2 quantum dots — •Hubert Dulisch[1,2], David Emmerich[1,2], Eike Icking[1,2], Katrin Hecker[1,2], Samuel Möller[1,2], Leonie Müller[1,2], Kenji

Watanabe[3], Takashi Taniguchi[4], Christian Volk[1,2], and Christoph Stampfer[1,2] — [1]2nd Institute of Physics, RWTH Aachen — [2]PGI-9, Forschungszentrum Jülich — [3]Research Center for Functional Materials, NIMS, — [4]International Center for Materials Nanoarchitectonics, NIMS

We investigated induced spin-orbit coupling (SOC) in a bilayer graphene (BLG) quantum dot (QD), which is in proximity to tungsten diselenide (WSe_2). Magneto-transport measurements were performed on the Coulomb-resonance of the first charge carrier to extract the spin-orbit gap Δ_{SO}. In-plane magnetic field measurements indicate an increased SOC-induced energy splitting. Out-of-plane field measurements demonstrate a reduced valley g-factor at larger displacement fields, consistent with weaker lateral confinement of the QD wavefunction. Our measurements reveal an enhanced SOC effect that decreases with the applied displacement field, distinguishing it from the behavior observed in pure BLG. We interpret this as a reduced influence of the WSe_2, which we attribute to the increased displacement field. This causes the QD to become more localized in the lower layer of the bilayer graphene. Being farther from the WSe_2, this layer experiences reduced induced SOC, leading to a diminished spin-orbit gap in the BLG QD.

HL 17.7 Tue 11:00 H15

High-Performance and Energy-Efficient Sub-5nm 2D Double-Gate MOSFETs Based on SiAs Monolayers — •Dogukan Hazar Ozbey and Engin Durgun — UNAM - National Nanotechnology Research Center and Institute of Materials Science and Nanotechnology, Bilkent University, Ankara 06800, Turkey

As the demand for high-performance, energy-efficient transistors grows, traditional silicon-based MOSFETs face significant scaling limitations. To overcome these challenges and sustain advancements in semiconductor technology, new materials and device architectures are being explored. In this study, sub-5nm double-gate metal-oxide-semiconductor field-effect transistors (MOSFETs) based on 2D SiAs are investigated using first-principles calculations and the Non-equilibrium Green's function (NEGF) formalism to assess their potential as a high-performance alternative. SiAs monolayers exhibit an indirect bandgap of 1.58 eV and demonstrate promising electronic properties. Key performance metrics such as the on/off current ratio, subthreshold swing (SS), gate capacitance (C_g), intrinsic delay time (τ), and power-delay product (PDP) are evaluated. Devices with 1 nm and 2 nm underlap (UL) structures show enhanced performance, achieving on-state current (I_{on}) values up to 1206 $\mu A/\mu m^{-1}$, meeting ITRS-2028 high-performance (HP) standards. The SS ranges from 112 to 142 mV/dec, and minimized delay and power-delay products indicate the suitability of SiAs transistors for ultra-scaled, energy-efficient applications. Results suggest that 2D SiAs transistors offer a promising solution to the scaling challenges of MOSFET technologies.

15 min. break

HL 17.8 Tue 11:30 H15

Resistance standards from artifact wire coils to graphene quantum Hall resistance — •Yefei Yin[1], Mattias Kruskopf[1], Stephan Bauer[1], Teresa Tschirner[1], Klaus Pierz[1], Frank Hohls[1], Rolf J. Haug[2], and Hans W. Schumacher[1] — [1]Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany — [2]Institut für Festkörperphysik, Leibniz Universität Hannover, 30167 Hannover, Germany

Historically, resistance standards were made by physical artifact wire coils before 1990 and quantum resistors based on GaAs heterostructures after 1990. However, conventional GaAs quantum Hall resistance (QHR) standards with the quantized resistance $R_H = h/2e^2$ are operating under high magnetic flux densities B > 10 T, limited currents I < 50 μA, and low temperatures T < 1.5 K, which significantly hinder the dissemination of primary resistance standards. In this work, we developed practical primary QHR standards based on n- and p-type epitaxial graphene. This study first systematically demonstrated that p-type epitaxial graphene can also be used for primary resistance standards, as accurate (10^{-9} accuracy) as GaAs and n-type graphene counterparts for realizing the SI unit ohm in quantum metrology. [1] The n-type graphene QHR standards achieved the world best performance so far with a 10^{-9} accuracy under relaxed conditions (B = 4.5 T, I = 232.5 μA, T = 4.2 K) simultaneously. [2-3] Our graphene QHR standards have been utilized in the national metrology institutes in European countries. [1] Appl. Phys. Lett., 125, 064001 (2024). [2] Adv. Phys. Res. 1, 2200015 (2022). [3] Phys. Rev. Applied, 2024

HL 17.9 Tue 11:45 H15

1D graphene superlattices and the influence of the potential shape — •Julia Amann[1], Alina Mreńca-Kolasińska[2], Angelika Knothe[1], Ming-Hao Liu[3], Takashi Taniguchi[4], Kenji Watanabe[4], Dieter Weiss[1], and Jonathan Eroms[1] — [1]University of Regensburg, Germany — [2]AGH University, Krakow, Poland — [3]National Cheng Kung University, Tainan, Taiwan — [4]National Institute for Materials Science, Tsukuba, Japan

One-dimensional superlattices (1DSLs) in graphene have been predicted to exhibit intriguing effects such as transport anisotropy, additional Dirac points and hence higher degeneracy, leading to a different quantum Hall plateau sequence compared to pristine graphene. We use a patterned few-layer graphene gate under an encapsulated monolayer graphene to fabricate a 1DSL device. With the combined effect of a global gate and a patterned bottom gate, we are able to control the superlattice potential strength and carrier density independently. We show low-temperature transport measurements on a gate-tunable 1DSL in monolayer graphene with a period of 50 nm in directions parallel and perpendicular to the modulation using an L-shaped Hall bar. We observe anisotropic transport and the appearance of multiple Dirac points and additional Landau fans in the modulation direction. We also see Weiss oscillations, confirming the 1DSL modulation. However, the predicted anomalous quantum Hall sequence was not observed and we looked more closely at the 1DSL potential we were applying. We found an asymmetric potential shape, which strongly influences the change in the band structure and degeneracy.

HL 17.10 Tue 12:00 H15

Ultrafast mid-infrared interferometric photocurrents in graphene-based two-terminal devices for femtosecond autocorrelation — •Sebastian Loy[1,2], Nina Pettinger[1,2], Johannes Schmuck[1,2], Xiaoyi Zhou[1,2], Sergey Zherebtsov[1,2], Christoph Kastl[1,2], and Alexander Holleitner[1,2] — [1]Walter Schottky Institute and Physics Department, Technical University of Munich, Am Coulombwall 4a, 85748 Garching, Germany — [2]Munich Center of Quantum Science and Technology (MCQST), Schellingstr. 4, 80799 Munich, Germany

We present the autocorrelation of femtosecond mid-IR pulses with wavelengths ranging from 5.5 μm to 14 μm and pulse durations of approximately 100 fs on graphene-based two-terminal devices. The results indicate that the interaction between the electric field and optoelectronic dynamics at the metal-graphene interface underlies the principle of ultrafast detection. Our approach stands out due to the ease of nanofabricating graphene two-terminal optoelectronic devices and their inherent robustness [1].

[1] Nina Pettinger et al., accepted (2024).

HL 17.11 Tue 12:15 H15

Enhancement of optoelectronic properties of layered 2D semiconductors — •Borna Radatović[1,2], Onur Çakiroğlu[2], Hao Li[2], Fedor Lipilin[1], Aljoscha Soll[1], Andres Castellanos-Gomez[2], and Zdenek Sofer[1] — [1]Department of Inorganic Chemistry, University of Chemistry and Technology Prague, Technicka 5, Prague 6, 166 28 Czech Republic — [2]2D Foundry group. Instituto de Ciencia de Materiales de Madrid (ICMM-CSIC), E-28049 Madrid, Spain

Standard semiconductor methods for the enhancement of electronic devices' properties, such as doping via ion implantation and similar approaches, do not apply to 2D materials due to their atomical thickness. However, various alternative methods for customization of optoelectronic properties of 2D devices have been investigated, from electric or magnetic fields to substitutional doping, that were demonstrated for many devices, such as light sources, optical modulators and photodetectors. In our work, we focus on photodetectors based on different 2D semiconductors (i.e. MoS2, ZrSe3, Sb2S2O and CuInP2Se6) in monolayer and few-layer forms. We investigated how external strain can modulate the intrinsic optical and electronic properties of 2D materials and enhance photodetectors' performances. Furthermore, we have demonstrated how 2D heterostructures can offer a practical approach to specific custom optoelectronic properties of 2D devices.

HL 17.12 Tue 12:30 H15

Surface acoustic wave-controlled photocurrent in few-layer TMDCs — •Benjamin Mayer, Felix Ehring, Matthias Weiss, Hubert Krenner, Ursula Wurstbauer, and Emeline Nysten —

Institute of Physics, University of Münster, Germany

Surface acoustic waves (SAWs) provide a versatile platform for integrating GHz-frequency control and sensing schemes at micron-scale wavelengths on a chip. Combining the SAWs dynamic electric field, high-resolution optical spectroscopy, and electrical transport allows a deep insight in the optical properties and carrier transport processes in nanoscale materials, paving the way for innovative acousto-optoelectronic devices [1].

Here, we study the SAW-driven acousto-electric current (AEC) and the underlying charge carrier dynamics in mechanically exfoliated transition metal dichalcogenide (TMDC) 2D materials. To this aim, few-layered TMDCs are placed on top of two gold electrodes integrated in hybrid lithium niobate-based SAW-devices with design frequencies of 150-250MHz. The power and directional dependence of the induced AEC offer an initial understanding of the contact barriers forming at the Au-TMDC interface. By locally photodoping our samples, we establish a qualitative model for the formed Schottky and tunneling barriers, enabling the investigation of their influence on the wavelength-dependent SAW-driven charge carrier dynamics [2].

[1] J. Phys. D:Appl. Phys. 52(35):353001 (2019)
[2] Adv. Mater. 2402799 (2024)

HL 17.13 Tue 12:45 H15

Accelerated electron-hole separation at the organic-inorganic anthracene/Janus MoSSe interface — •Hamid Mehdipour[1], Peter Kratzer[2], and Oleg Prezhdo[3] — [1]University of Duisburg-Essen, Duisburg, Germany — [2]University of Duisburg-Essen, Duisburg, Germany — [3]University of Southern California, Los Angeles, United States;

Organic light-absorbing materials with two-dimensional semiconductor layers as contact electrodes are promising for efficient and low-cost energy-harvesting applications. Considering anthracene as an absorber and a MoSSe Janus monolayer, and basing our work on a set of preliminary DFT calculations, we employ non-adiabatic molecular dynamics to show that electron transfer from anthracene to MoSSe is faster on the Se than on the S side. The transfer from anthracene to MoS_2 and $MoSe_2$ monolayers takes intermediate times. As a rule, we find that a shorter adsorption distance produces a stronger donor-acceptor coupling. The smaller distance on the Se side is rationalized by the attractive dipolar interaction between the intrinsic dipole moment of the Janus structure and the dipole induced upon molecule adsorption. Quantum coherence adjusted by the out-of-plane vibrations also has a significant impact on the transfer time. Our study provides detailed insights into adsorption of molecules on Janus structures and the resulting electronic and electron-vibrational interactions. The results suggest that the dipole interaction plays an important role in thermodynamic stability, alignment of electronic levels, and electron-vibrational dynamics.