NANONET+

Annual Workshop 2025

2D Materials for Electronics, Photonics and Sensing

10 –12 September 2025

Jugendherberge Schöneck/Vogtland, Germany

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HZDR
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Venue and organization

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This workshop is supported by the
Nanoelectronics Department of the Helmholtz-Zentrum Dresden - Rossendorf.

NanoNet+ Workshop 2025 - Schöneck

Agenda

Place: Jugendherberge Schöneck, Am Stadtpark 52, 08261 Schöneck, Tel.037464 - 8106
Web-site: www.hzdr.de/NanoNet-Workshop2025
Updated: 08.09.2025 (PZ)

Wednesday, 10 September 2025

Start	Who	Durat.	Title	Notes
from 11:00			Individual Arrival	
12:00			**Lunch**	
13:00	Erbe, A.	10	Welcome address	Chair: Erbe
13:10	Roudini, M.	20+5	Surface Acoustic Wave-Induced Aerosol Printing for Nanomaterial Deposition	
13:35	Gray, M.	20+5	Oxidation-driven spontaneous formation of internal p-and n-junctions in insynthetically derived 2D layered SnSe flakes	
14:00	**Kusch, P.**	40+10	**Imaging Propagating Surface Exciton-Polaritons in Ångstrom Thin WS_2 in Real Space**	
14:55		5	Group Photo	place tba.
15:00		90	**Coffee + Poster Session**	8 (9) Posters
16:45		90	**Walking Tour -** start in front of hostel, ca. 2 miles	
18:30			**Dinner - BBQ**	

Thursday, 11 September 2025

07:30			**Start breakfast**	
09:00	Ghosh, S.	20+5	Polarity-Controlled Junctionless Nanowire Transistors for Advanced Sensing Applications	Chair: Kusch
09:25	**Bolotin, K.**	40+10	**Quantum Stability in Topological Materials**	
10:20		30	**Break**	
11:00	Fejzaj, D.	20+5	Exfoliated MoS2-based resistive switching devices for artificial synapses	Chair: Lambeva
11:25	Jäger, O.	20+5	Mesoscopic electrical transport in top-down defined 4H-SiC	
11:50	Strobel, C.	20+5	Improved graphene based hot-electron transistor with an optimized emitter-base structure	
12:15			**Lunch**	
13:15	**Schlicke, H.**	40+10	**Mind the Gap: Tunable and Functional Interfaces between Nanomaterials**	Chair: Kielar
14:05	Garrity, O.	20+5	Interlayer Exciton–Phonon Coupling in MoSe2/WSe2 Heterostructures: a resonant Raman study	
14:45		25	**Break**	
15:15			**Transport -** start in front of hostel, walk few meters, Bus 15:30 sharp !!	
16:00		120	***Markneukirchen Violine Workshop* - 1D and 2D resonators**	
18:30			**Dinner**	
20:30			**Dwarf hamster on Elm Street (M. Gray) / Brain Storming**	

Friday, 12 September 2025

07:00			**Breakfast and empty the rooms until 9:00 - no exceptions**	
09:00	Chennur, M.	20+5	Defect-Driven Electrical Modulation of 2D materials by Helium ion irradiation	Chair: Krstic
09:25	Kreßler, M.	20+5	KPFM on 2D materials and molecular 2D TMDC heterostructures	
09:50	**Carroll, D.**	40+10	**Engineering 2D Systems for Strong Entanglement: A New Type of Topological Qubit**	
10:40		30	**Break**	
11:10	**Krstic, V.**	40+10	**Towards new quantized states in graphene by deliberate tailoring**	Chair: Caroll
12:00	Krause, M.	30+10	Raman spectra of 2D and 3D forms of transition metal dichalcogenides: Basics	
12:40	Erbe, A.	10	Prize Ceremony / Closing Words	
13:00			**Lunch**	
14:00			**Departure**: Individually	

Rooms won't be available at arrival on Wednesday, but around 3 pm.

Your Notes

Talks

updated: 08.09.2025 (PZ)

Presenter	No.	Title	Pg.
Invited Talks			
Bolotin, K.		Quantum Stability in Topological Materials	4
Carroll, D.		Engineering 2D Systems for Strong Entanglement: A New Type of Topological Qubit	5
Krstic, V.		Towards new quantized states in graphene by deliberate tailoring	6
Kusch, P.		Imaging Propagating Surface Exciton-Polaritons in Ångstrom Thin WS_2 in Real Space	7
Schlicke, H.		Mind the Gap: Tunable and Functional Interfaces between Nanomaterials	8
Contributed Talks			
Chennur, M.	T1	Defect-Driven Electrical Modulation of 2D materials by Helium ion irradiation	9
Fejzaj, D.	T2	Exfoliated MoS2-based resistive switching devices for artificial synapses	10
Garrity, O.	T3	Interlayer Exciton–Phonon Coupling in MoSe2/WSe2 Heterostructures: a resonant Raman study	11
Ghosh, S.		Polarity-Controlled Junctionless Nanowire Transistors for Advanced Sensing Applications	12
Gray, M.		Dwarf hamster on Elm Street	--
Gray, M.		Oxidation-driven spontaneous formation of internal p-and n-junctions in insynthetically derived 2D layered SnSe flakes	13
Jäger, O.	T4	Mesoscopic electrical transport in top-down defined 4H-SiC	14
Krause, M.		Raman spectra of 2D and 3D forms of transition metal dichalcogenides: Basics	15
Kreßler, M.	T5	KPFM on 2D materials and molecular 2D TMDC heterostructures	16
Roudini, M.		Surface Acoustic Wave-Induced Aerosol Printing for Nanomaterial Deposition	17
Strobel, C.		Improved graphene based hot-electron transistor with an optimized emitter-base structure	18

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List of Poster Contributions see page 19.

Ultrastrong electric fields in 2D materials

Kirill Bolotin

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We consider a new type of heterostructure: a 2D material with donor molecules on one side and acceptor molecules on the other. The charge transfer between the molecules generates an electrical field inside the 2D material. We experimentally measure the field produced by this “molecular gating” and show that it reaches > 4V/m, the highest field measured in a solid-state device. We then explore the effect of this intense field. First, we demonstrate that the field suffices to modify and eventually completely close the bandgap in bilayer 2D semiconductors, driving a semiconductor-to-metal transition. Second, we show that the field lifts degeneracies between excitons in a semiconductor 2D bilayer and brings different excitons into resonance. Finally, we demonstrate new types of excitonic states that arise as a result of this.

Quantum Stability in Topological Materials

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In this work we describe progress in using 2D topological insulating materials to establish quantum states suitable for information processing. The careful creation and characterization of complex 2D manifold geometries that lead to topologically protected states for systems of chalcogenides will be discussed together with various ways of establishing the properties of those states. Specifically, we compare complexity levels from 2D class one materials to non-orientable class two systems using EELS, Transport, Raman, IR, and MFM experimental techniques. In most of these systems we have been able to clearly identify *persistent current – like states* associated with the edge or pseudo-edge of the crystals. Moreover, we have found that such states can exhibit tunable energy levels within the topological-insulators bandgap based upon the manifold structure and its interplay with band topology.

Towards new quantized states in graphene by deliberate tailoring

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Graphene is a mono-atomic 2D material with unusual electronic behavior, rooted in its hexagonal lattice composes of two trigonal Bravais-lattices shifted by a constant vector relative to each other. In consequence, the π-fermions hosted in graphene are spinors accounting for the presence of the two trigonal lattices and have in the low-energy limit a linear dispersion. Based on this unusual electronic structure, in the presence of a magnetic field, integer as well as fractional quantum-Hall states are emerging with unconventionally quantized Hall-resistance values. The realization of such quantum states is strongly associated with the interactions between the fermions, which are acting between them, in particular electrostatic ones. Tuning of these interactions represents thus a lever to steer the formation of quantum states, also those, which may not intrinsically emerge due to the pristine interactions present in the system.

Imaging Propagating Surface Exciton-Polaritons in Ångstrom Thin WS_2 in Real Space

Patryk Kusch[1], Mira Kreßler[1], Denis Iagodkin[1], Niclas S Mueller[2], Sebastian Heeg[3], Kirill Bolotin[1], Stephanie Reich[1]

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In recent years, two-dimensional transition metal dichalcogenides (TMDCs) have garnered attention for their ability to host excitons at room temperature, thereby enabling tunable optical and electronic properties with potential applications, such as single-photon emitters. A key technique for investigating TMDCs is scattering-type scanning near-field optical microscopy (s-SNOM), which provides high-resolution dielectric imaging beyond the diffraction limit. It uses an atomic force microscope (AFM) tip to enhance light via near-field excitation, offering nanometer-scale spatial resolution.

Polaritons—quasi-particles resulting from strong light-matter coupling—are particularly significant in TMDCs, where exciton-polaritons can emerge even in ultrathin layers. We previously mapped polariton dispersion in MoS_2 and WS_2 slabs as thin as 10 nm using s-SNOM [1]. Visualizing these modes in monolayers remains challenging; however, early results suggest that they can persist in symmetric dielectric environments.

Here we emphasize the capabilities of s-SNOM to image the impact of defects and the appearance of interlayer excitons within TMDCs—features that are crucial for understanding and controlling polaritonic behavior. Interlayer excitons, formed across stacked 2D layers, exhibit long radiative lifetimes and unique valley properties, making them promising candidates for quantum technologies. s-SNOM's ability to capture both optical amplitude and phase enables detailed nanoscale mapping of local dielectric properties. With appropriate modeling, we extract excitonic transition energies and both radiative and non-radiative decay rates, not only for interlayer excitons but also for excitonic states modified by local defects.

In the second part, we focus on exciton-polaritons in a freestanding WS_2 monolayer. Using s-SNOM, we image their real-space propagation and extract their dispersion relation, revealing strong coupling near the A and B exciton resonances. By modeling the TE_0 mode, we identify the observed polariton as a surface exciton-polariton. This theoretically predicted quasi-particle we now directly observe for the first time, opening new possibilities for controlling light at the atomic scale.

1. Kusch, P., N.S. Mueller, M.T. Hartmann, and S. Reich, *Strong light-matter coupling in MoS2*, in *Physical Review B*. Vol. 103. p. 235409 DOI: 10.1103/PhysRevB.103.235409, (2021)

Mind the Gap:
Tunable and Functional Interfaces between Nanomaterials

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Nanomaterials, such as 0D quantum dots or metal nanoparticles, 1D nanowires or nanotubes and 2D structures, e.g., graphene, transition metal dichalcogenides (TMDs) or MXenes, offer a variety of unique and fascinating properties, which render them promising for application in advanced, high-performance next-generation devices.

When it comes to device fabrication, however, commonly thin films or structures composed of an immense number of these nanomaterials are integrated rather than individual nanostructures. This results in material characteristics, such as charge transport phenomena, not only being dependent on the properties of the individual nanostructures, but being strongly - if not predominantly - influenced by their interfaces.

In this contribution I will discuss challenges and opportunities related to interfaces between nanomaterials and highlight recent research focusing on hybrid systems composed of molecularly cross-linked nanostructures. Herein, approaches for cross-linking gold nanoparticles[1] and $Ti_3C_2T_x$ MXenes[2] with different molecular linkers will be outlined. Further, the ability to widely tune electronic, optical and mechanical properties of such systems will be discussed. Eventually, applications exploiting the sensitive charge transport across functional molecular interfaces between nanostructures in sensing will be presented. These encompass tunneling-based strain sensors for healthcare applications,[3] highly sensitive microelectromechanical pressure sensors,[4] and chemiresistive sensors for volatile organic compounds with high sensitivity and adjustable selectivity.[2,5,6]

[1] H. Schlicke, et al., *J. Phys. Chem. C* **2019**, *123*, 19165–19174
[2] Y. Bhattacharjee, et al., **2025**, arXiv:2504.11166
[3] B. Ketelsen, et al., *Adv. Funct. Mater.* **2023**, *33*, 2210065.
[4] H. Schlicke, et al., *Adv. Funct. Mater.* **2020**, *30*, 2003381.
[5] H. Schlicke, et al., *ACS Appl. Nano Mater.* **2021**, *4*, 10399–10408.
[6] H. Schlicke, et al., *ACS Appl. Electron. Mater.* **2020**, *2*, 3741–3748

Defect-Driven Electrical Modulation of 2D materials by Helium ion irradiation

Madhuri Chennur[1,2], Zahra Fekri[1,2], Ulrich Kentsch[1,2], Jens Zscharschuch[1,2] and Artur Erbe[1,2]

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Nanoelectronics provides the foundation for creating innovative, cost-effective, miniaturized, and multifunctional materials. Among them, two-dimensional (2D) materials offer unique opportunities to tailor functionalities at the nanoscale. Structural defects in 2D materials play a crucial role in shaping their properties, often scattering charge carriers and reducing mobility. Yet, such imperfections do not always hinder device performance; rather, careful examination of defect types, densities, and distributions can yield valuable insights. In many cases, these defects can even be harnessed advantageously—for example, to enable doping, tune band gaps, or enhance catalytic activity (1)(2)(3).

In this study, we examine multilayer WSe_2 defects induced by a single broad-beam helium ion irradiation at 7.5 keV, with particular focus on the role of substrates (Si/SiO_2 and hBN). Electrical contacts were patterned using electron beam lithography (EBL), and all measurements were carried out under ambient conditions to capture the evolution of defect states over time. Post-irradiation, device characteristics were monitored at one and two weeks. Interestingly, while the devices initially displayed degraded performance after one week, their current levels exceeded the pre-irradiation values after two weeks. Various parameters are extracted to depict the changes over a period of time. To further probe the underlying mechanisms, Raman spectroscopy was performed before and after irradiation.

References:

1) Wang, Dan, et al. "Engineering two-dimensional electronics by semiconductor defects", *Nano Today* **16** (2017): 30-45.
2) Fekri, Zahra, et al. "Tuning the Electronic Characteristics of Monolayer MoS2-Based Transistors by Ion Irradiation: The Role of the Substrate", *Advanced Electronic Materials* **10** (2024): 2400037.
3) Telkhozhayeva, Madina, and Olga Girshevitz. "Roadmap toward Controlled Ion Beam-Induced Defects in 2D Materials.", *Advanced Functional Materials* **34** (2024): 2404615.

Novel exfoliated-MoS_2 Resistive Switching Devices for Artificial Synapses

Deianira Fejzaj[1], Richard Schroedter[2], Thomas Mikolajick[1,3] and André Heinzig[1]

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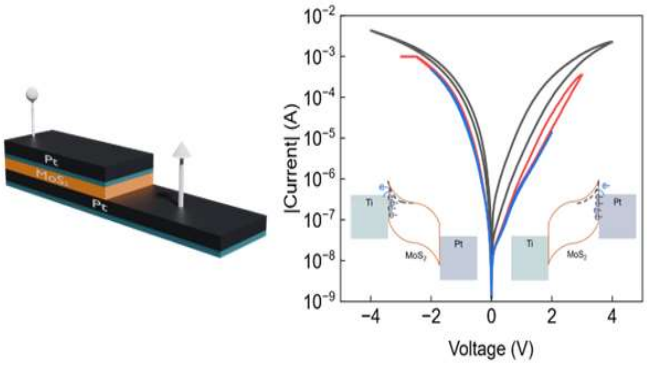
The topic of 2D materials has been growing rapidly, since the first isolation of the graphene flake in 2004. 2D materials exhibits properties such as inherent low thickness, the absence of dangling bonds, and their ability to maintain their properties down to sub-nanometer thickness. Due to their properties, they are used for fabrication of electronic devices that are regarded as artificial synapse candidates for neuromorphic computing. State-of-the-art memristors based on 2D materials class of transition metal dichalcogenides are promising devices for emulating artificial synaptic behavior due to their simple structure. Memristors using these materials as switching material owe their switching ability to the defects of said materials. Such 2D layers prepared by chemical vapor deposition are the most employed since they contain vacancies and grain boundaries. However, not much is said about the exfoliated active areas. Literature suggests that the exfoliated materials are not preferable because of the absence of the memory window. In this work, however, we demonstrate vertical memristors based on exfoliated molybdenum disulfide (MoS_2) which reveals a non-filamentary resistive switching mechanism based on Schottky barrier modulation. The devices operate without a forming step and show a gradual resistive switching behavior. The mechanism is attributed to charge trapping and detrapping, which modulates the Schottky barrier at the MoS_2/metal interface. Furthermore, the device demonstrates key synaptic functions including potentiation, depression and spike-amplitude-dependent plasticity, highlighting its potential as a fundamental building block for neuromorphic computing systems.

Keywords: memristor, molybdenum disulfide, exfoliation, Schottky barrier modulation, artificial synapses



Interlayer Exciton–Phonon Coupling in $MoSe_2/WSe_2$ Heterostructures: a resonant Raman study

September 2025

Oisín Garrity[a], Thomas Brumme[b], Annika Bergmann[c], Tobias Korn[c], Patryk Kusche[a], and *Stephanie Reich[a]

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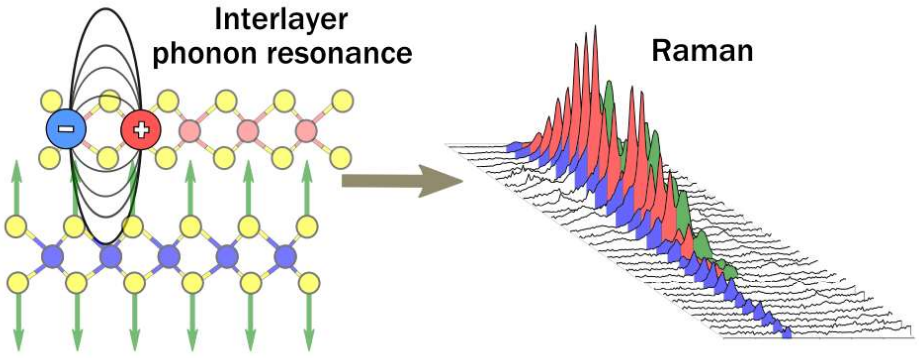
Abstract

Transition metal dichalcogenide heterostructures have garnered strong interest for their robust excitonic properties, mixed light-matter states like exciton-polaritons, and tailored properties vital for advanced device engineering. Two-dimensional heterostructures inherit their physics from the monolayers with the addition of interlayer processes that have been particularly emphasized for their electronic and optical properties. Here we demonstrate the interlayer coupling of the $MoSe_2$ phonons to WSe_2 excitons in a $WSe_2/MoSe_2$ heterostructure using resonant Raman scattering. The WSe_2 monolayer induces an interlayer resonance in the Raman cross-section of the $MoSe_2$ A_{1g} phonons. Frozen-phonon calculations within density functional theory reveal a strong deformation-potential coupling between the A_{1g} $MoSe_2$ phonon and the electronic states of the close-by WSe_2 layer approaching 20% of the intralayer coupling to the $MoSe_2$ electrons. Understanding the vibrational properties of van-der-Waals heterostructures requires going beyond the sum of their constituents and considering cross-material coupling.



Polarity-Controlled Junctionless Nanowire Transistors for Advanced Sensing Applications

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The scaling challenges of CMOS technology have driven interest in novel devices, advanced nanomaterials, and improved fabrication techniques. Silicon nanowires have emerged as promising components in sensors, solar cells, and logic devices due to their high surface-to-volume ratio and energy efficiency - critical for next-generation information processing [1]. Their compact geometry enables precise electrostatic control, making silicon nanowire FETs suitable for sensing applications [2]. A key innovation is the junctionless nanowire transistor (JNT) [3], featuring a uniformly doped nanowire channel controlled by the gate. Silicon JNTs have shown high sensitivity to low streptavidin concentrations in liquid [4], but their gas sensing capability remains unexplored.

In this work, we report the fabrication and characterization of silicon-based JNT devices and their suitability as gas sensors. Intrinsic silicon-on-insulator (SOI) substrates are ion-implanted with phosphorus (n-type) dopant. Millisecond range flash lamp annealing (FLA) is used for dopant activation and implantation defect healing. Top-down approach is carried out for nanowire fabrication using electron beam lithography patterning of the negative resist HSQ followed by reactive ion etching [5,6]. Successive processes of rapid thermal oxidation and atomic layer deposition are performed to create SiO_2 and Al_2O_3 shell around the silicon nanowires, respectively. UV lithography and metal evaporation are employed to create 50 nm thick Nickel contacts to the nanowires. Electrical characterization of these JNTs is performed by back and top gating the nanowires. Unipolar device behavior is observed. However, these characteristics are changed after contact annealing leading to the ambipolarity in the devices. These devices exhibit an on/off ratio of ~10^6. To further investigate the ambipolar nature of the silicon JNTs, output characteristics are measured, which shows Schottky barrier-based behavior of the devices. Furthermore, van der Pauw and Hall Effect measurements are performed to determine their carrier concentration and hall mobility. Successive measurements of electrical characteristics of these devices are also performed in vacuum to compare them with the usual ambient measurements. Unfunctionalized JNTs are tested as sensors in purified air, NO_2 and NH_3 atmosphere. These sensor tests exhibited characteristic shifts in the transfer curve and a systematic increase and decrease of p- and n-type current, respectively, under the influence of both the gases. These tests confirmed the potential suitability of the ambipolar JNT as sensors in gaseous environment. Additionally, these devices will be functionalized and tested for electrical detection of atmospheric free radicals.

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[6] Khan, M. B., et al. 2020 Device Research Conference (DRC). IEEE, 2020.

Oxidation-driven spontaneous formation of internal p-and n-junctions in synthetically derived 2D layered SnSe flakes

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Monochalcogenide 2D layered materials with crystalline structure akin to black phosphorus continue to attract attention as potential building blocks for next generation quantum electronic components and devices. Here, we study the electronic properties of synthetically derived SnSe as function flake thickness. Electrical DC and Hall effect characterization show an unconventional behaviour with thickness variation allowing two distinct thickness-dependent zones to be identified: an electrical conductivity increase and decrease towards lower layer number. These regimes are further distinguished by a change of majority carrier type from p- to n-type. The observed effect can be attributed to the singular specifics of the oxidation dynamics in SnSe material.

Mesoscopic electrical transport in top-down defined 4H-SiC

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Top-down defined mesoscopic devices in 4H-SiC constitute an exciting platform for exploring quantum mechanically dominated electric transport phenomena possibly even beyond cryogenic temperatures. Combining the exquisite properties of the wide-bandgap 4H-SiC polytype, namely a high degree of physical and chemical stability, a high breakdown electric field strength and high thermal conductivity, with unique properties stemming from their lower dimensionality, opens the path for a prominent role in a quantum computing era.

There are several benefits of the applied top-down sculpting or etching fabrication approach compared to the bottom-up CVD growth/synthesis. It has a high degree of controllability, reproducibility and flexibility by utilizing well-established lithography (optical and electron-beam) and RIE-etching methods, it allows for easier electric contacting and there is no unintentional doping due to the absence of a growth catalyst.

In the present work we investigated electric transport in different types of devices in a wide range of temperatures. Intriguing features in the sheet resistance R_S and in the Hall mobility were observed.

Raman spectra of 2D and 3D forms of transition metal dichalcogenides: Basics

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Two dimensional (2D) transition metal dichalcogenides (TMDs), i.e. single triple layers of metal ions sandwiched by nonmetal anions, have attracted the attention of the material scientist community meanwhile for more than 15 years because of properties like strong photoluminescence, switching ability and a reasonable charge carrier mobility.[1,2] Since these early days of 2D-TMD research, Raman spectroscopy has provided significant contributions to the understanding of the structural and disorder properties of this material class.[3]

In this talk I will provide some basic considerations for the interpretation of Raman spectra of well-ordered and structurally disordered TMD samples. Selection rules, factor group analysis, and phonon dispersion are introduced as basic concepts. Examples how these can be used to identify stacking order, number of layers and layer orientation will be given. Further on I plan to discuss the influence of external parameters on the spectra, which include substrate effects, biaxial and uniaxial strain, and point defects.

1 Mak, K. F., Lee, C., Hone, J., Shan, J. & Heinz, T. F. Atomically Thin MoS_2: A New Direct-Gap Semiconductor. *Physical Review Letters* **105**, 136805 (2010)
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3 Lee, C. *et al.* Anomalous Lattice Vibrations of Single- and Few-Layer MoS_2. *ACS Nano* **4**, 2695-2700 (2010)

KPFM on 2D materials and molecular 2D TMDC heterostructures

Mira Kreßler[1], Qing Cao[1], Fabian Grote[1], Siegfried Eigler[1], and Patryk Kusch[1]

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Kelvin Probe Force Microscopy (KPFM) is a powerful technique for probing local electronic properties in two-dimensional (2D) materials and their heterostructures with nanometer-scale resolution. Recent studies have demonstrated its effectiveness in visualizing surface potential variations arising from chemical functionalization and interfacial charge redistribution in functionalized graphene and molecularly engineered transition metal dichalcogenide (TMDC) heterostructures. For example, KPFM has been used to detect local work function changes induced by redox-active molecules on graphene, as well as dipole-driven potential shifts in TMDCs modified with self-assembled monolayers (SAMs). These spatially resolved measurements provide valuable insights into the role of molecular design and interface engineering in tuning the electronic and optoelectronic behavior of 2D systems. By enabling direct visualization of local charge effects and interfacial interactions, KPFM not only advances the understanding of electronic behavior in 2D systems but also complements spatially resolved photoluminescence and Raman measurements, providing higher spatial resolution and a more comprehensive picture of structure–property relationships.

Title: Surface Acoustic Wave-Induced Aerosol Printing for Nanomaterial Deposition

M. Roudini*, Y. Alsaadawi, S. Mohammad, A. Prudnikau, F. Paulus and A. Winkler

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The integration of low-dimensional nanomaterials into functional thin films remains a major bottleneck for their application in electronics and photonics. Existing deposition methods, such as inkjet and classical aerosol-jet printing, often compromise material integrity due to pressure, heat, or prolonged ultrasonic exposure—leading to particle aggregation, surfactant degradation, or nozzle clogging. We present a new approach to overcome these limitations by generating aerosols directly in the print head using surface acoustic waves (SAWs). This method allows for pulsed, pressure-free atomization under mild conditions, compatible with a wide range of solvents and surfactant systems.

Our initial studies show that SAW-induced aerosols can effectively deposit 0D nanocrystals, 1D nanorods, and liquid-exfoliated 2D materials with high uniformity and preserved functional properties. The droplet formation, film morphology, and material performance are strongly influenced by ink formulation, surface tension, substrate temperature, and air flow dynamics. By tuning these parameters, we achieve homogeneous films suitable for electronic and optoelectronic integration. This technique opens a scalable, nozzle-free route for printing fragile nanomaterials, bridging the gap between material design and device fabrication.

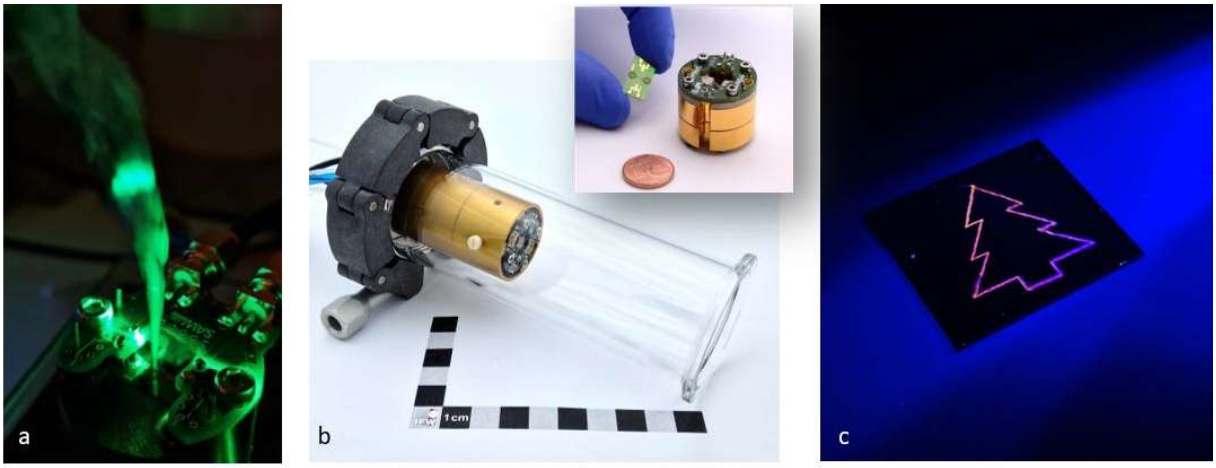

Figure 1 – a) Aerosol generator in operation. b) SAW-based aerosol generation setup showing the integration of the SAW atomizer into a flange system. c) Fluorescent quantum dots are printed onto a SiO_2-coated Si substrate using the SAW-induced aerosol jet.

Improved graphene based hot-electron transistor with an optimized emitter-base structure

Carsten Strobel[1], André Heinzig[1], Md Tarik Hossain[2], Andrey Turchanin[2], Thomas Mikolajick[1]

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2 Friedrich Schiller University Jena, GERMANY

Abstract: Graphene-based hot-electron transistors (GHETs) hold great promise for high-frequency applications due to the atomically thin nature of graphene as a novel base material. In this work, we present GHETs with enhanced DC characteristics achieved through systematic screening and optimization of different emitter–base (E/B) material combinations. This optimization promotes more efficient hot-electron injection into the graphene base, thereby enhancing charge transport and minimizing scattering losses. As a result, the common-emitter current gain (β) was significantly improved—from approximately 10 for a hBN/graphene E/B interface to about 400 when using a SiO_2/graphene structure. In contrast, employing a MoS_2/graphene E/B junction resulted in a reduced current gain of 20, but enabled a maximum output current density of 2000 A/cm², marking a substantial performance enhancement over previously reported GHETs.

The terahertz (THz) gap denotes the frequency band between microwaves and infrared light, typically spanning 0.1 to 10 THz. This spectral region remains challenging to access due to the limited efficiency of conventional electronic and photonic components, which struggle to perform effectively at such frequencies. Consequently, the development of high-performance sources, detectors, and semiconductor devices for applications in ultrafast communication, imaging, and spectroscopy has become a major technological priority. Traditional high-speed transistors generally operate below 1 THz cutoff frequencies, whereas graphene-based hot-electron transistors (GHETs) are emerging as promising candidates to reach operation up to 10 THz. This potential arises from the atomically thin monolayer graphene base, which drastically shortens the carrier base transit time—a critical parameter for achieving high-frequency operation in hot-electron transistors.

In the present work, n-type germanium (n-Ge) is employed as the collector material, while graphene serves as the ultrathin base electrode. To enhance performance, the E/B interface is systematically varied to lower both the barrier height ($q\varphi_{BE}$) and its thickness. Such optimization aims to decrease the GHET turn-on voltage and boost both output current density and common-emitter current gain (β). In earlier device iterations, multilayer hexagonal boron nitride (hBN, 4 nm) was used as the E/B insulator. However, due to its relatively high barrier height of $q\varphi_{BE}$ = 4 eV, the resulting GHET showed only moderate current gain (β ≈ 7) and a maximum output current density of 800 A/cm². The hBN was deposited onto graphene using a copper-based wet etching process, which unfortunately introduced Cu contaminants at the hBN/Gr interface. These metallic residues acted as scattering centers, limiting both current gain and current density. To address these issues, this study explores alternative E/B dielectrics such as SiO_2 and MoS_2, which offer lower interface contamination and reduced barrier heights. Devices incorporating SiO_2 demonstrated exceptional current gain, with β values exceeding 400. On the other hand, GHETs using MoS_2 as the E/B layer showed a lower turn-on voltage and achieved record output current densities up to 2000 A/cm². These significant enhancements in DC performance metrics pave the way for future implementation of ground-signal-ground (GSG) test structures, enabling high-frequency characterization of GHETs with target cutoff frequencies well into the THz regime.

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Posters

updated: 08.09.2025 (PZ)

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Kaliappan P., A.	P3	Study of Electronic Properties of Nano-Scaled Topological Insulators	22
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1) Posters should be mounted on arrival, and should be on display the whole time.
2) Please, remove your poster latest on the last day before lunch.

Graphene functionalized with TCNE

Simon Attenberger[1], Felix Hoffmann[1] and Vojislav Krstić[1,2]

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Graphene is a single-atom-thick material with unusual electronic behavior, making it an important subject of study. A common way to modify its electronic properties is by attaching molecules to its surface, a process called physisorption. However, the loading of graphene with molecular species also impacts translational symmetry, which can be detected in the Raman spectrum. This makes the choice of molecule and the overall molecule concentration critical and crucial for any further application of the material. In the present work we examine the development of the Raman spectra of graphene non-covalently functionalized with the molecule tetracyanoethylene (TCNE) at different molecule concentrations adsorbed.

Electrical transport in mesoscopic 4H-SiC with different nitrogen dopant profiles

Jain George[1], Ole Jäger[1], Maria Koleśnik-Gray[1], and Vojislav Krstić[1,2]

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The 4H-SiC polytype stands out due to its physical stability and wide bandgap contributing to high thermal conductivity, high breakdown electric field strength and chemical robustness. Leveraging these intrinsic properties at the nanoscale enables low-dimensional structures with promising applications in nanoscale devices. We investigate the electrical transport in shallow nitrogen implanted HPSI 4H-SiC substrates with varying doping profiles. The shallow implantation gives rise to a thin conductive n-type transport layer, decoupled from the highly resistive substrate via a strong doping contrast. Additional lateral confinement is achieved by well-established top-down etching methods. Sheet resistance, electron mobility and the average carrier density were studied. The mobility values were found to be substantially higher compared to bulk samples.

Study of Electronic Properties of Nano-Scaled Topological Insulators

Akshaya Kaliappan Poonthenral[1], Maria Koleśnik-Gray[1], Dave Carroll[2], and Vojislav Krstić[1,2]

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3D layered topological insulators such as Bi_2Te_3 and Sb_2Te_3 feature insulating bulk states and Dirac-like surface states with spin-momentum locking. In the nanoscale limit, hybridization of top and bottom surfaces opens an energy gap in the Dirac states but leaves spin-polarized edge channels (quantum spin Hall states) that are promising for quantum computing applications. Realizing such applications requires precise electrical control and characterization. In this work, we studied nanostructured Bi_2Te_3 platelets, focusing on electrical contacting and high frequency transport. Optimized Ni and Ag electrodes facilitated efficient current injection in DC fields allowing resistivity assessment. Time-domain AC measurements in the GHz regime where carried out, too.

DNA-Assisted Lithography (DALI) for Nanoelectronics

Charlotte Kielar[1], Christoph Hadlich[2], Borja Rodriguez-Barea[1], Mohammed Al-Obaidi[2], Ciarán Fowley[1], Andreas Worbs[3], Tommy Schönherr[1], Ralf Seidel[2], and Artur Erbe[1]

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The significance of nanotechnology has increased over the past few decades across various fields, ranging from medicine to electronics. Notably, the DNA-assisted lithography (DALI) has emerged as a powerful addition to the nanotechnology toolkit.

This work leverages the strengths of DNA origami to fabricate gold nanostructures based on DNA origami templates. This approach integrates the advantages of DNA origami with traditional lithography, enabling the fabrication of nanowires [1]. Here, the precise and parallel nature of DNA origami [2] is utilized to transfer origami patterns [3] onto “hard” stencil masks on sapphire substrates. Subsequent etching and deposition through the mask enable the production of bespoke nanowires, far beyond what is achieved by optical lithography. To achieve this goal, long DNA origami structures were assembled on sacrificial Si, and a thin film of silicon oxide (SiOx) is selectively grown around them using chemical vapor deposition (CVD). The growth thicknesses, patterning selectivity and resolution were characterized using AFM, SEM and FIB cross-sectioning.

DALI-fabricated nanostructures have so far [4] only been employed in optical applications. This project demonstrates how this method can be adapted to produce clean nanoscale electrical wires, facilitating the investigation of charge transport and the evaluation of the correlation of the deposited structural methods.

[1] Kemper, Weizmann, Kielar *et al., Nano Lett.* 24, 8, 2429-2436 (2024)
[2] Kielar *et al*., *ACS Appl. Mater. Interfaces* 10, 51, 44844-44853 (2018)
[3] Tapio, Kielar *et al.*, *Chem. Mater.* 35, 5, 1961-1971 (2023)
[4] Shen, Linko, Tapio *et al. Sci. Adv.* 4, eaap8978 (2018)

Resonance Raman and DFT analysis of structural and point defects in transparent conductive oxide SnO_2:X (X=Ta, F)

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Structural and point defects have a crucial influence on the electronic and optical properties of transparent conductive oxides. In this contribution we characterize different types of defects in SnO_2:X (X = Ta, F) by the combination of laser-wavelength dependent Raman spectroscopy and state-of-the-art density functional theory (DFT) calculations using hybrid functionals.

Sn-vacancy- and O-interstitial-type point defects are found in transparent conductive SnO_2:Ta thin films grown at 575 °C. These defects are responsible for strong, fingerprint-like Raman lines out of the phonon range of SnO_2 [1], which are resonance-enhanced in the visible spectral range. The defects induce strong distortions of the electronic structure in the upper range of the valence band of Ta-doped SnO_2. Moreover, the DFT calculation reveal a localized, molecular nature of the O interstitial and a delocalized nature of the Sn vacancy defect [2]. Secondary Sn oxide phases were identified in commercial, conductive SnO_2:F samples and in non-conductive SnO_2:Ta thin films deposited at low temperatures.

[1] M. Krause, et al., J. Mat. Chem. A **11**, 17686-17698 (2023).

[2] M. Krause, et al., J. Mat. Chem. A **13**, 15128-15139 (2025).

Electrically Driven Telecom-Wavelength Single-Photon Sources for Scalable Silicon Quantum Photonics

A. Puddu[1,2], J. Yang[2], A. Echresh[1], S. Zhou[1], K. Jamshidi[2] and Y. Berencén[1]

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Silicon-based quantum technologies are promising for scalable photonics due to CMOS compatibility and integration potential. Telecom-wavelength single-photon sources are vital for low-loss quantum networks and the emerging quantum internet. Integrating these sources with reconfigurable photonic elements and detectors on-chip is essential for scalable quantum hardware. However, optical excitation requires complex, alignment sensitive lasers, hindering integration. Electrically driven color centers offer a compact, fully integrated alternative.

We aim to achieve electrically driven single-photon emission from single color centers in silicon by integrating them into a PIN diode structure. The emission of the color centers in the telecom O- and L-bands is particularly suited for scalable quantum technologies, offering minimal loss and dispersion in optical fibers. To enhance emission efficiency and photon control, a single center will be coupled to a CMOS-compatible optical cavity, enabling Purcell-enhanced emission and efficient routing within silicon photonic circuits.

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DNA-assisted nanowires: progress and prospects for electronics

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The current state of DNA origami for nanoelectronics will be sketched. The direction of the PhD project started very recently will be explored.

Support by the DFG Research Training Group 2767 *Supracolloidal Structures: From Materials to Optical and Electronic Devices* is gratefully acknowledged.

Towards imposing spin-texture in graphene

Adith Vinod[1], Maria Kolesnik-Gray[1], and Vojislav Krstić[1,2]

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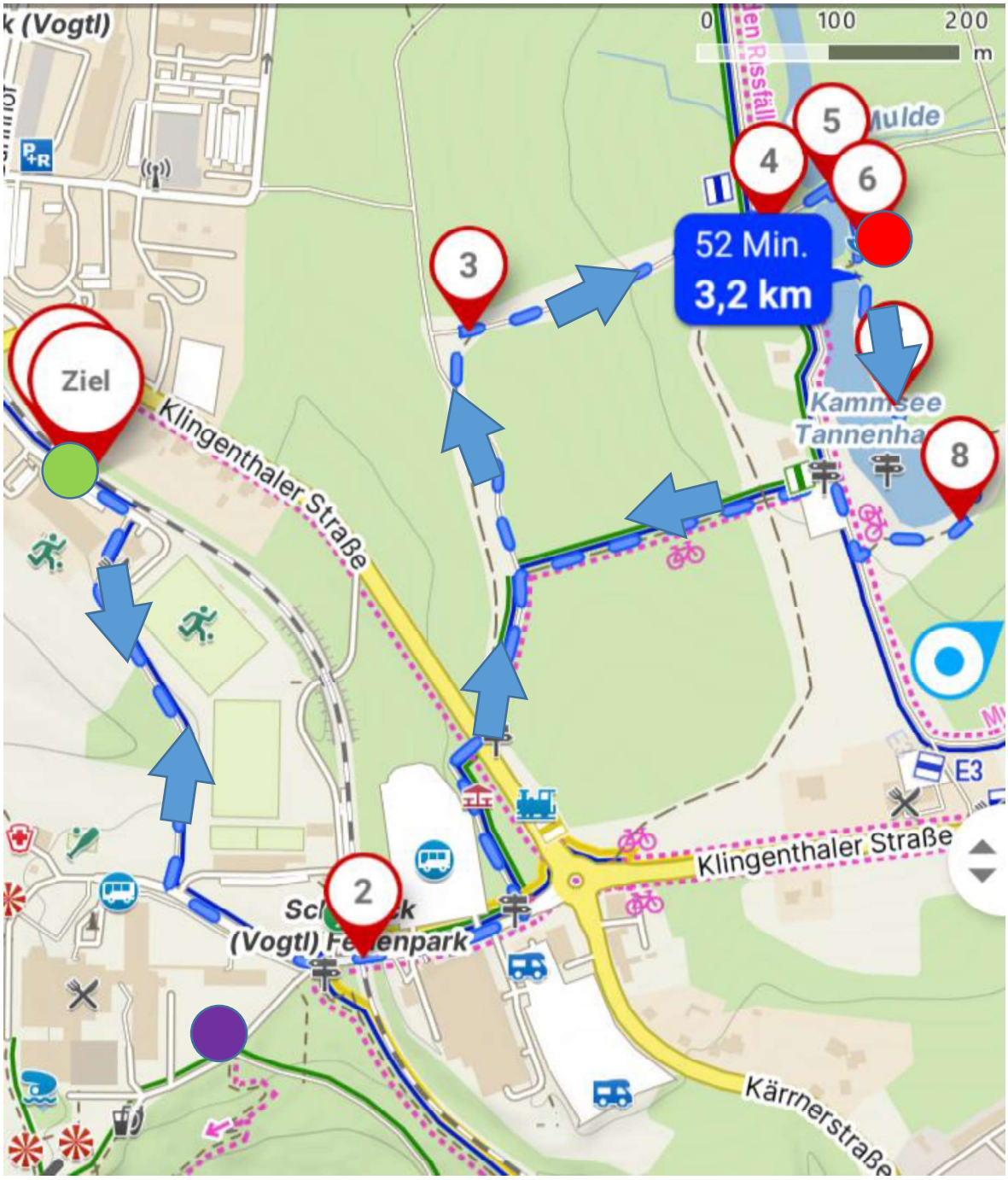
High-quality monolayer graphene was obtained by mechanical exfoliation and verified by Raman spectroscopy. We investigate the possibility of imposing a spin texture into graphene by defining nickel nanodots patterns on top pf the graphene. To trace the impact of the deposited patterns electrical transport measurements are performed.

Your Notes

Your Notes

Walking Tour: Mulde River Source



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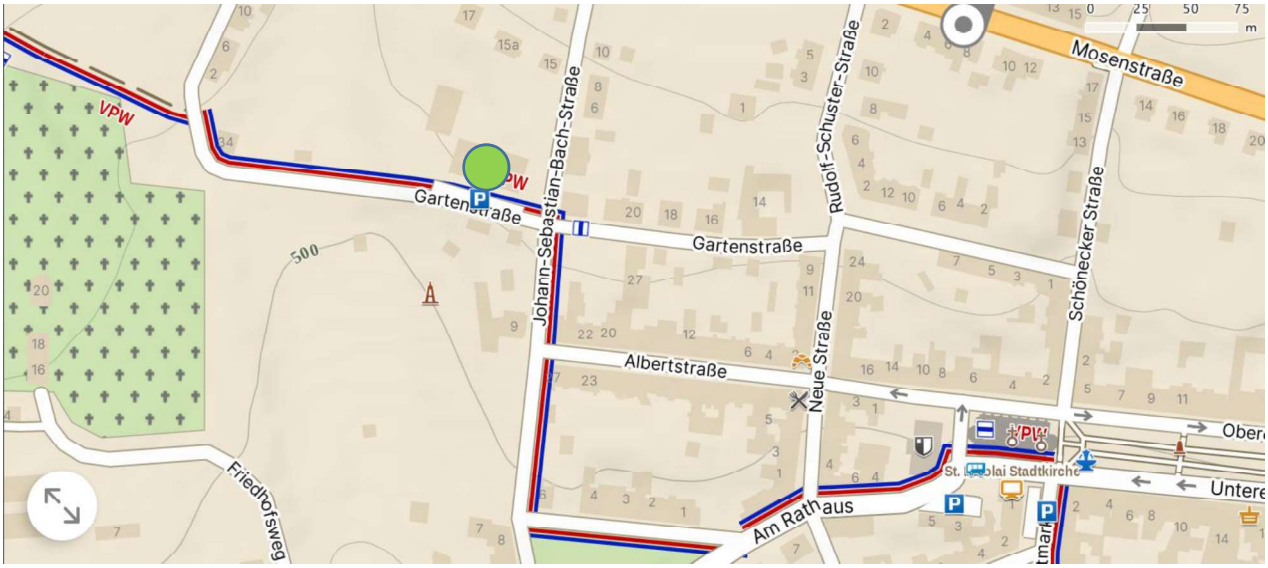
Youth Hostel (JH)

start Wed 4:45 pm.

Mulde Source

Markneukirchen



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3:30 pm. Departure Bus from JH to Markneukirchen

4:00 pm. English Tour – Schauwerkstatt (Workshop) ERLEBNISWELT MUSIKINSTRUMENTENBAU

Musicon Valley e.V.
Johann-Sebastian-Bach-Straße 13
08258 Markneukirchen

6:00 pm. Departure Bus – Schauwerkstatt

Your Notes

NanoNet+ Workshop 2025 - Schöneck

Participants

Updated: 05.09.2025 (PZ)

Name	First Name	Gender	Title	Institution
Aghvami	Banafsheh	Ms.		HZDR
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Attenberger	Simon	Mr.		FAU Erlangen
Bolotin	Kirill	Mr.	Prof.	FU Berlin
Carroll	David	Mr.	Prof.	Wake Forest Univ
Chennur	Madhuri	Ms.		HZDR
Echresh	Ahmad	Mr.	Dr.	HZDR
Erbe	Artur	Mr.	Prof.	HZDR
Fejzaj	Deianira	Ms.		TU Dresden
Fowley	Ciaran	Mr.	Dr.	HZDR
Garrity	Oisin	Mr.		FU Berlin
George	Jain	Ms.		FAU Erlangen
Ghosh	Sayantan	Mr.		HZDR
Gray	Maria	Ms.	Dr.	FAU Erlangen
Jäger	Ole	Mr.		FAU Erlangen
Kaliappan P.	Akshaya	Ms.		FAU Erlangen
Kielar	Charlotte	Ms.	Dr.	HZDR
Krause	Matthias	Mr.	Dr.	HZDR
Kreßler	Mira	Ms.		FU Berlin
Krstic	Vojislav	Mr.	Prof.	FAU Erlangen
Kusch	Patryk	Mr.	Dr.	FU Berlin
Lambeva	Nikol	Ms.	Dr.	HZDR
Puddu	Alessandro	Mr.		HZDR
Rohit Lal	Anju	Ms.	Dr.	HZDR
Roudini	Mehrzad	Mr.	Dr.	IFW Dresden
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Schönherr	Tommy	Mr.		HZDR
Shameem	Raufar	Mr.		HZDR
Strobel	Carsten	Mr	Dr.	TU Dresden
Vinod	Adith	Mr.		FAU Erlangen
Zahn	Peter	Mr.	Dr.	HZDR
Zscharschuch	Jens	Mr.		HZDR

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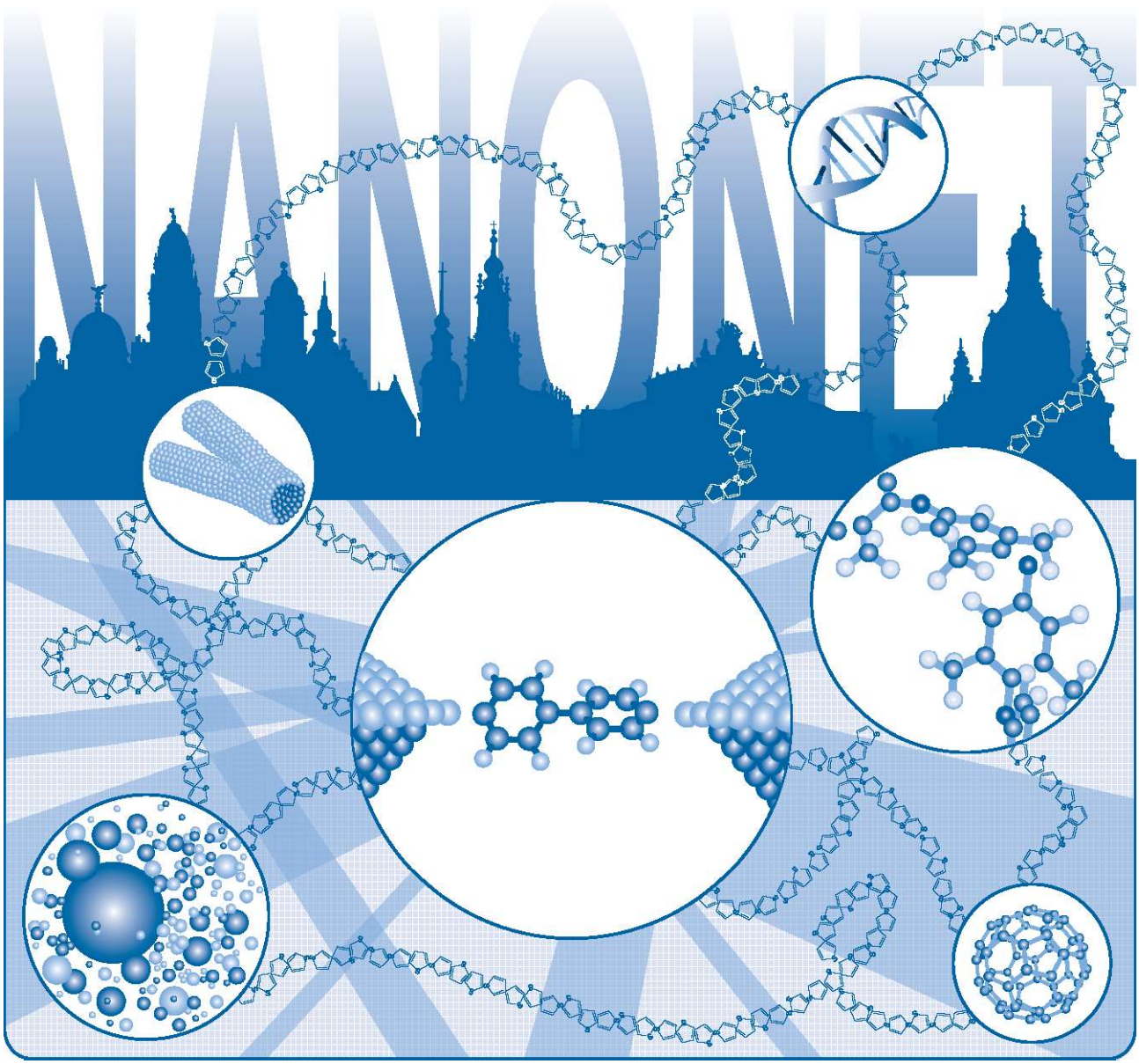

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