O 25: Focus Session: Atomic-Scale Characterization of Correlated Ground States in Epitaxial 2D Materials

The rapid expansion of the family of two-dimensional (2D) materials led to the observation of various quantum phases with correlated ground states in the 2D limit, such as unconventional superconductivity, charge density waves, and novel magnetic phases. On the fundamental level, there are various open questions regarding the mechanisms that underlie these correlated ground states, as well as the understanding of the role of the interface and dimensionality. The epitaxial growth of 2D materials on inert substrates under ultrahigh vacuum conditions and respective in situ investigation allows direct and unambiguous comparison between experimental findings and first-principles calculations. Experimentally, scanning tunneling microscopy methods are ideal to explore the electronic structure and magnetic properties of emerging 2D quantum phases with ultimate real-space and energy resolution at ultra-low temperatures. Theoretically, the use of density functional theory calculations requires atomically well-defined unit cells to precisely predict the electronic and magnetic properties. Combining these complementary approaches helps to elucidate the role of the substrate, defects, and the coupling between quasiparticles in stacked heterostructures.

Organizers: Nadine Hauptmann (Radboud University, Nijmegen), Jeison Fischer (University of Cologne), and Wouter Jolie (University of Cologne)

Time: Tuesday 10:30–13:00 Location: H2

Topical Talk O 25.1 Tue 10:30 H2

Designer electronic states in van der Waals heterostructures — •Peter Liljeroth — Department of Applied Physics, Aalto University, PO Box 15100, 00076 Aalto, Finland

Van der Waals (vdW) heterostructures provide unique opportunities for engineering exotic quantum states not found in naturally occurring materials. I will highlight this approach by describing our recent results on realizing topological superconductivity [1,2] and artificial heavy fermion systems in vdW heterostructures [3]. We use molecular-beam epitaxy (MBE) and low-temperature scanning tunneling microscopy (STM) for the sample growth and characterization. Topological superconductivity can be realized by combining ferromagnetic $CrBr_3$ on a superconducting $NbSe_2$ substrate [1,2], which brings together the necessary ingredients for topological superconductivity (out of plane ferromagnetism, Rashba-type spin-orbit interactions and s-wave superconductivity). On the other hand, the building blocks of heavy fermion systems - Kondo coupling between a lattice of localized magnetic moments and mobile conduction electrons - can be mimicked in a 1T-TaS_2 / 1H-TaS_2 heterostructure. These examples highlight the versatility of vdW heterostructures in realizing quantum states that are difficult to find and control in naturally occurring materials.

References: [1] S. Kezilebieke et al. Nature 588, 424 (2020). [2] S. Kezilebieke et al. Nano Lett. 22, 328 (2022). [3] V. Vaňo et al. Nature 599, 582 (2021).

Topical Talk O 25.2 Tue 11:00 H2

Magnetic order in a coherent Kondo lattice in the 1T/1H TaSe2 heterostructure — Wen Wan[1], Rishav Harsh[1], Paul Dreher[1], Sandra Sajan[1], Antonella Meninno[2], Ion Errea[2], Fernando de Juan[1], and •Miguel Ugeda[1] — [1]Donostia International Physics Center (DIPC), Paseo Manuel de Lardizábal 4, 20018 San Sebastián, Spain — [2]Centro de Física de Materiales (CSIC-UPV-EHU), Paseo Manuel de Lardizábal 5, 20018 San Sebastián, Spain

Kondo lattice systems are of fundamental importance for our understanding of quantum criticality and unconventional superconductivity. At the heart of their complexity lies the competition between the opposing forces of Kondo screening and magnetic interactions, which is revealed at very low temperatures as the moments start behaving coherently and eventually determines the fate of the ground state. While our understanding of Kondo lattices has traditionally relied on technically challenging strongly correlated bulk f-electron systems, new light is being shed on the problem thanks to heterostructures of 2D transition metal dichalcogenides, which realize a tunable Kondo lattice platform in a simple material. Here, we study the 1T/1H-TaSe2 heterostructure with high-resolution Scanning Tunneling Spectroscopy at 300 mK, and show a well resolved splitting of the Kondo peak, which increases monotonically in a non-linear fashion in the presence of an out-of-plane magnetic field. This behavior is unexpected for a fully screened Kondo lattice, and it originates instead from a ground state with residual magnetic order, consistent with a Kondo coupling much below the critical point in the Doniach phase diagram.

O 25.3 Tue 11:30 H2

Topological Surface State in epitaxial zz-GNRs — •M. Gruschwitz[1], T.T.N. Nguyen[1], N. de Vries[2], H. Karakachian[3], J. Aprojanz[1], A.A. Zakharov[4], C. Polley[4], T. Balasubramanian[4], U. Starke[3], C.F.J. Flipse[2], and C. Tegenkamp[1] — [1]Technische Universität Chemnitz, Chemnitz, Germany — [2]Eindhoven University of Technology, Eindhoven, The Netherlands — [3]Max Planck Institute for Solid State Research, Stuttgart, Germany — [4]MAX IV Laboratory and Lund University, Lund, Sweden

Protected and spin-polarized transport channels are the hallmark of topological insulators, coming along with an intrinsic strong spin-orbit coupling. Here we identified such corresponding chiral states in epitaxially grown zigzag graphene nanoribbons (zz-GNRs) on mesa-SiC(0001) templates, albeit with an extremely weak spin-orbit interaction. While the bulk of the monolayer zz-GNR is fully suspended across a SiC facet, the lower edge merges into the SiC(0001) substrate and reveals a surface state at the Fermi energy, which is extended along the edge and splits in energy toward the bulk. All of the spectroscopic details are precisely described within a tight binding model incorporating a Haldane term and strain effects. The concomitant breaking of time-reversal symmetry without the application of external magnetic fields is supported by ballistic transport revealing a conduction of $G = e^2/h$ [1,2]. [1] J. Baringhaus et al., Nature 506, 349 (2014); [2] T.T.N. Nguyen et al. Nano Lett. 21, 2876 (2021)

Topical Talk O 25.4 Tue 11:45 H2

Electron-lattice correlations and charge order in two-dimensional materials — •Tim Wehling — I. Institute of Theoretical Physics, Universität Hamburg, Germany

Electronic correlation phenomena in two-dimensional (2D) materials are often tightly linked to lattice degrees of freedom. Examples include superconductivity, periodic lattice distortions and charge density waves (CDWs), metal-insulator transitions, magnetic, *stripe,* or excitonic order across vastly different systems ranging from transition metal dichalcogenides to cuprate high-temperature superconductors. Here, we will address how to disentangle and eventually control the interplay of lattice and electronic degrees of freedom in 2D materials. We will discuss the concept of electron-phonon fluctuation diagnostics to identify the electronic processes behind phonon anomalies in materials like TaS2 [1] and VS2 [2]. We show how the coupling of low energy electrons and lattice degrees of freedom gives rise to anharmonicities and reveal an ultrastrong non-linear mode-mode coupling in VS2.

[1] J. Berges et al., Phys. Rev. B 101, 155107 (2020).
[2] C. van Efferen et al., Nature Communications 12, 6837 (2021).

O 25.5 Tue 12:15 H2

Superconductivity of ultrathin crystalline Al films — •Werner M.J. van Weerdenburg[1], Anand Kamlapure[1], Niels P.E. van Mullekom[1], Xiaochun Huang[1], Manuel Steinbrecher[1], Peter Krogstrup[2], and Alexander A.

Khajetoorians[1] — [1]Institute for Molecules and Materials, Radboud University Nijmegen, the Netherlands — [2]Center for Quantum Devices, Niels Bohr Institute, University of Copenhagen, 2100 Copenhagen, Denmark

While bulk Al is one of the best known BCS superconductors (SC), it exhibits strange SC behavior in the thin film limit, e.g. a strong enhancement of the critical temperature T_c [1]. The transition from bulk to thin film can modulate the electronic structure and quasiparticle excitations, and the interface with the substrate becomes relevant [2]. Understanding the role of reduced dimensionality, screening and interface effects is important for SC quantum technology.
Here, we study epitaxially grown crystalline Al films on Si(111) as a function of film thickness. Using scanning tunneling microscopy / spectroscopy with temperatures down to 30 mK, we show a strong increase of both the SC gap size Δ and T_c for coverages between 4 and 35 monolayers. Remarkably, we find that Δ is threefold enhanced compared to the bulk value. We characterize the SC state of the thin films in (vector) magnetic field and find a new vortex structure.

[1] P.W Adams et al., Phys. Rev. B 95, 094520 (2017)
[2] A. Kamlapure et al., arXiv:2109.08498 (2021)

O 25.6 Tue 12:30 H2

Realization of Pb honeycomb stuctures by intercalation of buffer layers on SiC(0001) — •Chitran Ghosal, Markus Gruschwitz, and Christoph Tegenkamp — Institut für Physik, TU Chemnitz

The growth of 2D honeycomb lattices of group IV-elements has attracted a lot of interest during the last years. In contrast to graphene, the 2D analogues of Si and Ge can be stabilized on metals, while stanene and plumbene were recently prepared on compound crystals and magnetic substrates, respectively. Here we report on the intercalation of Pb using buffer layers (BL) on SiC(0001), resulting in the formation of freestanding and charge neutral graphene [1]. Depending on the bias voltage, scanning tunneling microscopy reveals complex Moiré structures, which are consistently explained in consideration of two plumbene lattices. These are rotated each by $\pm 7.5^\circ$ with respect to graphene and, thus, are commensurate with the former $6\sqrt{3} \times 6\sqrt{3}$ symmetry of the BL on SiC(0001). Locally, a (2×2) pattern becomes visible in STM and is expected since the lattice constant of plumbene is twice as large as for graphene. Local spectroscopy (STS) done at 4 K reveals an electronic gap of 30 meV and is in qualitative agreement with the band structure of low-buckeled and charge-neutral plumbene.

[1] M. Gruschwitz et al., Materials 14, 7706 (2021)

O 25.7 Tue 12:45 H2

Sn intercalation of the buffer layer/SiC(0001) interface studied by SPA-LEED and STM — •Zamin Mamiyev, Chitran Ghosal, and Christoph Tegenkamp — Institut für Physik, Technische Universität Chemnitz, Chemnitz, Germany

Growth of graphene (Gr) with tailored properties and the simultaneous formation of an exotic 2D interface can be achieved by intercalation of different species below the buffer layer (BL) on SiC(0001). In this regard, Sn is interesting because of a potential Mott ground state imposed by the triangular lattice of Sn atoms at the interface and protected by the Gr layer. Therefore, we studied Sn-intercalation on BL/SiC(0001) by means of spot profile analysis low energy electron diffraction (SPA-LEED) and STM. Starting with a $6\sqrt{3} \times 6\sqrt{3}$ BL surface, we deposited monolayers of Sn at RT and annealed subsequently to higher temperatures. The formation of quasi-free standing monolayer graphene (QFMLG) is confirmed by an apparent 1×1 periodicity. Further insights for a successful decoupling of QFMLG were gained from inspecting the bell shape broadening of the diffraction spots, which is characteristic of weakly coupled 2D systems on surfaces. By further optimization of the post-intercalation treatment, a Sn-induced $\sqrt{3}\times\sqrt{3}$ reconstruction at the interface was achieved. Moreover, detailed studies showed a simultaneous transformation of $6\sqrt{3} \times 6\sqrt{3}$ periodicity into a $(\sqrt{39} \times \sqrt{39})$R16.1° reconstruction with corresponding domains. Interestingly, the new periodicities formed by the intercalant atoms are triggered by the former symmetry of the BL structure.