# DS 21: Focus Session: Growth, Properties and Application of Epitaxial Graphene (joint session DS/O/HL)

Graphene is the only 2D material, which up to now can be grown almost defect-free on large scales. The application of epitaxial concepts has turned out as a breakthrough in graphene research, because it provides control over the interface and surface structure of epitaxial graphene (EG) layers with atom-scale precision and in an efficient and technologically compatible way. A wide variety of physical phenomena have been observed in graphene-based structures, including topologically protected states, high charge carrier mobility, electron correlation or superconductivity. This versatility makes EG an ideal platform for the integration of graphene-based structures into electronic applications.

This Focus Session aims at fostering the cooperation between groups working in the field of the synthesis, characterization and integration of systems based on large, structurally well-ordered graphene layers. For this purpose it collects state-of-the-art contributions to all involved aspects of EG research, from the growth, functionalization and characterization to the integration of EG-based materials.

**Organizers:**
- Sibylle Gemming, Institut für Physik, TU Chemnitz, D-09107 Chemnitz
- Christoph Tegenkamp, Institut für Physik, TU Chemnitz, D-09107 Chemnitz

Time: Thursday 9:30–12:45 Location: H32

**Invited Talk** DS 21.1 Thu 9:30 H32

**Epitaxial graphene on SiC(0001) studied by electron spectroscopy and microscopy** — •Florian Speck — Professur für Technische Physik, TU Chemnitz, Reichenhainer Str. 70, D-09126 Chemnitz, Germany

The growth of epitaxial graphene (EG) on silicon carbide (SiC) by sublimation of silicon in an inert atmosphere has received considerable attention due to its scalability up to wafer size, and over the past years, the homogeneity of the graphene films could be significantly enhanced by a polymer assisted growth process [1]. Intricate transfer procedures can be dispensed with when semi-insulating SiC substrates are used, facilitating the use of EG in electronics. Yet, interfaces to other materials and the presence of a substrate can affect the graphene layers, e.g. with respect to their structural and electronic properties. As will be shown in this talk, EG grown on SiC(0001) constitutes an intriguing model system to study such interactions due to diverse possibilities of manipulating its properties for instance by intercalation of different elements at the interface to the substrate. To this end, we employ mainly surface science methods such as electron spectroscopies, low-energy electron diffraction and microscopy. Discussed topics include doping of EG induced by hexagonal SiC polytypes, interface modification by means of intercalation, dislocations in EG and investigations of graphene prepared by polymer assisted growth.
[1] M. Kruskopf et al., 2D Mater. **3**, 041002 (2016).

DS 21.2 Thu 10:00 H32

**Uniform large-scale quasi-freestanding monolayer and bilayer graphene on SiC** — Davood Momeni Pakdehi[1], •Klaus Pierz[1], Stefan Wundrack[1], Johannes Aprojanz[2], T.T. Nhung Nguyen[3], Thorsten Dziomba[1], Frank Hohls[1], Andrey Bakin[4,5], Rainer Stosch[1], Christoph Tegenkamp[2,3], Franz J Ahlers[1], and Hans. W. Schumacher[1] — [1]Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig — [2]Institut für Festkörperphysik, LU Hannover, Appelstraße 2, 30167 Hannover — [3]Institut für Physik, TU Chemnitz, Reichenhainer Straße 70, 09126 Chemnitz — [4]Institut für Halbleitertechnik, TU Braunschweig, 38106 Braunschweig, — [5]Laboratory of Emerging Nanometrology, TU Braunschweig, 38106 Braunschweig

Epitaxial graphene growth is often accompanied by step bunching of the underlying SiC substrate and graphene bilayer formation which can deteriorate the quality of graphene-based devices, e.g., the resistance quantization of the quantum Hall effect. We show AFM, STM, Raman and electronic transport data which indicate that improved buffer layer growth is the key to obtain homogenous large-area monolayer graphene. Particularly, the substantial impact of the so-far less regarded Ar flow rate on the graphene quality is investigated in this study and explained by a quasi-equilibrium model at the growing surface. The quality of our ultra-smooth graphene layers is proven by the high uniformity of quasi-freestanding graphene sheets obtained by hydrogen intercalation which is underlined by the very small resistance anisotropy of such samples on um and mm scales.

DS 21.3 Thu 10:15 H32

**Influence of minivalleys and Berry curvature on electrostatically induced nanostructures in gapped bilayer graphene** — •Angelika Knothe and Vladimir Fal'ko — National Graphene Institute, University of Manchester, United Kingdom

We theoretically investigate the properties electrostatically confined nanostructures in gapped bilayer graphene (BLG). We show how the spectrum of subbands in a quantum wire in gapped BLG, and the energy levels in a quantum dot, manifest the minivalley structure and Berry curvature via the associated magnetic moment of the states in the low-energy bands. These features determine the degeneracies of the low-energy minibands / -levels and their valley splitting, which develops linearly in a weak magnetic field. In a quantum point contact, magneto-conductance reflects such degeneracies in the heights of the first conductance steps which develop upon the increase of the channel doping: $8e^2/h$ steps in a wide channel in BLG with a large gap, $4e^2/h$ steps in narrow channels, all splitting into a staircase of $2e^2/h$ steps upon lifting valley degeneracy by a magnetic field B. For quantum dots, we investigate how optical selection rules are influenced by the minivalleys and the orbital magnetic moment, as well as by shapes of the confinement.

References: A. Knothe and V. Fal'ko, Phys. Rev. B 98, 155435 (2018); H. Overweg, A. Knothe, V. I. Fal'ko, K. Ensslin, T. Ihn, et al., arXiv:1809.01920; R. Kraft, I.V. Krainov, V. Gall, A.P. Dmitriev, R. Krupke, I.V. Gornyi, R. Danneau, arXiv:1809.02458

DS 21.4 Thu 10:30 H32

**Tuning the doping level of graphene near the Van Hove singularity via ytterbium intercalation** — •Hrag Karakachian, Philipp Rosenzweig, Stefan Link, Kathrin Müller, and Ulrich Starke — Max-Planck-Institut für Festkörperforschung, Heisenbergstr. 1, 70569 Stuttgart, Germany

At extremely high doping levels, when pushing the Fermi level to the vicinity of graphene's Van Hove singularity (VHs), exotic electronic ground states are expected to occur driven by many-body interactions. These competing electronic phases such as chiral superconductivity, charge or spin density waves, find their stability based on the amount of doping induced in the graphene layer [1]. In this work, we present a method for effectively tuning graphene's doping level near its VHs. Epitaxially grown graphene on SiC(0001) is decoupled from the SiC substrate and strongly $n$-doped up to its VHs via ytterbium intercalation. By annealing the graphene/Yb system at different temperatures, a topological transition at the Fermi level is observed and a continuous shift in Dirac point energy is measured, indicating a change in carrier density. The Yb atoms go through different order patterns at different heating stages, and their concentration is modified as a function of temperature. These variations significantly affect the amount of charge transferred to the graphene layer and allow the systematic control of graphene's doping level near its VHs. Thus, the Yb intercalation technique can provide a reliable way of accessing and switching between different possible ordered electronic ground states in graphene.

[1] A.M. Black-Schaffer et al., J. Phys. CM **26**, 423201 (2014).

DS 21.5 Thu 10:45 H32

**Substrate induced nanoscale resistance variation in epitaxial graphene** — •Anna Sinterhauf[1], Georg A. Traeger[1], Davood Momeni Pakdehi[2], Philip Schädlich[3], Florian Speck[3], Philip Willke[4,5], Thomas Seyller[3], Christoph Tegenkamp[3], Klaus Pierz[2], Hans Werner Schumacher[2], and Martin Wenderoth[1] — [1]IV. Physikalisches Institut, Universität Göttingen, 37077 Göttingen, Germany — [2]Physikalisch-Technische Bundesanstalt, 38116 Braunschweig, Germany — [3]Institut für Physik, Technische Universität Chemnitz, 09126 Chemnitz, Germany — [4]Center for Quantum Nanoscience, Institute for Basic Science (IBS), Seoul 03760, Republic of Korea — [5]Department of Physics, Ewha Womans University, Seoul 03760, Republic of Korea

Electron transport in graphene is often crucially influenced by the underlying substrate which induces scattering mechanisms on a local scale. Using scanning tunneling potentiometry we investigate the transport properties of graphene on 6H-silicon carbide (0001) grown by polymer-assisted sublimation growth (PASG) down to the nanometer scale. We find a significant variation in the sheet resistance of up to 195% on neighboring terraces directly related to the stacking of the 6H-SiC substrate. Thus, our data clearly shows the strong influence of the substrate below the graphene layer on its local transport properties. In addition, we performed temperature dependent measurements to gain insight into the dominant scattering mechanism. This work is financially supported by the DFG through the SFB1073.

**15 min. break.**

**Invited Talk** DS 21.6 Thu 11:15 H32

**Patternable non-polar epigraphene for nanoelectronics and Dirac point physics** — Vladimir Prudkovskiy[1,3], Yiran Hu[1], Hue Hu[1], Lei Ma[2], Claire Berger[1,3], and •Walt de Heer[1,2] — [1]Georgia Institute of Technology, Atlanta USA — [2]TICNN, Tianjin China — [3]Neel Institute, CNRS, Grenoble, France

Recently reported measurements of epitaxial graphene nanoribbons grown on sidewalls etched in the 0001 face of h-SiC, Nature,506, 349, (2014) indicate that both spin and valley degeneracies are lifted, resulting in the observed 10 micron scale, temperature independent, single channel transport. These highly unusual properties were further investigated in SiC wavers that were cut at an angle to the 0001 face were prepared at the Tianjin International Center for Nanoparticles and Nanostructures. The wafers were graphitized and 10 micron scale top gated Hall bar structures were patterned using standard lithography methods. Magnetotransport measurements revealed striking transport properties. Single channel ballistic transport is observed even at the Dirac point. Moreover, an anomalous quantum Hall plateau is observed. Its anomalous value is caused by a quantized current that does not have a Hall effect, and that is in parallel with an equal current that does have a Hall effect. These properties are likely to be caused by edge currents, with energies that are pinned at the Dirac point. The ballistic transport is essentially temperature independent and consistent with that observed in sidewall ribbons. These results indicate that nonpolar epigraphene is a promising candidate for epigraphene nanoelectonics and important for Dirac point physics.

DS 21.7 Thu 11:45 H32

**Epitaxial growth of ferromagnetic semiconducting $CrBr_3$ monolayer** — •Weijiong Chen[1], Zeyuan Sun[1], Lehua Gu[1], Shiwei Wu[1,2], and Chunlei Gao[1,2] — [1]State Key Laboratory of Surface Physics, Key Laboratory of Micro and Nano Photonic Structures (MOE), Department of Physics, and Institute for Nanoelectronic Devices and Quantum Computing, Fudan University, Shanghai 200433, China — [2]Collaborative Innovation Center of Advanced Microstructures, Nanjing 210093, China

Recent discovery of two-dimensional (2D) ferromagnetic semiconducting materials greatly expands the family of 2D materials and invokes tremendous interests in novel magnetic related applications in 2D limit. Similar to most 2D materials, ferromagnetic 2D semiconductor is also firstly found in the mechanically exfoliated micrometer sized flakes, which hinders its further application. Here, we report the successful growth of ferromagnetic semiconducting monolayer $CrBr_3$ by compound source molecular beam epitaxy (CS-MBE). $CrBr_3$ compounds are directly evaporated onto the Highly Oriented Pyrolytic Graphite (HOPG) substrate and form $CrBr_3$ thin films with a precise thickness control. The atomic, electronic and magnetic properties were characterized by in-situ spin-polarized scanning tunneling microscopy. This growth method can be applied to other layered transition metal trihalides (LTMTs) as well, which provides a simple way of growing LTMTs for exploring their electronic and magnetic properties to the monolayer limit.

DS 21.8 Thu 12:00 H32

**Tuning the electronic properties of PbPb molecules by epitaxial graphene** — •T.T.Nhung Nguyen[1], U. Gerstmann[2], T.N.Ha Nguyen[1], and C. Tegenkamp[1,3] — [1]TU Chemnitz, Germany — [2]Universität Paderborn, Germany — [3]Leibniz Universität Hannover, Germany

Functionalization of graphene aimed for its application in nanoelectronics is an important step. Among a variety of surface tailoring methods, molecular self-assembly gives rise to precisely control their interface by choosing appropriate molecules, e.g. non-planar lead-phthalocyanine (PbPc). By means of scanning tunneling microscopy and density functional theory (DFT) we studied in detail the adsorption of PbPc on graphene/SiC(0001). Thereby, we used as template both n-doped monolayer (MLG) and neutral quasi-free monolayer graphene (QFML). On both surfaces PbPc forms almost identical monolayer structures, in agreement with DFT. Upon adsorption of the molecules, where the central atom points away from the surface, the benzene rings undergo pronounced distortions, where adjacent rings rotate and bend in opposite directions giving rise to a chiral single domain structure. Despite the same adsorption geometry, the molecular states of PbPc on these two surfaces are strongly shifted with respect to each other. First DFT results show that the negatively charged MLG is responsible for this effect.

**Invited Talk** DS 21.9 Thu 12:15 H32

**Intrinsic stacking domains in graphene on silicon carbide: A pathway for intercalation** — Tobias A de Jong[1], Eugene E Krasovskii[2], Christian Ott[3], Rudolf M Tromp[4,1], Sense Jan van der Molen[1], and •Johannes Jobst[1] — [1]Leiden Institute of Physics, Leiden, The Netherlands — [2]Universidad del Pais Vasco, San Sebastián/Donostia, Spain — [3]Lehrstuhl für Angewandte Physik, Universität Erlangen-Nürnberg, Erlangen, Germany — [4]IBM T. J. Watson Research Center, Yorktown Heights, USA

Graphene on silicon carbide (SiC) bears great potential for future graphene electronic applications because it is available on the wafer scale and its properties can be custom tailored by inserting various atoms into the graphene/SiC interface. It remains unclear, however, how atoms can cross the impermeable graphene layer during this widely used intercalation process. Here we demonstrate that in contrast to the current consensus, graphene layers grown in argon atmosphere on SiC are not homogeneous, but instead are composed of domains of different crystallographic stacking as they have been observed in other systems. We show that these domains are the AB and AC versions of Bernal stacking, that they are intrinsically formed during growth and that dislocations between domains dominate the (de)intercalation dynamics of hydrogen. Tailoring the resulting dislocation networks, e.g., through substrate engineering, will increase the control over the intercalation process and could open a playground for topological and correlated electron phenomena on the wafer scale.