

# TT 66: Graphene: Electronic Properties, Structure and Substrate Interaction I (joint session DY, DS, HL, MA, O, TT, organized by O)

Time: Thursday 10:30–13:00

Location: WIL A317

TT 66.1 Thu 10:30 WIL A317

**Charge Puddles in Graphene near the Dirac Point** — ●SAYANTI SAMADDAR<sup>1,2,3</sup>, INDRA YUDHISTIRA<sup>4</sup>, SHAFFIQUE ADAM<sup>4,5</sup>, HERVÉ COURTOIS<sup>2,3</sup>, and CLEMENS WINKELMANN<sup>2,3</sup> — <sup>1</sup>II. Physikalisches Institut, RWTH Aachen Otto-Blumenthal-Straße, Turm 28 D-52074 Aachen, Germany — <sup>2</sup>Université Grenoble Alpes, Institut NEEL, F-38042 Grenoble, France — <sup>3</sup>CNRS, Institut NEEL, F-38042 Grenoble, France — <sup>4</sup>Centre for Advanced 2D Materials and Department of Physics, National University of Singapore, 2 Science Drive 3, Singapore 117551, Singapore — <sup>5</sup>Yale-NUS College, 16 College Avenue West, Singapore 138527, Singapore

The charge carrier density in graphene on a dielectric substrate such as SiO<sub>2</sub> displays inhomogeneities, the so-called charge puddles. Because of the linear dispersion relation in monolayer graphene, the puddles are predicted to grow near charge neutrality, a markedly distinct property from conventional two-dimensional electron gases. By performing scanning tunneling microscopy/spectroscopy on a mesoscopic graphene device, we directly observe the puddles' growth, both in spatial extent and in amplitude, as the Dirac point is approached. Self-consistent screening theory, together with the consideration of the impact of the STM tip as an electric gate, provides a unified description of both the macroscopic transport properties and the microscopically observed charge disorder.

TT 66.2 Thu 10:45 WIL A317

**Ab-initio study of the effective Coulomb interactions and Stoner ferromagnetism in hydrogenated graphene** — ●ERSOY SASIOGLU<sup>1</sup>, HANIF HADIPOUR<sup>2</sup>, CHRISTOPH FRIEDRICH<sup>3</sup>, STEFAN BLÜGEL<sup>3</sup>, and INGRID MERTIG<sup>1</sup> — <sup>1</sup>Institut für Physik, Martin-Luther-Universität Halle-Wittenberg, D-06099 Halle (Saale) Germany — <sup>2</sup>Department of Physics, University of Guilan, 41335 Rasht, Iran — <sup>3</sup>Peter Grünberg Institut and Institute for Advanced Simulation, Forschungszentrum Jülich and JARA, 52425 Jülich, Germany

Hydrogenation provides a novel way to tune the electronic and optical properties of the graphene. Recent scanning tunneling microscopy experiments have demonstrated that local graphene magnetism can be selectively switched on and off by hydrogen dimers [1]. Employing *ab-initio* calculations in conjunction with the constrained random-phase approximation [2] we study the strength of the effective Coulomb interaction  $U$  in hydrogenated graphene. It is found that the calculated  $U$  parameters are smaller than the ones in pristine graphene and depend on the hydrogen concentration. Moreover, the  $U$  parameters are very sensitive to the position of hydrogen atoms adsorbed on the graphene lattice. We discuss the instability of the paramagnetic state towards the ferromagnetic one on the basis of calculated  $U$  parameters within the Stoner model. Spin-polarized calculations reveal that the experimentally observed itinerant ferromagnetism in hydrogenated graphene can be well described by the Stoner model.

- [1] H. González-Herrero *et al.*, Science **352**, 437 (2016).  
[2] E. Şaşıoğlu *et al.*, Phys. Rev. B **83**, 121101(R) (2011).

TT 66.3 Thu 11:00 WIL A317

**Characterization of CVD-grown graphene on germanium at the atomic scale** — ●ANDREAS P. BECKER, WOLFGANG M. KLESSE, MINDAUGAS LUKOSIUS, and THOMAS SCHROEDER — IHP microelectronics GmbH, Frankfurt (Oder), Germany

Graphene is a two-dimensional carbon allotrope where the atoms are arranged in a honeycomb lattice. Especially its extraordinarily high carrier mobility, plasmonic activity and impermeability make it a promising candidate for novel applications in microelectronics, such as high-frequency transistors, sensors and optical modulators.

Direct growth of graphene on silicon is hampered by the formation of covalent bonds. CVD growth of high-quality graphene on transition metal substrates and subsequent transfer of the sheets has proved feasible, however, tenacious metallic contamination obstructs its use in the front-end-of-line of CMOS technology.

As a resort, graphene can be grown on germanium buffer layers, which is one current research focus of the IHP. Specifically, samples grown in the cleanroom are already being routinely investigated by e.g. scanning electron microscopy (SEM) and Raman spectroscopy. But only scanning probe microscopy (SPM) allows to scrutinize graphene

layers at the atomic scale and can therefore be an essential complement to such established methods of quality assessment on larger scales.

Accordingly, I will present our latest results on the ex- and in-situ structural characterization of such gr/Ge structures by means of SPM depending on the growth parameters and post-growth annealing procedures.

TT 66.4 Thu 11:15 WIL A317

**Observation of photoemission "dark lines" for Ir(111) and graphene/Ir(111) via high-resolution ToF k-microscopy** — ●ANNA ZAPOROZHCHENKO-ZYMAKOVÁ<sup>1,2</sup>, DMYTRO KUTNYAKHOV<sup>1,3</sup>, KATERINA MEDJANIK<sup>1</sup>, CHRISTIAN TUSCHE<sup>4</sup>, OLENA FEDCHENKO<sup>1</sup>, SERGEY CHERNOV<sup>1</sup>, MARTIN ELLGUTH<sup>1</sup>, SERGEJ A. NEPIJKO<sup>1</sup>, HANS-JOACHIM ELMERS<sup>1,2</sup>, and GERD SCHÖNHENSE<sup>1,2</sup> — <sup>1</sup>Inst. für Physik, Univ. Mainz — <sup>2</sup>MAINZ graduate school — <sup>3</sup>DESY, Hamburg — <sup>4</sup>PGI-6, Forschungszentrum Jülich

ToF k-microscopy [1,2] has been used to analyze emergent photoelectron diffraction effects for UHV/Ir(111) and graphene/Ir(111). We observed a regular pattern of dark lines with circular shape and six-fold symmetry that have been overlooked in previous experiments. Quantitative evaluation along with a model calculation reveals that electrons initially located within the first Brillouin zone can with finite probability be scattered by a reciprocal lattice vector into a state that propagates parallel to the surface. Such electrons vanish due to inelastic scattering events in the vicinity of the surface. This leads to a reduced intensity observed as dark lines. The relevant reciprocal lattice vector corresponds to the lattice of the topmost layer (in our case Ir or graphene). The dark lines appear in a certain photon energy range satisfying the congruence of lattice constant and wavelength. The parallel momentum of the dark lines decreases with increasing photon energy in agreement with the model. The effect has been observed with both p- and s-polarized light at BESSY II (10m NIM). [1] Chernov *et al.*, Ultramic. **159**, 453 (2015); [2] Tuschke *et al.*, APL **108**, 261602 (2016).

TT 66.5 Thu 11:30 WIL A317

**Landau Level Spectroscopy of Twisted Graphene Layers on Ir(111)** — ●SABINA SIMON<sup>1</sup>, FELIX FÖRSCHNER<sup>1</sup>, VIVIEN ENENKEL<sup>1</sup>, FABIAN GEML<sup>1</sup>, YURIY DEDKOV<sup>1</sup>, TIMO KNISPEL<sup>2</sup>, CHARLOTTE HERBIG<sup>2</sup>, THOMAS MICHELY<sup>2</sup>, and MIKHAIL FONIN<sup>1</sup> — <sup>1</sup>Department of Physics, University of Konstanz, 78457 Konstanz, Germany — <sup>2</sup>Institute of Physics II, University of Köln, 50937 Köln, Germany

Epitaxial growth on metal substrates is known to be one of the most powerful approaches in producing large-scale, high-quality, monolayer graphene. Yet it remains a major challenge to realize the growth of multilayers.

This work is devoted to the investigation of multilayered graphene systems epitaxially grown on a transition metal, namely Ir(111). We address the growth and the structure of large scale twisted graphene bilayers by intercalation of atomic carbon under graphene on Ir(111). We show that the intercalated graphene buffer layer provides sufficient decoupling from the metal substrate, giving a possibility to access the local electronic properties of graphene by means of Landau level spectroscopy. We further discuss the influence of the twist angle on the local electronic properties of the top graphene layer, upon the analysis of the doping level, Fermi velocity of charge carriers, and quasiparticle lifetimes.

TT 66.6 Thu 11:45 WIL A317

**Epitaxial growth of graphene via flash annealing of SiC studied by STM, AFM and LEED** — ●ISMAIL BALTACI, MALTE SCHULTE, EUGENIA WODOPIAN, PATRICK MEHRING, and CARSTEN WESTPHAL — Experimentelle Physik 1, TU Dortmund, Otto-Hahn-Straße 4, 44227 Dortmund

Due to its unique electronic and structural properties graphene is of particular interest for the semi-conductor industry, e.g. as a new material in transistor applications.

In this study we concentrate on an epitaxial growth based on cyclic heating of SiC by direct current, known as flash annealing. In order to yield large and homogeneous graphene layers multiple parameters have to be taken into account such as heating and cooling rates as well as the number of heating cycles.

Determining the number of graphene layers on SiC is achieved by utilizing Scanning Tunneling Microscopy (STM), Atomic Force Microscopy (AFM) and Low Energy Electron Diffraction (LEED). Especially the structural differences between buffer layer and graphene is visualized by STM and LEED measurements. Furthermore, we report on the growth mechanism of graphene.

TT 66.7 Thu 12:00 WIL A317

**Surface-assisted self-assembly of graphene nanoribbons** — ●AXEL ENDERS<sup>1,2</sup>, PAULO COSTA<sup>2</sup>, JACOB TEETER<sup>2</sup>, DANIEL MILLER<sup>3</sup>, EVA ZUREK<sup>3</sup>, and ALEXANDER SINITSKII<sup>2</sup> — <sup>1</sup>Experimentalphysik Va, Universität Bayreuth — <sup>2</sup>University of Nebraska, Lincoln NE 68588, USA — <sup>3</sup>State University of New York at Buffalo, Buffalo 14260, USA

The physical properties of graphene are sensitive to the presence of structural defects, dopants and edges. This creates opportunities to design an electronic bandgap in graphene, which is most consequently exploited in graphene nanoribbons (GNRs), which have edges that are amenable to structural and chemical modification. It is shown that surface-assisted self-assembly is a powerful strategy to build GNRs from the bottom up. As in solution-based self-assembly, also on surfaces the edge structure and chemistry of GNRs is determined by the precursor molecules. But on surfaces the substrate itself can be a control parameter during growth, as can be the method of deposition. Specifically here the self-assembly of 6,11-dibromo-1,2,3,4-tetraphenyltriphenylene and related, appropriately modified precursor molecules was studied on Au(111) and on Cu(111) surfaces. The precursors were deposited under ultrahigh vacuum by two different methods for comparison, which are thermal evaporation and nanoimprinting. Among the significant findings of these studies are the substrate-dependent epitaxial alignment of the ribbons, considerably lower dehalogenation temperatures on Cu(111), and entirely different GNR architectures that can emerge from the same precursors under different conditions.

TT 66.8 Thu 12:15 WIL A317

**Lifting Graphene by Alkali Intercalation** — ●CAIO SILVA<sup>1</sup>, JIAQI CAI<sup>1</sup>, WOUTER JOLIE<sup>2</sup>, DANIELA DOMBROWSKI<sup>1,2</sup>, FERDINAND FARWICK ZUM HAGEN<sup>2</sup>, ANTONIO MARTÍNEZ-GALERA<sup>2</sup>, CHRISTOPH SCHLUETER<sup>3</sup>, TIEN-LIN LEE<sup>3</sup>, and CARSTEN BUSSE<sup>1,2</sup> — <sup>1</sup>Institut für Materialphysik, Münster, Germany — <sup>2</sup>II. Physikalisches Institut, Köln, Germany — <sup>3</sup>Diamond Light Source Ltd, Didcot, United Kingdom

Intercalation is a versatile tool to tune the properties of graphene grown epitaxially on metal surfaces. Especially alkali metals are efficient to decouple graphene from its substrate and, in addition, induce a strong n-doping on graphene.

In the present work, we used the x-ray standing wave (XSW) technique to compare the structures resulting from intercalation of a small (Li) and a rather large (Cs) alkali metal between graphene and Ir(111). We noted an opposing behavior during deintercalation: In the case of Cs, different phases  $[(\sqrt{3} \times \sqrt{3})R30^\circ_{Ir}, (2 \times 2)_{gr}]$  coexist, each with a characteristic height of graphene with respect to Ir(111), as revealed by XSW. In the case of Li, however, we find just a single phase of gr/Li/Ir(111) for a wide range of intercalant coverage (1 - 0.2 ML), with a distance between the graphene sheet and the metal surface that is independent on the amount of Li intercalated in be-

tween. We explain the contrast between Li and Cs by differences in the delamination energy that has to be paid in order to intercalate the different species.

TT 66.9 Thu 12:30 WIL A317

**Giant magneto-photoelectric effect at a graphene edge** — ●FRIEDEMANN QUEISSER, RALF SCHÜTZHOLD, JENS SONNTAG, ANNIKA KURZMANN, MARTIN GELLER, and AXEL LORKE — Fakultät für Physik, Universität Duisburg-Essen, Lotharstraße, Duisburg 47048, Germany

Graphene is a promising material for optical or infrared absorption, as its pseudo-relativistic energy-momentum relation allows for a broad absorption bandwidth. An efficient charge separation can be achieved at a graphene edge in a magnetic field. By solving the Dirac equation, it can be shown that particles and holes move in antipodal directions along the edge [1]. Motivated by the proposed mechanism, an surprisingly high magneto-photocurrent has been measured in suspended graphene [2]. The observed photoresponsivity (100 incident photons create up to 17 particle-hole pairs) strongly exceeds the predicted value. A possible mechanism to explain the amplification of the magneto-photoeffect relies on the strong Coulomb interaction in graphene: Due to the huge effective fine-structure constant ( $\alpha_{\text{graphene}} \gg \alpha_{\text{QED}}$ ) and the enlarged phase space at the graphene edge, inelastic (Auger-type) scattering amplifies the magneto-photocurrent.

[1] F. Queisser and R. Schützhold *Phys. Rev. Lett.* **111**, 046601 (2013)

[2] J. Sonntag, A. Kurzmann, M. Geller, F. Queisser, A. Lorke, R. Schützhold, arXiv:1505.01762

TT 66.10 Thu 12:45 WIL A317

**Magnetism in graphene induced by transition metal and rare earth atomic layers** — ●VASILE CACIUC, NICOLAE ATODIRESEI, and STEFAN BLÜGEL — Peter Grünberg Institut (PGI-1) and Institute for Advanced Simulation, Forschungszentrum Jülich and JARA, Germany

On the Ir(111) surface graphene is physisorbed with a local chemical modulation [1] whose structural and electronic properties can be engineered via atomic intercalation [2,3,4] or molecular adsorption [5,6]. In particular, our *ab initio* density functional theory (DFT) simulations performed for 3d transition metal (TM) atoms such as Co [3] and Fe [4] intercalated at the interface between graphene and Ir(111) clearly demonstrated that the graphene layer exhibits a spin-split electronic structure. On the other hand, the strong hybridization between the  $\pi$  electronic states of graphene and the  $d$  ones of the TM monolayer significantly changes the magnetic properties of the intercalated atoms. Moreover, we investigated if this physical picture remains valid also in the case of the rare earth (RE) atoms with spatially localized magnetic moments such as 4f Eu intercalated between graphene and the Ni(111) surface.

This work is supported by DFG through SFB 1238 (Project C01).

[1] C. Busse *et al.*, *Phys. Rev. Lett.* **107**, 036101 (2011).

[2] W. Jolie *et al.*, *Phys. Rev. B* **89**, 155435 (2014).

[3] R. Decker *et al.*, *Phys. Rev. B* **87**, 041403(R) (2013).

[4] R. Decker *et al.*, *J. of Phys.: Cond. Matter.* **26**, 394004 (2014).

[5] R. Brede *et al.*, *Nature Nanotech.* **9**, 1018 (2014).

[6] F. Huttmann *et al.*, *Phys. Rev. Lett.* **115**, 236101 (2015).