HL 76: Graphene: Electronic properties (organized by O)

Time: Wednesday 16:00–19:15 Location: WIL C107

HL 76.1 Wed 16:00 WIL C107

Monomer Doping of Self-Assembled Graphene Nanoribbons for Band Gap Alignment — •Christopher Bronner[1,3], Stephan Stremlau[1,3], Marie Gille[2], Felix Brausse[2], Anton Haase[1], Stefan Hecht[2], and Petra Tegeder[1,3] — [1]Freie Universität Berlin — [2]Humboldt-Universität zu Berlin — [3]Ruprecht-Karls-Universität Heidelberg

In order to exploit the technologically interesting electronic properties of graphene, several concepts have been discussed which would lead to the opening of a band gap. One approach is spatial confinement of the charge carriers in quasi-one-dimensional graphene nanoribbons (GNRs). The band gap of a GNR scales inversely with its width and particularly nanometer-scale widths are desirable for application e.g. in transistor devices. Since the electronic properties of GNRs depend critically on their structure, precise synthesis is necessary but challenging for conventional methods such as lithography. In contrast, self-assembly from molecular precursors is an intriguing approach which has been employed to fabricate defect-free GNRs with well-defined widths and edge structures. Only this high level of structural precision allows introduction of dopant atoms at specific doping sites and concentrations in the graphene lattice. Nitrogen doping has been known to shift the band structure of GNRs with respect to the Fermi level which is interesting for GNRs in contact with electrodes and other device materials. Using surface-sensitive electron spectroscopies we demonstrate a continuous down-shift of the band structure with increased nitrogen doping of the monomers.

HL 76.2 Wed 16:15 WIL C107

Transport in chemically gated graphene p-n junctions — •Jens Baringhaus[1], Alexander Stöhr[2], Ulrich Starke[2], and Christoph Tegenkamp[1] — [1]Leibniz Universität Hannover, Institut für Festkörperphysik, 30167 Hannover, Germany — [2]Max-Planck Institut für Festkörperforschung, 70569 Stuttgart, Germany

The chirality of charge carriers in graphene allows them to get through potential barriers without any reflection (known as Klein tunneling). To study this effect the fabrication of well-defined p-n junctions is necessary. We use the intercalation of Ge to convert the buffer layer on the SiC(0001) surface into graphene with local p-type or n-type doping depending on the local Ge coverage. The buffer layer is initially patterned using optical lithography, to fabricate isolated n-p, n-p-n and p-n-p structures. The n- and p-type doping (340 meV, -290 meV) is confirmed by STS which also reveals very narrow p-n junctions with a length below 5 nm. The corresponding electric fields are as high as 10^6 V/cm and therefore significantly higher than those induced by field effects, providing a perfect environment to study Klein tunneling. Transport experiments are carried out by means of a 4-tip STM system, on n-p-n as well as p-n-p structures. Their resistance was found to be strongly dependent on temperature and the inner barrier length. While short barriers (< 200 nm) appear almost transparent, the resistance increases rapidly for barrier widths exceeding the coherence length (> 600 nm). The resistance of a single p-n junction fits to the theoretically predicted value for a Klein tunneling junction.

HL 76.3 Wed 16:30 WIL C107

Exceptional ballistic transport in epitaxial graphene nanoribbons — Jens Baringhaus[1], Frederik Edler[1], Claire Berger[2], Walter A. de Heer[2], and •Christoph Tegenkamp[1] — [1]Leibniz Universität Hannover, Institut für Festkörperphysik, 30167 Hannover, Germany — [2]Georgia Institute of Technology, Atlanta, Georgia 30332-0430, USA

The patterning of graphene into graphene nanoribbons is an essential task for the development of graphene based devices. For such ribbons with a well-ordered edge geometry the presence of one-dimensional edge states has been predicted. We use a selective graphitization process on SiC-mesa structures to produce graphene nanoribbons with a width of 40 nm. The local electronic properties of the ribbons are investigated by means of a 4-tip STM. In combination with a SEM, the precise positioning of all four tips on the nanometer range is possible to perform local transport measurements. Additionally, local tunneling spectroscopy reveals characteristic features of ferromagnetic zig-zag graphene nanoribbons. Transport experiments carried out on the very same ribbon show a conductance close to e^2/h for a wide temperature range from 30 K up to room temperature and probe spacings between 1 μm and 10 μm. Description within the Landauer formalism is possible assuming ballistic transport dominated by a single channel. Transport in the second zeroth subband is only detectable for probe spacings smaller than 1 μm due to the short localization length of carriers in this subband manifesting in the increase of the conductance to 2 e^2/h at probe spacings below 200 nm.

HL 76.4 Wed 16:45 WIL C107

Electrical Transport in Freestanding Epitaxial Graphene: Evidence of an AB-Stacked Bilayer — •Johannes Jobst[1,2], Shriram Shivaraman[3], Michael G. Spencer[3], and Heiko B. Weber[2] — [1]Leiden University, Kamerlingh Onnes Laboratorium, P.O. Box 9504, NL-2300 RA Leiden, Netherlands — [2]Lehrstuhl für Angewandte Physik, Universität Erlangen-Nürnberg, 91058 Erlangen, Germany — [3]School of Electrical and Computer Engineering, Cornell University, Ithaca, NY 14853, USA

We investigate the properties of freestanding epitaxial graphene devices, which are created using a photo-electrochemical etching technique. This technique allows to selectively remove the silicon carbide (SiC) substrate on which the graphene was grown by thermal decomposition of SiC. We focus on completely freestanding devices of various geometries and devoid of any graphene-substrate interactions. We prepare freestanding Hall bars in order to study the low-temperature transport and Shubnikov-de Haas oscillations. We find evidence that the buffer layer is transformed to an additional graphene layer upon the etching process, and that the formed bilayer is AB stacked. Inhomogeneities in the buffer layer or introduced during the etching process are discussed.

HL 76.5 Wed 17:00 WIL C107

Scattering mechanisms in Tl-doped epitaxial graphene — •Carola Strasser[1], Bart Ludbrook[2], Andrea Damascelli[2], Christian R. Ast[1], and Klaus Kern[1,3] — [1]Max Planck Institute for Solid State Research, 70569 Stuttgart, Germany — [2]Quantum Matter Institute, UBC, Vancouver, BC V6T 1Z4, Canada — [3]Ecole Polytechnique Fédérale de Lausanne, 1015 Lausanne, Switzerland

Since the charge carrier density in graphene can very easily be tuned by means of chemical doping this approach counts as a promising way to design graphene-based future electronic devices. It was shown [1] that the Fermi level can be shifted over a wide range in either direction. But one has to consider that the dopants do not just donate or take the electrons but they have an impact on the electronic structure: they act as scattering centres and change the charge carrier mobility.

We investigated small amounts of Thallium atoms on a monolayer of epitaxial graphene by angular resolved photoemission spectroscopy and did a careful analysis of the line width. Although Tl is very weakly bound and at first sight a paradigm long-range scatterer, we found that it introduces a sizeable short-range contribution. Only by using a model which combines both, long-range and short-range scattering we were able to describe our observations. This allowed us to put an upper limit on the dielectric constant for Tl-doped epitaxial graphene.

[1] H. Liu et al., *J. Mater. Chem.* **21**, 3335 (2011)

HL 76.6 Wed 17:15 WIL C107

Excited electron dynamics in spatially aligned 7a-graphene nanoribbons on Au(788) — •Nils Fabian Kleimeier[1], Alexander Timmer[1], Harry Mönig[1], Xinliang Feng[2], Klaus Müllen[2], Harald Fuchs[1], and Helmut Zacharias[1] — [1]Physikalisches Institut, Universität Münster, Wilhelm-Klemm-Str. 10, 48149 Münster, Germany — [2]Max-Planck-Institute for Polymer Research, Ackermannweg 10, 55128 Mainz, Germany

Photoelectron spectroscopy of spatially aligned straight 7-armchair graphene nanoribbons (7-aGNRs) on Au(788) was carried out under ultra high vacuum conditions utilizing a time-of-flight spectrometer and a multi-anode detector. We found two unoccupied states at energies of E_1=3.6 eV and E_2=3.9 eV above the Fermi energy by exciting the sample with different photon energies (3.94 eV to 4.35 eV) from a femtosecond OPA. When exciting the sample with ultrashort pules (20 fs) at λ=390 nm ($h\nu$=3.15 eV) by frequency- doubling the output of a femtosecond Ti:sapphire laser amplifier, these states can further be investigated by 3-photon photoemission using a third state at an energy of

E_3-E_F=0.6 eV as intermediate. All three states are in agreement with IPE measurements we performed previously on this system [1]. Thus the electronic dynamics of the state can be measured by time-resolved 3-photon photoemission spectroscopy with cross-polarized laser pulses. Preliminary evaluation of these measurements indicates electronic lifetimes of the unoccupied states of τ ∼110 fs and 85 fs for the states at E-E_F 3.9 eV and 3.6 eV, respectively.

References: [1] S. Linden et al., Phys. Rev. Lett. 108 (2012) 216801

HL 76.7 Wed 17:30 WIL C107

Optical characterization of atomically precise graphene nanoribbons — •Richard Denk[1], Michael Hohage[1], Jinming Cai[2], Pascal Ruffieux[2], Roman Fasel[2], and Peter Zeppenfeld[1] — [1]Experimental Physics, JKU Linz, Altenbergerstrasse 69, 4040 Linz, Austria — [2]nanotech@surfaces, EMPA, Überlandstasse 129, 6800 Dübendorf, Switzerland

Graphene nanoribbons (GNRs) promise high potential for future nanoscale electronic devices. While 2-dimensional graphene is semimetallic, electron confinement and edge effects in narrow (<10nm) GNRs can result in the opening of a band gap. The electronic and optical properties, however, strongly depend on the structural details of the GNRs. Only recent advances in the bottom-up fabrication of atomically precise GNRs [1] have enabled reliable experimental investigations of well-defined GNRs.

We have studied the fabrication process and the optical properties of GNRs on Au(788) using reflectance difference spectroscopy (RDS), taking advantage of the optical anisotropy due to the uniaxial alignment of the GNRs parallel to the step edges of the vicinal Au(788) surface. We find that the optical properties of the GNRs are highly anisotropic and dominated by three excitonic transitions, in excellent agreement with theoretical calculations.

[1] J. Cai at el, Nature, 466 (2010) 470.

HL 76.8 Wed 17:45 WIL C107

Electronic and transport properties of BNC heterostructures, a first-principles investigation. — •Simon Dubois and Jean-Christophe Charlier — Institute of Condensed Matter and Nanosciences, UCL, Louvain-La-Neuve, Belgium

Two dimensional hexagonal BN (h-BN), an isomorph of graphene with a lattice mismatch of only 1 .7%, is a wide gap insulator as its bulk counterpart. Advances in the synthesis of hybrid BNC heterostructures offer new opportunities to engineer the electronic properties of low-dimensional systems. Recently, it has been shown that the introduction of h-BN nanodomains into graphene enables to induce a tunable band gap in the honeycomb lattice. Lateral junctions between electrically conductive graphene and insulating h-BN provide new ways to embed electrically isolated elements within single atomic layers. Not only the two-dimensional BNC heterostructures hold promises for new applications but also the corresponding quasi-1D nanoribbons as well as the few layers structures obtained by plane stacking.

We report on the properties of low energy carriers in various kind of BNC heterostructures investigated by means of first-principles calculations: quasi one dimensional junctions made of h-BN and graphene ribbons, two-dimensional atomic layers made of hybridized domains, as well as few-layers stacks.

HL 76.9 Wed 18:00 WIL C107

Time- and Angle-Resolved Photoemission Studies of Epitaxial Graphene — •Søren Ulstrup[1], Jens C. Johannsen[2], Federico Cilento[3], Alberto Crepaldi[3], Michele Zacchigna[3], Jill A. Miwa[1], Philip D. C. King[4], Cephise Cacho[5], Edmond Turcu[5], Emma Springate[5], Felix Fromm[6], Christian Raidel[6], Thomas Seyller[6], Fulvio Parmigiani[3], Marco Grioni[2], and Philip Hofmann[1] — [1]Aarhus University, Aarhus, Denmark — [2]EPFL, Lausanne, Switzerland — [3]Sincrotrone Trieste, Trieste, Italy — [4]University of St. Andrews, St. Andrews, United Kingdom — [5]STFC Rutherford Appleton Laboratory, Didcot, United Kingdom — [6]Technical University of Chemnitz, Chemnitz, Germany

Understanding of the ultrafast carrier dynamics in graphene is of central importance for many electronic and optoelectronic applications. With the advent of high harmonic laser-based time- and angle-resolved photoemission (TR-ARPES) it is possible to gain a direct view of the non-equilibrium electronic structure around the Dirac point in graphene with femtosecond time resolution. Here, we characterize the dynamic processes around the Dirac point in epitaxial graphene using TR-ARPES measurements. In particular, we study the time-scales and significance of hot electron thermalization processes and electron-phonon coupling, and address the possibility of carrier multiplication.

HL 76.10 Wed 18:15 WIL C107

Electronic and Transport Properties of Epitaxial Graphene on the Atomic Scale — •Philip Willke[1], Thomas Druga[1], Alexander Schneider[2], Rainer Ulbrich[1], and Martin Wenderoth[1] — [1]IV. Physikalisches Institut, Georg-August Universität Göttingen, Germany — [2]Lehrstuhl für Festkörperphysik, FAU Erlangen, D-91058, Germany

The application of graphene in future devices requires a thorough understanding of its transport properties on the nanometer scale. We present a scanning tunneling potentiometry study at 6 K of electron scattering in mono- and bilayer graphene on n-doped SiC. Using STP we combine the imaging of local transport fields and sample topography. By probing simultaneously the thermovoltage signal [1] created due to slightly different temperatures of sample and tip, we can moreover obtain sensitive information on the electronic structure at the Fermi energy. We demonstrate how both transport and electronic information can be disentangled from STP measurements. We identify substrate steps and monolayer-bilayer junctions as local scattering centers which impede the electronic current and create local voltage drops that we compare to recent measurements at 72 K. [2] Moreover, wrinkles and substrate inhomogeinities have been identified as further sources of scattering. We acknowledge the financial support by the SPP 1459 "Graphene".

[1] K. J. Engel, M. Wenderoth, N. Quaas, T. Reusch, K. Sauthoff and R.Ulbrich, Phys. Rev. B 63, 165402 (2001)

[2] S. H. Ji et al., Nature Materials 11, 114-119 (2012)

HL 76.11 Wed 18:30 WIL C107

Exchange coupling between 3*d*-transition metal adatoms and Ni(111) mediated by graphene — •Simon Fichtner, Paolo Ferriani, and Stefan Heinze — Institut für Theoretische Physik und Astrophysik, Christian-Albrecht-Universität zu Kiel, D-24098 Kiel, Germany

Recently, 3*d*-transition metal (TM) adatoms on graphene have been intensively studied both experimentally (e.g. [1]) and theoretically (e.g. [2]). However, the possibility to stabilize their magnetic moment by exchange coupling to an underlying magnetic substrate has received little attention so far. Graphene on Ni(111) is a very good candidate in this respect as it has been experimentally shown to grow pseudomorphically. Here, we determine the electronic and magnetic properties of 3*d*-TM adatoms adsorbed on graphene on Ni(111) based on density functional theory as implemented in the VASP code. We perform a systematic study on the dependence of the exchange interaction across the 3*d*-TM series and take local correlations into account using the DFT+U formalism. We demonstrate the essential influence of the alignment of the adatoms 3d-states with the spin-polarized graphene states on the magnetic coupling with the Ni surface.

[1] Eelbo et al., Phys. Rev. Lett. **110**, 136804, 2013

[2] Wehling et al., Phys. Rev. B **84**, 235110, 2011

HL 76.12 Wed 18:45 WIL C107

Highly spin-polarized Dirac fermions at the graphene-Co interface — •Dmitry Marchenko[1,2], Andrei Varykhalov[1], Jaime Sánchez- Barriga[1], and Oliver Rader[1] — [1]Helmholtz-Zentrum Berlin für Materialien und Energie, Berlin, Germany — [2]Physikalische und Theoretische Chemie, Freie Universität Berlin, Berlin, Germany

The interface of graphene with ferromagnets is very interesting for spintronics due to possible use of peculiar graphene electronic structure in transport and spin-filter applications when graphene is used together with nickel or cobalt as ferromagnetic contacts for spin injection and detection [1]. Despite a strong hybridization between graphene and ferromagnetic substrate states the graphene Dirac cone was observed by angle-resolved photoemission without gap between pi and pi* parts [2]. Here we report strong spin polarization of the Dirac cone measured by spin- and angle-resolved photoemission. Wave-vector dependent measurements exclude a Rashba-type spin-orbit contribution to the spin polarization; ferromagnetic origin is verified by reversal of the remanent magnetization. The importance of the spin polarization at the interface for spin filtering is pointed out.

[1] V. M. Karpan et al., Phys. Rev. Lett. 99, 176602 (2007) [2] A. Varykhalov et al., Phys. Rev. X 2, 041017 (2012)

HL 76.13 Wed 19:00 WIL C107

Controlling and understanding the non-linear photoluminescence in graphene on a femtosecond time scale —

•Richard Ciesielski[1], Alberto Comin[1], Matthias Handloser[1], Kevin Donkers[1], Torben Winzer[2], Ermin Malic[2], and Achim Hartschuh[1] — [1]Ludwig Maximilians Universität München & CeNS — [2]TU Berlin

Upon excitation, graphene exhibits nonlinear photoluminescence [1-3] that reflects the charge-carrier population and relaxation around the K-point. We present microscopic measurements on high quality exfoliated graphene samples with a pulsed laser system of ca. 18fs and a broad spectrum centred at 800nm.

Using a pulse shaping setup we can measure and manipulate the incident pulse in amplitude and phase. We find that the PL intensity depends sensitively on the temporal shape of the laser pulse, which we use to study and control the charge-carrier relaxation processes of graphene. Our findings are compared to numerical calculations.

[1] Stöhr, Wachtrup, Phys. Rev. B 82, 121408(R) (2010)
[2] Malic, Winzer, Bobkin, Knorr, Phys. Rev. B 84, 205404 (2011)
[3] Malic, Knorr, John Wiley & Sons (2013)