# HL 102: Transport: Graphene 2 (jointly with TT, MA, DY, DS, O)

Time: Friday 9:30–12:45 Location: BH 334

HL 102.1 Fri 9:30 BH 334

**Transport study of graphene with artificially induced defects** — •Verena Martin, Johannes Jobst, Michael Krieger, and Heiko B. Weber — Lehrstuhl für Angewandte Physik, Universität Erlangen-Nürnberg, Staudtstr. 7, 91058 Erlangen

We report on transport properties of ion irradiated graphene which is grown epitaxially on 6H semi-insulating silicon carbide (SiC) substrate. We investigate both monolayer graphene [1] and quasi-free standing epitaxial graphene [2]. Subsequent irradiation steps of argon and carbon ions with different ion energies into the graphene/SiC stack are performed at low temperature (4K) and room temperature. The resistivity of the graphene layer is monitored in situ. After each irradiation step temperature dependent measurements and magnetoresistance measurements are performed to study the effect of the damage. An increase of resistivity with decreasing temperature as well as a broadening of the weak localization peak could be correlated to an increase of the defect amount.

[1] K. Emtsev et al., Nat. Mater. **8**, 203 (2009)
[2] C. Riedl et al., Phys. Rev. Lett. **103**, 246804 (2009)

HL 102.2 Fri 9:45 BH 334

**Inelastic Raman scattering on electronic excitations in graphene and carbon nanotubes** — •Oleksiy Kashuba[1] and Vladimir Fal'ko[2] — [1]Institut für Theorie der statistischen Physik, RWTH Aachen, 52056 Aachen, Deutschland — [2]Department of Physics, Lancaster University, Lancaster, LA1 4YB, UK

Raman measurements in carbon allotropes are generally associated with the exploration of the vibrational modes. We present a theory of the non-resonant inelastic light scattering accompanied by the excitations of electron-hole pairs and predict the selection rules and polarization properties of the dominant Raman active modes. The prediction of the Raman plot profile for graphene at high magnetic field with pronounced peaks corresponding to the inter-Landau-level transitions [1,2] was confirmed by subsequent experiment [3]. We also provide a theory of Raman scattering on intersubband electron-hole pairs in large diameter carbon nanotubes predicting dominant polarisations and Raman spectra featuring a pattern of van Hove singularities [4].

[1] O. Kashuba and V. I. Fal'ko, Phys. Rev. B 80, 241404(R) (2009).
[2] M. Mucha-Kruczyński, O. Kashuba, and V. I. Fal'ko, Phys. Rev. B 82, 045405 (2010).
[3] C. Faugeras et. al., Phys. Rev. Lett. 107, 036807 (2011).
[4] O. Kashuba and V. I. Fal'ko, submitted to PRL (2011), arXiv:1111.1413

HL 102.3 Fri 10:00 BH 334

**Transport in clean side-gated graphene nanoribbons** — •Bernat Terrés[1,2], Jan Dauber[1,2], Uwe Wichmann[1], Stefan Trellenkamp[2], and Christoph Stampfer[1,2] — [1]JARA-FIT and II. Institute of Physics B, RWTH Aachen, 52074 Aachen, Germany — [2]Peter Grünberg Institut (PGI-8/9), Forschungszentrum Jülich, 52425 Jülich, Germany

Graphene is a two dimensional form of crystalline carbon with unique electrical properties. However, due to its gap-less nature it is hardly possible to implement concepts of state-of-the-art electronic devices. Recently, it has been shown that by tailoring graphene into narrow ribbons an effective band gap can be induced. Extensive studies have been reported on the transport mechanism in graphene nanoribbons and although being successfully demonstrated as tunneling barriers in quantum dots, graphene nanoribbons show a Coulomb blockade dominated transport behavior. In this work we report on the effects of a symmetrically applied side gate voltage on clean (hydrofluoric acid treated) graphene nanoribbons. In particular we show low-temperature experiments where the overall conductance can be tuned up to a level of about $8e^2/h$. Measurements show evidence that the local resonances in the transport gap can be strongly suppressed by adjusting the side-gate voltages. In summary, the high conductance values together with the observation of onsets of quantized conductance plateaus at integer multiples of $2e^2/h$ indicates that the disorder potential can be dramatically reduced, even though the transport mechanism is still mainly dominated by substrate and rough-edge induced disorder.

HL 102.4 Fri 10:15 BH 334

**Coulomb drag in graphene: perturbation theory** — •Boris Narozhny[1], Michael Titov[2,3], Igor Gornyi[3,4], and Pavel Ostrovsky[3,5] — [1]Institut für Theorie der Kondensierten Materie, Karlsruher Institut für Technologie, 76128 Karlsruhe, Germany — [2]School of Engineering and Physical Sciences, Heriot-Watt University, Edinburgh EH14 4AS, UK — [3]Institut für Nanotechnologie, Karlsruher Institut für Technologie, 76021 Karlsruhe, Germany — [4]A.F. Ioffe Physico-Technical Institute, 194021 St. Petersburg, Russia — [5]L.D. Landau Institute for Theoretical Physics RAS, 119334 Moscow, Russia

We study the effect of Coulomb drag between two closely positioned graphene monolayers. In the limit of weak electron-electron interaction and small inter-layer spacing $d$ ($\mu_{1(2)}, T \ll v/d$) the drag is described by a universal function of the chemical potentials of the layers $\mu_{1(2)}$ measured in the units of temperature $T$. When both layers are tuned close to the Dirac point, then the drag coefficient is proportional to the product of the chemical potentials $\rho_D \propto \mu_1\mu_2$ (when any of the layers is precisely at the Dirac point, then the drag vanishes due to electron-hole symmetry). In the opposite limit of low temperature the drag is inversely proportional to both chemical potentials $\rho_D \propto T^2/(\mu_1\mu_2)$. In the mixed case where the chemical potentials of the two layers belong to the opposite limits $\mu_1 \ll T \ll \mu_2$ we find $\rho_D \propto \mu_1/\mu_2$. In the case of strongly doped graphene $\mu_{1(2)} \gg v/d \gg T$ the drag coefficient acquires additional dependence on $d$ and we recover the usual Fermi-liquid result if the screening length is smaller than $d$.

HL 102.5 Fri 10:30 BH 334

**Dirac boundary condition at the reconstructed zigzag edge of graphene** — Jan van Ostaa, Anton Akhmerov, Carlo Beenakker, and •Michael Wimmer — Instituut-Lorentz, Universiteit Leiden, The Netherlands

Edge reconstruction modifies the electronic properties of finite graphene samples. We formulate a low-energy theory of the reconstructed zigzag edge by deriving the modified boundary condition to the Dirac equation. If the unit cell size of the reconstructed edge is not a multiple of three with respect to the zigzag unit cell, valleys remain uncoupled and the edge reconstruction is accounted for by a single angular parameter $\vartheta$. Dispersive edge states exist generically, unless $|\vartheta| = \pi/2$. We compute $\vartheta$ from a microscopic model for the "reczag" reconstruction (conversion of two hexagons into a pentagon-heptagon pair) and show that it can be measured via the local density of states. In a magnetic field there appear three distinct edge modes in the lowest Landau level, two of which are counterpropagating.

HL 102.6 Fri 10:45 BH 334

**Dielectric properties of graphene in the presence of spin-orbit interactions** — •Andreas Scholz[1], John Schliemann[1], and Tobias Stauber[2] — [1]Institute for Theoretical Physics, University of Regensburg, 93040 Regensburg, Germany — [2]Departamento de Fisica de la Materia Condensada and Instituto Nicolas Cabrera, Universidad Autonoma de Madrid. E-28049 Madrid. Spain

We study the dielectric function of graphene in the presence of pseudo-Rashba and intrinsic spin-orbit interactions (SOI) for arbitrary frequency, wave vector, doping, and spin-orbit coupling (SOC) parameters. In the static limit, the asymptotic behavior of the screened potential due to charged and magnetic impurities is derived. Due to the existence of a sharp Fermi surface in doped graphene, the screened potential exhibits characteristic (Friedel) oscillations. These oscillations are absent in the undoped case. An analytical expression for the plasmon dispersion is derived from the long-wavelength limit of the dielectric function and afterwards compared to the numerical result. For finite SOC parameters we find the existence of several new plasmon modes. Several limiting cases, namely the case of pure Rashba or pure intrinsic SOC, the case of equally large Rasbha and intrinsic coupling and of zero SOC are opposed.

**15 min. break.**

HL 102.7 Fri 11:15 BH 334

**Monolithic Epitaxial Graphene Electronics** — •Stefan Hertel[1], Daniel Waldmann[1], Johannes Jobst[1], Sergey Reshanov[2], Adolf Schöner[2], Michael Krieger[1], and Heiko

B. Weber[1] — [1]Chair of Applied Physics, Erlangen, Germany — [2]ACREO AB, Kista, Sweden

We developed a scheme to fabricate transistors with high switching performance by employing the whole system epitaxial graphene consisting of the graphene itself, but also include the semiconducting silicon carbide substrate and their common interface.

We used n-type SiC as conducting channel and tailored two different interfaces to the graphene: (a) monolayer epitaxial graphene [1] to provide ohmic contacts and (b) quasi-freestanding bilayer graphene [2](as achieved by hydrogen intercalation of MLG) to get Schottky-like contacts. We developed a method to produce both species side-by-side on the same chip. The resulting transistor works similar to a MeSFET with graphene as source and drain material but also as gate metal. In principal one single lithography step is sufficient to fabricate a transistor.

We demonstrate an epitaxial graphene transistor with on/off ratios exceeding 4 orders of magnitude at room temperature which can operate in both normally-on and normally-off operation mode, adjustable using a parametric backgate voltage. No damping was observed up to MHz frequencies.

[1] Emtsev et al., Nature Material **8**, 203-207 (2009).
[2] Speck et al., Applied Physics Letters **99**, 122106 (2011).

HL 102.8 Fri 11:30 BH 334

**Field Effect Superconductivity in Multigraphene** — •Ana Ballestar[1], Srujana Dusari[1], Jose Barzola-Quiquia[1], Pablo Esquinazi[1], Robson da Silva[2], and Yakov Kopelevich[2] — [1]Division of Superconductivity and Magnetism, Institut für Experimentelle Physik II, Universität Leipzig, Linnéstraße 5, D-04103 Leipzig, Germany — [2]Instituto de Fisica, Unicamp, 13083-970 Campinas, Sao Paulo, Brasil

We have studied the temperature and magnetic field dependence of the electrical resistivity of mesoscopic tens of nanometers thick multigraphene samples as a function of bias voltage applied perpendicular to the graphene planes. We found that the resistivity changes asymmetrically with the bias voltage. For large and negative bias voltages the resistivity shows non-percolative superconducting-like transitions at $T \sim 15 \ldots 20$ K . The transition can be suppressed at high enough magnetic fields applied normal or parallel to the main plain of the samples. We discuss the obtained results in terms of electric field induced superconductivity at localized near surface regions of the graphite sample.

HL 102.9 Fri 11:45 BH 334

**Graph theory meets ab-initio molecular dynamics: atomic structures and transformations at the nanoscale** — •Fabio Pietrucci[1] and Wanda Andreoni[1,2] — [1]CECAM - EPFL Lausanne, Switzerland — [2]Institute of Theoretical Physics - EPFL Lausanne, Switzerland

We introduce a set of Social PeRmutation INvarianT (SPRINT) coordinates which describe the topology of the network of bonds among atoms [1]. These coordinates are obtained from the contact matrix, they are invariant under permutation of identical atoms, and provide a clear signature of the transition between ordered and disordered structures. In combination with first-principles molecular dynamics and metadynamics, the topological coordinates are employed to explore low-energy structures of silicon clusters and organic molecules, demonstrating the possibility of automatically simulating isomerization, association, and decomposition reactions without prior knowledge of the products or mechanisms involved.

Finally we discuss the application of this new approach to the simulation of carbon nanostructures: we obtain transformation pathways for the reconstruction of zig-zag edges of graphene ribbons to 5-7 rings, as well as the folding of graphene into fullerene-like cages. Our results show that it is now feasible the blind exploration of complex structural rearrangements of nanostructures at finite temperature and at density-functional theory level of accuracy.

[1] F. Pietrucci and W. Andreoni, Phys. Rev. Lett. 107 (2011) 085504.

HL 102.10 Fri 12:00 BH 334

**Localization behavior of Dirac particles in disordered graphene superlattices** — Qifang Zhao[1], Jiangbin Gong[1], and •Cord Müller[2] — [1]Department of Physics and Centre for Computational Science and Engineering, National University of Singapore — [2]Centre for Quantum Technologies, National University of Singapore

Graphene superlattices (GSLs) can be used to engineer band structures and, from there, charge transport properties, but these are sensitive to the presence of disorder. We study the localization behavior of massless 2D Dirac particles induced by weak disorder for both scalar-potential and vector-potential GSLs. By an analytical weak-disorder expansion, we investigate how the localization length depends on the incidence angle to a 1D GSL. Delocalization resonances are found for both scalar and vector GSLs. The sharp angular dependence of the Lyapunov exponent may be exploited to realize disorder-induced filtering devices [1].

[1] Q. Zhao, J. Gong, and C. A. Müller, `arXiv:1111.3436`

HL 102.11 Fri 12:15 BH 334

**Thermal Transport in Graphene: a Large-scale Molecular Dynamics Study** — •Luiz Felipe C Pereira and Davide Donadio — Max Planck Insitute for Polymer Research, Mainz, Germany.

Carbon-based materials show exceptional thermal properties. The thermal conductivity of carbon allotropes can range five orders of magnitude. In the bulk, amorphous carbon is a very poor heat conductor, with $\kappa \approx 0.01$ W/m/K, whereas diamond has the highest thermal conductivity among elemental solids, $\kappa \approx 2000$ W/m/K at room temperature. Carbon nanostructures extend the range even further. Thermal conductivities as large as 5000 W/m/K have been measured for suspended graphene and carbon nanotubes. Nonetheless, there is still much controversy over the thermal transport properties of graphene, both experimentally and theoretically. We have performed extensive equilibrium and non-equilibrium molecular dynamics simulations aimed at understanding the mechanism of heat transport in graphene. In order to address the influence of system size on the simulation results, an aspect frequently overlooked in similar computational studies, we perform large scale molecular dynamics simulations of micrometer-size models containing more than $10^6$ atoms. Furthermore, we investigate the influence of uniaxial strain on the thermal conductivity of graphene, and show that the resulting strain-induced anysotropy has a profound influence on its thermal conductivity.

HL 102.12 Fri 12:30 BH 334

**Effect of short-range interactions on the phase diagram of graphene** — •David Mesterhazy[1], Jürgen Berges[1], and Lorenz von Smekal[2] — [1]Institut für Theoretische Physik, Universität Heidelberg — [2]Institut für Kernphysik, Technische Universität Darmstadt

We study low-energy theories of suspended monolayer graphene at the charge neutral point by means of functional renormalization group methods. In particular, the role of residual short-range interactions for the expected chiral phase transition is investigated. The resulting effective low-energy description can provide a firm basis for a study of the universal properties of the quantum phase transition. Furthermore, first results for the phase diagram at finite temperature are presented.