TT 12: Graphene: Transport (Joint session of DS, DY, HL, MA, O and TT organized by HL)

Time: Monday 14:45–17:45 Location: H17

Invited Talk TT 12.1 Mon 14:45 H17

Advances in Raman Spectroscopy of Graphene and Layered Materials — •Andrea C. Ferrari — Cambridge Graphene Centre, University of Cambridge, Cambridge, CB3 OFA, UK

Raman spectroscopy is an integral part of graphene research [1]. It is used to determine the number and orientation of layers, the quality and types of edges, and the effects of perturbations, such as electric and magnetic fields, strain, doping, disorder and functional groups[2,3]. I will review the state of the art, future directions and open questions in Raman spectroscopy of graphene and related materials, focussing on the effect of disorder[3,4], doping[5,6] and deep UV laser excitation[7]. I will then consider the shear [8] and layer breathing modes(LBMs)[9], due to relative motions of the planes, either perpendicular or parallel to their normal. These modes are present in all layered materials[10,11]. Their detection allows one to directly probe the interlayer interactions [10,11]. They can also be used to determine the elastic constants associated with these displacements: the shear and out-of-plane elastic moduli[12]. This paves the way to the use of Raman spectroscopy to uncover the interface coupling of two-dimensional hybrids and heterostructures[10-12].

1. A. C. Ferrari et al. Phys. Rev. Lett. 97, 187401 (2006) 2. A.C. Ferrari, D.M. Basko, Nature Nano. 8, 235 (2013) 3. A.C. Ferrari, J Robertson, Phys. Rev. B 61, 14095 (2000) 4. G. Cancado et al. Nano Lett. 11, 3190 (2011) 5. M. Bruna et al. ACS Nano 8, 7432 (2014) 6. A. Das et al. Nat. Nanotechnol. 3, 210 (2008) 7. A.C. Ferrari, S. Milana, P. H. Tan, D. M. Basko, P. Venezuela, submitted (2016) 8. P. H. Tan et al. Nature Materials 11, 294 (2012) 9. X. Zhang et al. Phys. Rev. B 87, 115413 (2013) 10. J. B. Wu et al. Nature Comms. 5, 5309 (2014) 11. J.B. Wu et al. ACS Nano, 9, 7440 (2015) 12. S. Milana et al. submitted (2016)

TT 12.2 Mon 15:15 H17

Landau Quantization in Twisted Bilayer Graphene — •Johannes C. Rode, Dmitri Smirnov, Christopher Belke, Hennrik Schmidt, and Rolf J. Haug — Institut für Festkörperphysik, Leibniz Universität Hannover

The bandstructure of bilayer graphene is highly sensitive to rotational mismatch between layers. At large angles, the twisted bilayer effectively behaves like two decoupled monolayers, while the dispersions merge in low-energy van Hove singurities for small interlayer twist[1]. Whereas the regime of large rotational mismatch has been extensively studied in transport experiments[2], there have been few reports on small angle samples[3,4] and none for the transition between the two angular regimes so far. We here examine the magnetotransport behavior across this transition, closing the gap in experimental evidence. The results are discussed with respect to theory[5] and and under special consideration of gate-induced layer asymmetries.

[1] Lopes dos Santos, J. M. B., Perez, N. M. R., Castro Neto, A. H. *Phys. Rev. Lett.* **99**, 25682.
[2] Schmidt, H. *et al. Appl. Phys. Lett.* **93**, 172108.
[3] Schmidt, H., Rode, J. C., Smirnov, D., and Haug, R. J. *Nat. Commun.* **5**, 5742.
[4] Lee, D. *et al. Phys. Rev. Lett.* **107**, 216602.
[5] de Gail, R., Goerbig, M. O., Guinea, F., Montambaux, G., Castro Neto, A. H. *Phys. Rev. B* **84**, 045436.

TT 12.3 Mon 15:30 H17

Magnetic exchange coupling across a graphene layer — •Alessandro Barla[1], Valerio Bellini[2], Stefano Rusponi[3], Paolo Ferriani[4], Marina Pivetta[3], Fabio Donati[3], François Patthey[3], Luca Persichetti[5], Sanjoy K. Mahatha[1], Marco Papagno[6], Cinthia Piamonteze[7], Simon Fichtner[4], Stefan Heinze[4], Pietro Gambardella[5], Harald Brune[3], and Carlo Carbone[1] — [1]Istituto di Struttura della Materia, CNR, I-34149 Trieste, Italy — [2]S3-Istituto di Nanoscienze-CNR, I-41125 Modena, Italy — [3]Institute of Condensed Matter Physics, EPFL, CH-1015 Lausanne, Switzerland — [4]Institute of Theoretical Physics and Astrophysics, University of Kiel, D-24098 Kiel, Germany — [5]Department of Materials, ETH Zürich, CH-8093 Zürich, Switzerland — [6]Dipartimento di Fisica, Universitá della Calabria, I-87036 Arcavacata di Rende, Italy — [7]Swiss Light Source, PSI, CH-5232 Villigen PSI, Switzerland

In order to access the potential of graphene in spintronic devices, its ability to mediate magnetic exchange interactions has to be verified. We present the results of our investigations of the magnetic coupling between Co atoms and Ni(111) mediated by epitaxial graphene. Experimental and theoretical calculations reveal that individual Co atoms occupy two distinct adsorption sites, with different magnetic coupling to the underlying Ni(111) surface. We further report a transition from an antiferromagnetic to a ferromagnetic coupling with increasing Co coverage. Our results highlight the extreme sensitivity of the exchange interaction mediated by graphene to the adsorption site and to the in-plane coordination of the magnetic atoms.

TT 12.4 Mon 15:45 H17

Transport studies in laterally density-modulated graphene-boron nitride-heterostructures — •Martin Drienovsky[1], Christian Baumgartner[1], Felix Simbürger[1], Takashi Taniguchi[3], Kenji Watanabe[3], Ming-Hao Liu[2], Fedor Tkatschenko[2], Klaus Richter[2], Dieter Weiss[1], and Jonathan Eroms[1] — [1]Institut für Experimentelle und Angewandte Physik Universität Regensburg, 93053 Regensburg — [2]Institut für Theoretische Physik Universität Regensburg, 93053 Regensburg — [3]National Institute for Materials Science, 1-1 Namiki, Tsukuba 305-0044, Japan

We report on ballistic transport in graphene-boron nitride heterostructures with a tunable charge carrier density profile. Employing a dry van-der-Waals stacking method, we prepare high mobility graphene devices, where the charge carrier mean free path can exceed the lattice period of the induced multibarrier system by several times. These potential barriers are generated by multiple local top gate electrodes and a global back gate, and yield a pronounced Fabry-Pérot interference pattern in the bipolar transport regime. The extended ballistic length - in comparison to former samples - gets us within reach of the superlattice effect, which we highlight by matching the experimental data to a model calculation. We additionally apply a high, perpendicular magnetic field to our multibarrier systems and observe mode-mixing in the Quantum-Hall-regime of a 4-point measurement setup. By comparing samples with different top gate periods and separately controllable top electrodes, we study adiabatic and equilibrated unipolar edge channel transmission and suppression of equilibration at bipolar junctions.

15 min. Coffee Break

Invited Talk TT 12.5 Mon 16:15 H17

Thermodynamic picture of ultrafast conduction in graphene — •Dmitry Turchinovich[1], Zoltan Mics[1], Klaas-Jan Tielrooij[1,2], Ivan Ivanov[1], Xinliang Feng[1], Klaus Müllen[1], and Mischa Bonn[1] — [1]Max Planck Institute for Polymer Research, 55128 Mainz, Germany — [2]ICFO, 08860 Barcelona, Spain

Graphene has very high steady-state conductivity, which, however, does not hold in the regime of ultrafast, sub-picosecond electric fields corresponding to the terahertz (THz) frequencies. Here we show that in graphene, the electron conduction on an ultrafast timescale is determined by a simple thermodynamic balance maintained within its electronic system acting as a thermalized electron gas [1]. The energy of ultrafast electric currents passing trough graphene is near-instantaneously converted into the thermal energy of its entire charge carrier population, thereby raising the electronic temperature and reducing the chemical potential. The interplay between electron heating and cooling dynamics in graphene ultimately defines its ultrafast conductivity. We demonstrate that this simple thermodynamic picture describes very well the THz linear, nonlinear, and photo-induced conductivity of this remarkable material [1-3].

[1] Z. Mics, K.-J. Tielrooij, K. Parvez, S. A. Jensen, I. Ivanov, X. Feng, K. Müllen, M. Bonn, and D. Turchinovich, Nat. Commun. 6, 7655 (2015). [2] S. A. Jensen, Z. Mics, I. Ivanov, H. S. Varol, D. Turchinovich, F. H. L. Koppens, M. Bonn, and K. J. Tielrooij, Nano Lett. 14, 5839 (2014). [3] I. Ivanov, M. Bonn, Z. Mics, and D. Turchinovich, EPL - Europhys. Lett. 111, 67001 (2015).

TT 12.6 Mon 16:45 H17

Magnetotransport in graphene antidot arrays: semiclassics and moiré lattices — •Andreas Sandner[1], Tobias Preis[1],

Christian Schell[1], Paula Giudici[1], Kenji Watanabe[2], Takashi Taniguchi[2], Dieter Weiss[1], and Jonathan Eroms[1] — [1]Institut für Experimentelle und Angewandte Physik, Universität Regensburg, Germany — [2]NIMS, 1-1 Namiki, Tsukuba, Japan

Embedding graphene into a heterostructure with hexagonal boron nitride (hBN) on both sides was shown to be an efficient way of achieving a high bulk mobility. However, nanopatterning graphene can add extra damage and drastically degrade the intrinsic properties by edge disorder. But graphene encapsulated between hBN is protected during a top-down fabrication procedure. In this way, we can prepare graphene-based antidot lattices where the high mobility is preserved.

We performed magnetotransport experiments in monolayer-graphene antidot lattices with lattice periods down to 50 nm. We observe pronounced commensurability features in ρ_{xx} stemming from ballistic orbits around one or several antidots. Due to the short lattice period in our samples, we can explore the boundary between the semi-classical and the quantum transport regime, as the Fermi wavelength of the electrons approaches the smallest length scale of the artificial potential.

Additionally, we study the interplay between a moiré and the imposed antidot superlattice potential in several of our samples. There is a gradual suppression of the classical commensurability features by approaching the satellite Dirac points of the moiré potential.

TT 12.7 Mon 17:00 H17

Influence of disordered edges on transport properties in graphene — Dmitri Smirnov[1], Galina Yu. Vasileva[1,2,3], •Christopher Belke[1], Johannes C. Rode[1], Yurij B. Vasilev[2], Yurij L. Ivanov[2], and Rolf J. Haug[1] — [1]Institut fuer Festkoerperphysik, Leibniz Universitaet Hannover — [2]Ioffe Institute, Russian Academy of Sciences, St. Petersburg — [3]Peter the Great Polytech University, St. Petersburg

The influence of plasma etched edges on electrical transport and doping on graphene devices is studied. Mono- and bilayer samples were fabricated into a specific Hall bar geometry with differing width. The fabrication was done via transfer on a Si/SiO_2 substrate and structuring and contacting via plasma oxygen etching and e-beam lithography. The specific shape allows to investigate the influence of edge disorder on the overall doping and the effective mobility.
The doping concentration, calculated from the charge neutrality point, differs for every region and an inverse dependence on the region width was observed. The sample edge was determined as a strong p-doping source, dominating the bulk doping component and the edge doping contribution and efficiency was obtained.
A further study of the mobility for different regions was used to quantify the edge scattering. We find, that for decreasing region width the mobility decreases as well. This behavior can be attributed to the samples edge, establishing it as a further scattering mechanism.

TT 12.8 Mon 17:15 H17

Acoutoelectric currents in coated graphene on SiC — •Alberto Hernández-Mínguez, Abbes Taharoui, Marcelo Lopes, and Paulo Santos — Paul-Drude-Institut für Festkörperelektronik, Berlin, Germany

Surface acoustic waves (SAWs) provide useful mechanisms for the dynamic modulation and transport of carriers in two-dimensional semiconductor heterostructures. In the case of graphene, we have recently shown that the piezoelectric fields accompanying SAWs can induce unipolar electric currents in lithographically patterned graphene layers grown on SiC. Due to the weak piezoelectricity of SiC, however, the interaction between SAW and carriers in graphene is relatively small. Future applications of the acoustic transport require the generation of strong SAWs for their efficient coupling to graphene, as well as the control of the density and type of carriers transported by the SAW. In this contribution, we study structures for efficient generation of high frequency acoustic transport (> 1 GHz) in graphene grown on SiC that are also compatible with top gates for the electric control of the carrier density. Several Rayleigh modes with frequencies up to 7 GHz are efficiently generated in our structure, inducing acoustic currents for the fundamental frequency that are 300 times larger than the ones reported in our previous devices. These results are an important step towards the dynamic control of carriers in graphene at the sub-micrometer regime, as well as for the dynamic manipulation of the electron spin by strain-induced gauge fields.

15 min. Coffee Break