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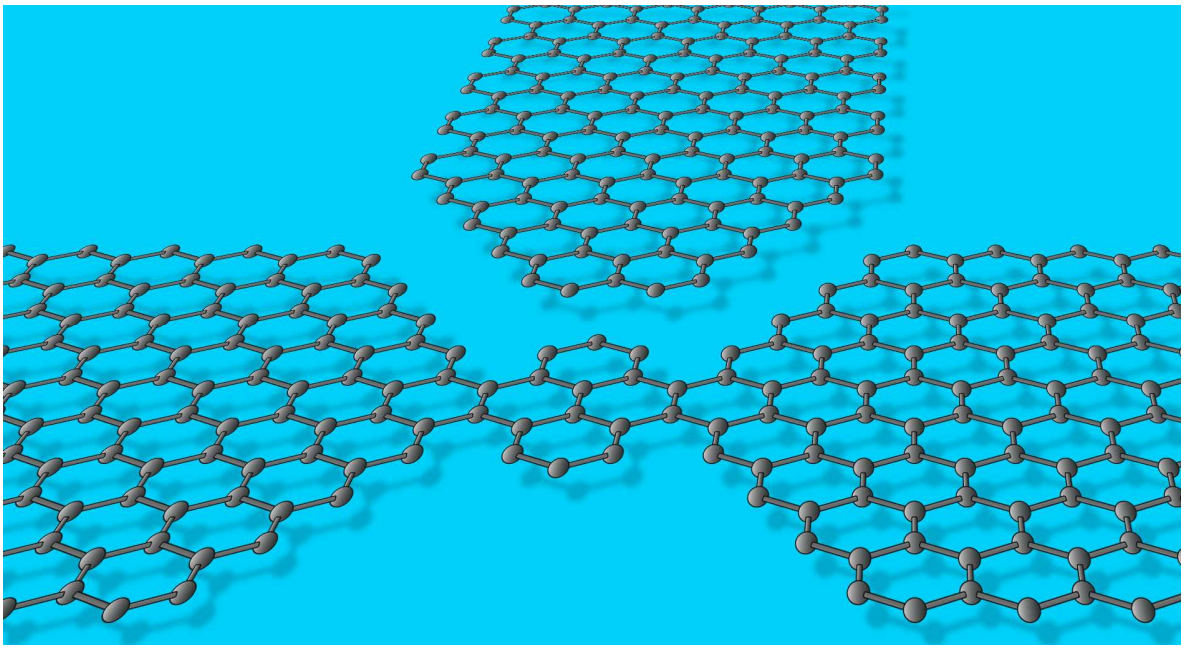

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David ABERGEL
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Long range Coulomb interaction in bilayer graphene

We show the results of our studies of electron-electron interactions in biased and unbiased bilayer graphene in a magnetic field. We demonstrate that the long range Coulomb interactions are highly important. This manifests itself by causing the mixing of Landau levels in the unbiased bilayer, and by precipitating spin transitions in the ground state of the biased bilayer for half-filled valence band Landau levels.

Hideo AOKI
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Photo-induced Hall Effect in Graphene,

Takashi Oka and Hideo Aoki, Department of Physics, University of Tokyo, Hongo, Tokyo 113-0033, Japan

While transport properties such as the quantum Hall effect are hallmarks of the massless Dirac dispersion in graphene, fascinating properties should also arise in optical properties. Here we theoretically propose to irradiate graphene with circularly polarized light, for which we predict a "photovoltaic Hall effect", i.e., a dc Hall current photo-induced in the absence of static, uniform magnetic fields. The effect, although not quantized, bears a geometric origin, traced back to the non-adiabatic (Aharonov-Anandan) phase acquired by the motion of k-points in the Brillouin zone when they encircle the Dirac cones, so the effect amounts to controlling a transport property via a charge pumping in the massless Dirac cones.

Analaytically, the Kubo formula is extended to the nonlinear Hall coefficient with the Floquet formalism for non-equilibrium phenomena in strong ac fields, which is used to calculate the "photo-induced Berry curvature". Energetically, the irradiation induces a dynamical gap at the Dirac point which gives rise to a ac Wannier-Stark ladder in Dirac systems. We further combine the Floquet method with the Keldysh Green's function to analyze finite graphene systems. When we apply a bias across the electrodes attached to the sample to degrade the K-K' symmetry, the photovoltaic dc Hall current is confirmed from a numerical calculation. The required strength of the circularly polarized light to observe these effects is estimated to be O(10^7 eV/m), which is within an accessible range for present laser sources.

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Defects in Epitaxial Graphene

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Transmission Electron Microscopy (TEM), Kelvin Force Microscopy (KFM) and Atomic Force Microscopy (AFM) investigations of structural defects in graphene layers on Si terminated 4H-SiC are presented. The graphene layers have been obtain by decomposition of silicon carbide in Epigress VP508 hot-wall chemical vapor deposition (CVD) reactor.

Two kind of graphene layers have been investigated: 1) grown on substrates with on-axis orientation, 2) grown on substrates with 4° and 8° off-axis orientation in respect of c-axis of SiC. Three types of defects: puckers, dislocations, and discontinuities of monolayers were found in those graphene layers. The puckers were up to 20 nm high, emerged at the locations where graphene layers loose contact with SiC surface. Those defects created a random network of long undulations. These defects originate from thermal expansion difference between graphene and SiC as the sample is cooled after graphitization. They gave contrast in KFM, which showed that they differed in band structure. The second defect type – edge dislocations were created at atomic steps of SiC substrate. The discontinuities of graphene monolayers have been observed at the step trains or at macrosteps of SiC substrate where apparently dislocations could not relax the strain. They extend linearly over large distances, following the steps arrangement created due to misorientation of the SiC substrate. These defects are also detected in KFM indicating disturbance of potential distribution on atomic steps of SiC

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Ultra-high electron current through graphene devices and its application

Graphene is an appealing system for basic research due to its unusual electronic properties and also holds promise for technological applications, such as in nanoelectronics. Yet, what makes graphene an enticing material is also the source of great technological difficulties: being in essence a surface, graphene proves to be extremely sensitive to contamination by adsorbates, which can modify its transport properties.

We present a simple yet highly reproducible method to suppress contamination and to improve sample quality of graphene at low temperature inside the cryostat. The method is based on the application of a large current around 1 mA through the graphene device, which generates several tens of mW dissipation over a few μm2 large surface. Remarkably, graphene can sustain such extreme conditions while the adsorbed contamination gets removed.
Graphene layers are contacted by multiple electrodes arranged in a Hall-bar geometry. The degenerately doped silicon substrate serves as a back gate electrode. We measure the 4-point conductance of the sample as a function of the back gate voltage, which tunes the carrier density.
Prior to current-induced cleaning, the mobility is typically in the range 800 – 5000 cm2V-1s-1 and the graphene devices are heavily doped (the conductivity is minimum for gate voltages between 10 and 50 V). After we apply the current-induced cleaning technique, the mobility improves to values typically 15000 – 25000 cm2V-1s-1, while the doping is suppressed to close to 0.
Remarkably, this simple cleaning technique allows us to observe the anomalous, half-integer quantum Hall effect that is the signature of a clean, single graphene layer. Evidence of very high quality samples is demonstrated by measuring an additional plateau at the Landau level n=0 at relatively low magnetic field (9 T). Interestingly, this plateau is visible only after the current- induced cleaning process.

We will then report on the electron transport properties of graphene devices in the high current regime. The current is observed to saturate when the applied voltage is increased. The current saturation depends on the Fermi energy and scales linearly with the width of the device. These results are compared to a model where high-energy electrons scatter with the optical phonons of graphene.

Fabienne BARROSO-BUJANS
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Adsorption phenomenon in graphite oxide

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In this work, we have studied the behavior of graphite oxide (GO) after intercalation and evaporation of several common solvents. Three different series of solvents were studied: chlorine compounds (dichloromethane, chloroform, and carbon tetrachloride), aromatic compounds (benzene, toluene, and p-xylene) and alcohols (1-metanol, 1-propanol, and 1-pentanol). The intercalation process was simply done by stirring the organic solvent without sonication. After intercalation of each solvent, GO was filtrated and extensively drying at 110 ºC. We will show that this procedure is not enough to completely evaporate the solvent which remains adsorbed on the graphite oxide galleries in a permanent way. We have used solid state 13C NMR to confirm the presence of the solvent in GO. On the other hand, X-ray diffraction (XRD) experiments showed an increase of the graphitic interlayer distances caused by the intercalation of such solvents. In the case of aromatic compounds, the intercalation of the solvent was uncompleted leaving unoccupied galleries. Moreover, the C-C distances of graphite oxide were also perturbed by the presence of solvents, being specially modified by methanol. Finally, we have studied the decomposition temperature (Td) of GO by using differential scanning calorimetry (DSC). For all the studied solvent-intercalated compounds Td strongly decreases when compared with the untreated GO. In addition, Td has shown a particular behavior for each solvent series. In this work, we will explain these different behaviors for each series. The synergic effect of the solvent molecules in the thermal decomposition of GO could help to understand, in future works, the chemical mechanism in the thermal decomposition of this type of materials.

Colin BENJAMIN
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Graphene Josephson Qubit

We propose to combine the advantages of graphene, such as easy tunability and long coherence times, with Josephson physics to manufacture qubits. These qubits can either be built around a 0 and π junction and controlled by external flux or a d-wave Josephson junction can itself be tuned via a gate voltage to create superpositions between macroscopically degenerate states. We show that ferromagnets are not required for realizing π junction in graphene, thus considerably simplifying its physical implementation. We demonstrate that one qubit gates, such as arbitrary phase rotations and the exchange gate, σ_x, can be implemented easily.

Keyan BENNACEUR
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Hall resistance plateaus in high quality Graphene samples at large currents.

Graphene Hall bars prepared from exfoliated natural graphite of large size and high quality have been measured in the quantum Hall effect regime. The monolayer Graphene sheet shows Hall quantization robust upon applying very large current. Low longitudinal resistance is found up to 10 A with finite width h/2e2 Hall plateau at 4.2 K and 16 T. The TiAu/Graphene contact resistance is found low, typically 20 ohmsto 50 ohms.
A systematic study of the longitudinal resistance versus applied current points toward a variable range hopping mechanism
for high bias suppression of the Hall current, (although some samples also show activated law)(alternative : for most samples studied so far) . The results strongly indicate that Graphene is a promising new material for quantum metrology.

Rafi BISTRITZER
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High Tc superfluidity in bilayer graphene

We predict a high temperature superfluid state in bilayer graphene that emerges due to electron-hole pair condensation and study the influence of disorder and screening on the bilayer mean field and Kosterlitz-Thouless critical temperatures. We find that the zero temperature phase stiffness scales with the Fermi energy allowing for exceptionally high transition temperatures that may even reach room temperature under favorable experimental conditions. Exploiting an analogy between a disordered bilayer system and a superconductor contaminated with magnetic impurities we find the influence of disorder on the critical temperatures. Applying the Thomas-Fermi approximation consistently in the condensed state we show that inter-layer coherence survives the influence of screening. Furthermore, we conjecture a first order normal to superfluid phase transition as a function of both the temperature and the distance between layers.

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Four-band RPA theory of exchange and correlation effects in bilayer graphene

The RPA theory for the Dirac model of single-layer graphene is effective in describing the crystal energy properties, whose peculiarities come from the linear massless dispersion of the particles and a large "vacuum" sea of excitations.
In this poster we show the analytical and semi-analytical results for the RPA response function of bilayer graphene at zero temperature, and the dispersion of the inversion-symmetric and inversion-antisymmetric plasmons.
We give comments about the effect of the chirality 2 of quasiparticles and the crossover from four to three bands filling, discussing the effect of the latter on the damping of the plasmons.
We also comment on the reliability of the two band model in capturing the low-doping physics.

Stefano BORINI
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Quantitative optical contrast analysis for the assessment of graphene quality.

We describe a method to achieve a quantitative analysis of the optical contrast spectra of graphene deposited on SiO2 / Si substrates. First, we demonstrate that the optical constants of graphene in the visible range can be estimated by means of a very simple procedure involving their consistence with universal optical conductivity and experimentally measured optical spectra, within the framework of Fresnel coefficients calculation. The obtained complex refractive index allows for accurate prediction of the optical behavior of graphene in the visible range, from the 2D limit (single atomically thick graphene layer) to the bulk limit (graphite). Then, we describe how the effect of the objective numerical aperture should be taken into account in the contrast measurements, basing on an experimental study of patterned thin films with well known refractive index and thickness. Finally, we show that the implemented quantitative analysis can successfully be employed in order to assess the quality of exfoliated graphene as far as the presence of organic contaminants due to devices processing is concerned. For instance, we show that the graphene cleanness during various process steps (e.g. resist spin coating and lift-off) can be easily monitored in an easy and effective way by optical inspection.

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High-resolution transmission electron microscopy (HRTEM) simulations of graphene layers on 4H-SiC (0001) surface

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High-resolution transmission electron microscopy (HRTEM) was used in investigation of the structure of graphene layers grown on Si terminated face of 4H-SiC substrate. HRTEM observations were performed in [11-20] and [1-100] cross-sectional orientations of the SiC sample. Two perpendicular directions of sample observations provide more information on two-dimensional structure of the interface between carbon (graphene) layers and the SiC substrate. These observations were carried out under and at near Scherzer defocus conditions. The observation results indicate that the first carbon layer was located about 2Å above the SiC surface. The subsequent graphene layers have been found to be spaced by 3.3Å, i.e. at the distance similar to the interlayer spacing in the graphite bulk structure. Additionally, some corrugations of graphene layers about 0.6Å high were noticed. Quantitative interpretation of the HRTEM images was based on the differences in contrast of the atomic columns or layers created by arrangement of carbon-silicon carbide crystallographic structure. Image simulations for the structure containing 1-3 graphene layers, located on the SiC substrate were carried out and compared with experimental images. The simulations of the HRTEM patterns, based on the calculations employing multi-slice method, were performed using JEMS software {P.A. Stadelmann, Ultramicroscopy 21 (1987) 131-146}.

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Impermeable Atomic Membranes from Graphene Sheets

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Membranes are fundamental components of a wide variety of physical, chemical, and biological systems, used in everything from cellular compartmentalization to mechanical pressure sensing. They divide space into two regions, each capable of possessing different physical or chemical properties. A simple example is the stretched surface of a balloon, where a pressure difference across the balloon is balanced by the surface tension in the membrane. Graphene, a single layer of graphite, is the ultimate limit: a chemically stable and electrically conducting membrane one atom in thickness1-3. An interesting question is whether such an atomic membrane can be impermeable to atoms, molecules and ions. In this letter, we address this question for gases. We show that these membranes are impermeable and can support pressure differences larger than one atmosphere. We use such pressure differences to tune the mechanical resonance frequency by ~100 MHz. This allows us to measure the mass and elastic constants of graphene membranes. We demonstrate that atomic layers of graphene have stiffness similar to bulk graphite (E ~ 1 TPa). These results show that single atomic sheets can be integrated with microfabricated structures to create a new class of atomic scale membrane-based devices.

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Very Large Graphene Monolayer Grown on SiC

We present the first very large isolated graphene monolayers grown on on-axis semi-insulating 6H-SiC (000-1) wafers. Using high temperature growth at 1700°C in vacuum with a graphitic wafer covering the SiC sample, graphene growth takes place from surface defects that act as nucleation centers. After the SiC surface reconstruction in large terraces, it yields to the formation of very large and uniform isolated graphene monolayers ribbons (100 µm long and 4-5 µm wide). These graphene islands were investigated by Optical Microscopy (OM), Atomic Force Microscopy (AFM) and Scanning Electron Microscopy (SEM). Raman spectroscopy allowed distinguishing without any doubt between monolayer and few layers graphene flakes. This growth method opens the way towards full wafer processing for application in electronics.

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Koshino-Taylor effect in graphene

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The possibility of fabricating free-standing graphene sheets has recently been demonstrated experimentally [1]. In this form graphene combines its unusual electronic features with additional mechanical peculiarities, giving rise to new specific properties (see, e.g., Ref. [2]). The resistivity of suspended graphene, for example, exhibits a clear dependence on temperature [3] unlike in the samples supported by a substrate [4].

The most distinctive feature of graphene is the Dirac spectrum of its charge carriers, which is a direct consequence of the honeycomb structure of its lattice. Suspended graphene, in its own turn, is inevitably subjected to both in-plane and out-of-plane distortions [2]. As shown in Ref. [5], this gives rise to two different contributions in its low-temperature resistivity. Whereas the scattering of electrons with in-plane phonons provides a T^4 contribution (see also [6]), the scattering with out-of-plane ones gives an unusual $T^{5/2}\ln T$ behavior. On the other hand, the residual (temperature-independent) resistivity observed at the lowest temperatures in metals is known to have its origin in the scattering with defects (impurities, vacancies, etc.) [7]. The renormalization of this scattering due to electron-electron interaction is another source of temperature-dependent contributions to the resistivity. Specifically in graphene, Friedel oscillations in the exchange field yield a linear-in-T behavior (which is absent in the case of Coulomb scatterers) [8].

We consider the phonon-assisted scattering of electrons by defects, i.e., the socalled Koshino-Taylor effect [9], and show that it is unusually large in graphene. This effect is operative for any kind of defect and for both in-plane and out-of-plane distortions. The key ingredient in the Koshino-Taylor effect are the local fluctuations of the lattice which, in graphene, can be considerably larger than in ordinary metals due to the two-dimensional character of the system. As a result we show that the finite temperature defect-induced resistivity of graphene formally diverges in the thermodynamic limit, having a non-analytic $T\ln T$ component when finite size effects are taken into account [10].

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Gaped bilayer graphene in the Hartree-Fock approximation

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A remarkable property of graphene double layer is the ability to open a gap in the presence of a perpendicular electric field. Even more remarkable, this gap can be externally controlled by tuning the applied electric field, which has been demonstrated through ARPES measurements, Shubnikov de Haas and quantum Hall effect, and transport experiments. A simple tight-binding theory, where the screening correction of the external field is treated at the Hartree level, has shown to correctly account for the observed behavior as long as the gap is much smaller than the interlayer coupling. However, with increasing gap the theory seems to reach its validity limits, as is clearly seen by comparing theoretical and measured cyclotron mass. Also recent infrared spectroscopy measurements give evidence for such a failure. Here, we present the the theory extensions in order to include also the Fock term, within a four-band continuum model, and discuss the obtained results for the gap behavior and cyclotron mass.

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Current manipulation in graphene nanoribbons

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We propose a model nanoswitch for the control of current flow in graphene nanoribbons. By 'current switch,' we mean a multiterminal device able to direct the current to a chosen exit by means of local gates. Such a system could be useful in the development of nanoelectronics devices or, after further implementations, in the field of quantum information.
The proposed device [1] is made up of a graphene nanoribbon with a longitudinal semi-infinite septum over one side. The septum defines two terminals, where the current can be selectively directed by means of a high magnetic field and an adjustable potential step induced by a top gate. A further back gate enables the variation of the global charge density. The device working mechanism is based on the spatial chirality of currents in high magnetic fields [2,3] and on the possibility of determining the electron-like or hole-like nature of the particles involved in transport by means of the adjustable potential step. The spatial chirality of currents consists in the spatial separation of the currents flowing in opposite directions. When a ribbon is threaded by a perpendicular, homogeneous and outgoing magnetic field, electron-like charges can only move from the right to the left along the lower edge of the ribbon and from the left to the right along the upper edge. The opposite occurs for hole-like particles, which are then said to have an opposite chirality with respect to the former. By controlling the nature of the particles locally, it is thus possible to select the edge involved by transport.

In the perspective of concrete applications, we require that the current switch works at high temperature and in the presence of a reasonable degree of disorder in the sample. We show that the device working mechanisms themselves guarantee the fulfilling of these requirements for reasonable widths of the nanoribbon and reasonable magnetic field strengths.

For our simulations, we adopted a tight-binding Hamiltonian with nearest neighbour interactions and made use of the Green's function formalism, which allowed us to obtain global transport and electronic properties, as conductance and density-of-states, as well as local quantities, as microscopic current distribution and local density-of-states.

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Shot noise in etched graphene nanoribbons

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One way to create a gap in the band structure of graphene is to form a constriction or a nano-sized ribbon in this two-dimensional material [1,2]. A gap was experimentally demonstrated in both etched [3,4] and smooth edge [5,6] graphene nanoribbons (GNR). However, the early theory did not consider any effect of disorder at the edges of the ribbons. Indeed, the experiments demonstrated that part of the nanoribbons near the edges do not conduct. A model suggested that such behaviour could be explained by representing the nanoribbons not as a perfect ribbon but like a series of dots [7]. Early experiments tend to validate this idea [4,8]. However, the physical origin of the gap remains unclear.

Here, we present shot noise measurements done in etched GNRs. While a gate dependent Fano factor of 1/3 was found in large and short graphene strips [9], we have obtained a much smaller Fano factor in GNR, quasi-independent of the carrier density. In addition to this, we have analysed the conductance fluctuations using autocorrelation functions. We show that etched GNR conductance and noise are strongly dominated by disorder arising from the rough edges [10].

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Graphene/Ni(111) System: Spin- and Angle-Resolved Photoemission Studies

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Here we report spin- and angle-resolved photoemission studies of the inert graphene layer formed on the surface of a ferromagnetic material, Ni(111). X-ray photoemission and spin-resolved spectroscopy of secondary electrons reveal that graphene behaves like a protection layer on the Ni(111) surface preventing its reaction with adsorbed oxygen. Angle-resolved photoelectron spectroscopy of PI-states of graphene on Ni(111) shows a strong dependence of binding energy of these states on the direction of magnetization of the sample. We conclude that the observed extraordinary high "splitting" up to 225 meV of the PI-band in the graphene layer is a manifestation of the Rashba effect which provides a direct possibility to a flexible control of an electron spin in a graphene-based spin-FET.

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Local oxidation of graphene

The aim of this project is to establish a high precision process to create nanoscale features on graphene sheets, which allow for strong charge carrier confinement and desirably even for control over the edge structure on the atomic scale. SPM-lithography has been shown to be applicable on graphene sheets deposited on SiO2 substrate.

Using this technique lines down to 20 nm in width have been accomplished on graphite, few layer graphene and single layer graphene. Depending on the applied bias voltage the sp2-structure either is transformed to sp3 or the material is etched away completely. Presently, the properties of the oxidized lines as well as studies of the influence of environmental parameters are investigated.

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The semimetal-insulator transition in graphene.

J. E. Drut
The Ohio State University

In this short talk I will outline the lattice Monte Carlo approach recently applied to the study of the semimetal-
insulator transition in graphene. Using that technique we have computed the chiral condensate and the corresponding
susceptibility as functions of the Coulomb coupling. Based on that data, we have estimated the location of the critical
coupling for the transition, which we have found to be consistent with an insulating phase for graphene in vacuum.

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Weak Localization and Transport Gap in Graphene Antidot Lattices

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We have studied transport in antidot lattices in single layer graphene. The samples were prepared from exfoliated natural graphite and antidot lattices with a period between 90 nm and 400 nm were patterned using electron beam lithography and plasma etching.
Going from large periods to small lattice spacings we observe a gradual reduction of the quantum Hall effect owing to the geometrical condition that a cyclotron orbit has to fit through the constrictions between the antidots.
Samples with narrow channels between the antidots can be regarded as a network of graphene nanoribbons and correspondingly show a transport gap of a few mV at low temperatures.
Studying magnetotransport we observe a pronounced weak localization effect. The strong visibility is due to intervalley scattering at the antidot edges. By a careful examination of the temperature and geometry dependence we conclude that our short-period antidot lattices are best described as an array of phase-coherent cavities.

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Collective Excitations in Graphene in a Magnetic Field

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We study optically-induced excitations in graphene in the presence of a single Coulomb impurity and an applied strong perpendicular magnetic field. We consider the limits of (i) low electron density in the lowest zero Landau level and (ii) a completely filled Landau level. In the former limit, the relevant states are the D- impurity (a positive impurity bound to two electrons). We calculate the energies and optical transitions of the D-, taking into account the direct and exchange interactions in graphene. In particular, we predict the absorption pattern consisting of a set of additional lines both above and below the cyclotron resonance of free electrons in graphene. We also examine the spectrum of collective excitations (magnetoplasmons) bound to an isolated impurity in a system with filling factor =1 and predict the absorption spectrum of the impurity-modified cyclotron resonance. We compare our theoretical results with the existing experimental data.

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Graphene nanoribbons in crossed electric and magnetic fields

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Effect of strong transverse electric (E) and magnetic (B) fields on ballistic transport and energy spectrum of a side-gated graphene ribbon is studied analytically and numerically. Qualitatively different behavior is found depending on which of the two fields dominates. In the
E-field controlled regime, a number of interesting effects is found, including nonmonotonic (e.g., Mexican-hat) dispersion of the subband energies and their (avoided) level crossings. Self-consistent screening leads to a power-law falloff the electric field of the side gate into
the interior of the ribbon. As the B-field increases beyond the local electric field, the subbands evolve into Landau levels separated by cyclotron gaps. Due to the nonuniformity of the screened electric field, the onset of Landau quantization sweeps through the ribbon in a gradual
manner. The ballistic magnetoconductance of the ribbon is shown to change as a function of B and the side-gate voltage in a nontrivial manner.

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Collective excitations of doped graphene in a strong magnetic field

A doped graphene layer in the integer quantum Hall regime reveals a highly unusual particle-hole excitation spectrum, which is calculated from both the dynamical polarizability and by semiclassical methods. Long-range Coulomb interactions are treated within the random phase approximation. We find that elementary neutral excitations in graphene in a magnetic field are unlike that of a standard two-dimensional electron gas: in addition to a plasmon (or
upper-hybrid) mode, the particle-hole spectrum is reorganized in linear magneto-plasmons instead of the usual magneto-excitons. See
arXiv:0809.2667 .

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Title: Band gap opening on doped bilayer graphene by ab-initio calculations.

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The recent discovery that the application of an external electric field induces a band gap opening in bilayer graphene [1], attracted a lot of interest on this system,
due to important applications in nanoelectronics.
By means of ab-initio calculations, we investigated the electronic properties of doped bilayer graphene, in presence of different bottom and top gate. In particular, the dependence of the band gap on the doping, on the average external electric field and temperature has been analysed.
We find that our ab-initio results differ from those obtained with standard Tight Binding (TB) calculations [2]. In particular, we show important charge screening effects, which are crucial for the proper description of the electronic properties of bilayer graphene, and which are not included in TB models. Interestingly, in agreement with our findings, recent experimental results of infrared measurements on electrostatically gated bilayer graphene, questioned the TB prediction of gate-induced band gap [3].

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Tilted Dirac Cones in Graphene and 2D Organic Materials,

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The Dirac cones, which describe the low-energy electronic properties in graphene, may be tilted if strain is applied to the graphene sheet. In this case, the Dirac points are shifted away from the K and K' points with high crystallographical symmetry. Next-nearest-neighbour hopping then yields a linear correction, which effectively tilts the cones. This situation naturally arises in another 2D (organic) material, alpha-(BEDT-TTF)_2I_3. We investigate, here, the minimal structure of the model to account for tilted Dirac cones and how the tilt affects the Landau quantisation in a strong magnetic field. The problem of the quantum Hall effect, yet unobserved in the organic compound, will also be briefly discussed.

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Electron transport in p-n-p graphene structures with 'air-bridge' top gates

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We describe the fabrication of graphene p-n-p structures with a top gate separated from graphene by an air gap [1]. Avoiding deposition of a dielectric under the top gate allows one to sustain high mobility of carriers along the whole sample and clearly observe unusual propagation of chiral carriers through ballistic p-n junctions, with suppressed transmission at angles away from the normal to the junctions.

To determine the value of the increase in the resistance and compare it with theory [2], we calculate the band profile of graphene p-n-p structures taking into account the density of electron states in graphene. Our results show that the increase in the resistance is only seen in high-mobility structures with ballistic p-n junctions where its value agrees well with theoretical predictions.

We discuss the origin of resistance oscillations which are observed with varying top-gate voltage, as well as the origin of the positive magnetoresistance of graphene p-n-p structures.

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Electronic properties of pristine and doped graphene layers from angle-resolved photoemission spectroscopy

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Electrons in individual graphene layers are a prototype of a two-dimensional gas of massless Dirac Fermions. In realistic devices,however, the electronic properties are modified by elastic deformations, interlayer coupling[1], substrate interaction[2] or electron-electron correlation effects[1]. In order to resolve these problems we unravel the electronic structure of doped graphene by revisiting the stage one graphite intercalation compound KC8 using a combined angle—resolved photoemission spectroscopy (ARPES) and ab--initio study[3]. We prove an almost complete charge transfer to the graphene layers yielding a Fermi level shift of the Dirac point by 1.35~eV. This highlights that AA stacked graphene sheets in KC8 have negligible interlayer coupling. Thus Dirac Fermion behaviour is preserved and for the first time we directly determine the full experimental Dirac cone of graphene.
Based on our ARPES data we provide a new set of tight-binding (TB) parameters for efficient calculation on the quasiparticle dispersion in pristine and doped few-layer graphene and graphite including electron-electron correlations[4]. This is the first set of TB parameters that can describe both the low and high energy optical properties relevant for transport and optical absorption experiments, respectively. Within a tight-binding picture we examine the transition from few-layer graphene to graphite and predict a semimetal to metal transition in graphite.
Finally, using in-situ time-resolved photoemission we study the growth dynamics of a graphene monolayer on a Ni(111) surface from chemical vapour deposition. In order to quantitatively understand the reaction processes we solve the rate equations that lead to the formation of graphene and find excellent agreement to the measured photoemission intensities.
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[4] A. Grüneis et al. in print Phys. Rev. B. , cond-matt 0808.1467 (2008)

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Energy gaps in etched graphene nanoribbons

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We report transport measurements on an etched graphene nanoribbon. It is shown that two distinct voltage scales can be experimentally extracted that characterize the parameter region of suppressed conductance at low charge densitiy in the ribbon. Finite source–drain voltage measurements in narrow ranges of voltages applied to local in-plane gates and the back gate reveal the presence of localized states characterized by a source–drain voltage scale related to a charging energy of 10 meV. Sweeps of the back gate voltage over a large range allow to extract a back gate voltage scale which is likely to be characteristic mainly for the disorder potential present in the ribbon. The lever arms of gates vary for different localized states by up to 30% indicating their spread in position along the ribbon. A single-electron transistor situated close to the nanoribbon is used to prove the addition of individual electrons to the localized states experimentally. We discuss the relation of the two experimental voltage scales to the charging energy, the energy gap created by the lateral confinement, and the magnitude of the disorder potential in the ribbon which is estimated to be of the order of 100 meV.

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Coherence and noise in graphene samples with superconducting contacts

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Superconductor-Graphene-Superconductor (SGS) systems provide interesting objects for studies of the Josephson effect which is one of the most spectacular phenomena of quantum coherent matter. The coupling between the ordered states across a Josephson tunnel junction can be described by the Josephson energy E(\phi) where \phi denotes the phase difference between the order parameter fields on opposite sides of the junction or, equivalently, the Josephson junction can characterized by its current-phase relation (CPR) I(\phi).

The distribution of transmission channels influences the CPR: for a nearly ballistic junction the CPR becomes strongly non-sinusoidal and discontinuous while for a diffusive/pseudodiffusive junction the CPR is remains nearly sinusoidal. This difference can be observed by measuring the Josephson inductance of the junctions using microwave reflection measurements [1] that we are set up to do with graphene junctions. If the number of channels in a ribbon-shaped graphene can be cut down to 1, Andreev level/Landau-Zener spectroscopy will also be a powerful tool [2].

We have performed both DC and AC transport measurements with 300 nm long and 1.2 micron wide SGS samples. In our DC experiments, we have been able to tune supercurrents from 5 nA at the Dirac point to 50 nA far away from it. The measured IV curves present current plateaus at a spacing of 0.8 microV in bias voltage.

In our AC experiments, the samples are exposed to an increased level of noise, although a circulator and microwave filters are employed to thermalize the pass band at 600-900 MHz to 30 mK, the base temperature of the refrigerator. The IV curves are hysteretic and show well controlled phase diffusion before transition to the voltage state. The measured noise displays a multitude of features in the subgap regime and analysis for determining the effective Fano-factor is presently going on.

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Topological aspects of the n=0 Landau level in graphene : chiral symmetry and Hall plateau transition

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One important factor governing the electronic structure of graphene in general and graphene quantum Hall effect(QHE) in particular is the chiral symmetry of the honeycomb lattice, which gives rise to a topological stability of the QHE as long as the symmetry is preserved [1]. The chiral symmetry especially makes the n=0 Landau level in graphene special and unusually robust. One manifestation of this appears in QHE edge states, where, unlike the usual QHE system where the charge distribution is depleted from the edge, the charge is accumulated along zigzag edges. This selectively occurs for n=0, with the bulk states hybridizing in the boundary charge via what we call a "topological compensation" [2], and the effect should be observed by STM experiments. We further discuss the robustness of the n=0 Landau level and the quantum Hall plateau transition against randomness based on the lattice model and topological methods [3].

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Superconducting transport properties of a three-terminal kink-junction in graphene

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We investigate numerically the transport properties of a three-terminal graphene kink-junction, with one superconducting and two normal terminals. Electron transfer and crossed Andreev processes are identified, and the competition between the two processes is studied by means of the non-local signal between the two normal terminals.

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Nonlinear screening of charges induced by metal contacts in graphene

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Making devices with graphene necessarily involves making contacts with metals.
Recently, we have studied how graphene is doped by adsorption on metal substrates [Phys. Rev. Lett. 101, 026803 (2008)]. Here we extend this work to a device geometry that consists of a graphene sheet covered with a metal strip (electrode) of finite width. Two regions can then be identified that correspond to metal-covered and "free-standing" graphene. Understanding of the screening of charges induced by the metal contact in "free-standing" graphene as well as the electrostatic barrier formation at the contact is then essential for a graphene-based device. We calculate the induced potential and charge density using the Thomas-Fermi theory, and find that the screening in graphene is strongly suppressed as compared to a normal metal due to the ultra-relativistic nature of the electron spectrum near the Fermi energy. The induced potential slowly decays as x^{-1/2} away from the metal contact, breaking spatial homogeneity of graphene. At the contact region the metal contact causes the formation of a p-p, n-n or p-n junction that contributes to the overall resistance of the graphene sample, and destroys the electron-hole symmetry in graphene.

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Fabrication of side-gated graphene quantum dots

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We present the preparation and characterisation of graphene quantum dots etched out of mechanically exfoliated graphene flakes on silicon dioxide. Cleanliness of the flakes is determined by atomic force microscopy, while the single layer thickness is verified by quantum hall measurements.
Finally we will investigate the behaviour of the confined states of the quantum dots in magnetic fields at low temperature.

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Laser-induced disassembly of a graphene single crystal into a nano-crystalline network

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For graphene studies, Raman has proven a valuable tool as it provides information for instance about disorder, defects and doping. Furthermore it even allows to distinguish monolayer graphene from bilayers and multilayers. While Raman spectroscopy has usually been considered non-invasive, we will show here that laser irradiation of graphene or few-layer graphene either has to be dosed carefully to avoid structural modifications or can on purpose be exploited to induce structural changes in graphene in a controlled manner. The time evolution of the Raman spectrum of a graphene monolayer under laser exposure reveals two different effects: on a short time scale, dopants, initially present on the flake, are removed due to laser heating. This can be seen directly in the redshift of the G and D* Raman peak as well as in the field effect behavior of the graphene device. The longer time scale behavior points to a laser induced gradual local decomposition of single crystal graphene into a network of interconnected nano-crystallites with a characteristic length scale of approximately 10 nm due to bond-breaking. The effects of phonon confinement due to the small characteristic length scale are born out in the Raman spectrum. The broken bonds offer additional docking sites for adsorbates as confirmed in transport and AFM height studies. These controlled structural modifications may for instance be valuable for enhancing the local reactivity and trimming graphene based gas sensors.

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Lattice Monte Carlo studies of quantum critical phenomena in graphene

The study of graphene using the Lattice Monte Carlo method is of very recent date. Such an approach is non-perturbative and takes full account of quantum fluctuations, and is therefore well suited to the study of strongly interacting fermionic systems such as the quasirelativistic charge carriers in graphene. This presentation outlines the status of Lattice Monte Carlo studies
of graphene close to the semimetal-insulator critical point, which is likely to be highly relevant for the physics of graphene in vacuum (see abstract by Joaquin Drut) as the presence of this critical point suggests that graphene in vacuum should be an insulator rather than a semimetal.

At this time, the main objective is the establishment of the precise properties of this critical point, in order to settle the question of whether the transition to an insulating phase is of second order or of infinite order. In addition, recent Lattice Monte Carlo results for the DC conductivity of graphene are presented. This observable is of particular interest as current analytical studies underpredict the experimental data by approximately a factor of 3. Moreover, it has often been pointed out that a realistic description of the conductivity should account for non-perturbative effects due to the long-range Coulomb interactions between the fermionic quasiparticles in graphene.

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Structure, Stability, Edge States and Aromaticity of Graphene Ribbons

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The recent demonstration that graphene sheets spontaneously break into ribbons of narrow width and smooth edges, by means of chemical methods as solution-dispersion and sonication [1] or by means of controlled cutting through thermally activated metallic nanoparticles [2], has opened a breakthrough towards graphene-based nanoelectronics. In fact, the lateral confinement in a ribbon opens an electronic gap (function of the ribbon width) which makes graphene suitable for direct application as, e.g., a channel in field-effect transistor. In this regard, the knowledge of the structural and thermodynamical stability properties of the possible edges is crucial to achieve the experimental control necessary for technological applications.
By means of ab-initio calculations, we determine the stability, the geometric, the electronic and magnetic structure of graphene-nanoribbons edges terminated with those molecules which are likely to be found in the typical experimental condition for the ribbon-formation (hydrogen, oxygen and H+/OH- ions from water dissociation) as a function of their chemical potential. Antiferromagnetic mono-hydrogenated zigzag ribbons are stable only at extremely-low ultra-vacuum pressures. At high hydrogen-concentrations graphene is not stable and spontaneously breaks to form hydrogenated edges [3]. This fact is the key to explain the spontaneous breaking of graphene into small-width nanoribbons observed experimentally in organic compounds solution [1]. The stability and the existence of exotic edge electronic-states and/or magnetism is rationalized in terms of simple concepts from organic chemistry (Clar's rule). Finally, by simulating scanning tunneling microscopy (STM) images of the ribbons, we identify those characteristics of the various terminations which could be made visible in the measured STM, thus providing an effective approach to distinguish experimentally among various possible terminations.

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'Graphene: a perfect nanoballoon'

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We have performed a first-principles density functional theory investigation of the penetration of small atoms and molecules through a graphene monolayer with defects. We focused our examination on the penetration of helium atoms because this is the smallest inert atom. This means that if helium cannot penetrate through graphene probably nothing can get through. We first examined the potential barrier for penetration through a fixed intrinsic graphene sheet. Then we did some first-principles molecular dynamics simulations: we put a helium atom above the centre of a graphene hexagon and gave it a certain velocity towards the graphene sheet. When the helium atom impinges on the intrinsic graphene surface, there will be some relaxation of the carbon atoms in the graphene sheet. However, when we compare the result of the molecular dynamics simulations with the unrelaxed case, we notice that the relaxation does not have a strong influence on the kinetic energy of the He atom that is needed for penetration. This is due to the fact that the time scale for relaxation of the graphene is larger than the time scale during the He atom interacts with the graphene layer. The relaxation of the graphene layer occurs after the He atom has left the graphene layer. Therefore we can neglect any relaxation of the graphene layer. Intrinsic graphene appears to be impermeable for helium atoms and even if small defect are included, this impermeability remains. However, the penetration barriers decrease exponentially with the size of the defects but they are still sufficiently high that large defects are needed to make the graphene sheet permeable for small atoms and molecules. This makes graphene a very promising material for the construction of nanocages and nanomembranes.

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Interface structure of epitaxial graphene on SiC(0001)

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In spite of the enormous efforts devoted to the study of the epitaxial growth of graphene on SiC, no consensus has been reached regarding the structure of the interface between graphene and the substrate. Long standing discrepancy exists between low energy electron diffraction (LEED) patterns and scanning tunneling microscopy (STM) images on the periodicity of graphene on SiC(0001). Theoretical studies of reconstructions with 6rt3x6rt3 and rt3xrt3 periodicities, while describing some aspects of the experimental results, disagree in important details with STM observations. In this work, we present a combined experimental and theoretical study, employing density functional theory calculations and STM, to investigate this issue. We find that the graphene growth proceeds by first the formation of a defected carbon layer at the interface, and then the subsequent growth of well-ordered graphene layers. The calculated energy-dependent densities of states are in good agreement with our STM images, which provides insights into the details of the interface structure of epitaxial graphene on SiC(0001).

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Oscillating nanomembranes within a monolayer of graphene probed by STM

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Using scanning tunneling microscopy (STM) at low temperatures (5 K) in ultra-high vacuum, we investigate graphene flakes deposited by exfoliation on a Si/SiO2 (300 nm) surface.
On flakes which are partly freely suspended [1], nanometer-sized areas of the flake can be lifted by a few 100 pm using a voltage applied to the tip while still achieving stable tunneling conditions. From voltage and distance dependent tunneling data, we separate the influence of Van-der-Waals forces from electrostatic interaction. A model using a parallel-plate capacitor and a clamped circular membrane allows the determination of mechanical properties of the nanomembrane, such as pretension and Young`s modulus, in good agreement with previous data using atomic force microscopy (AFM) [2]. Application of an ac voltage leads to oscillations of the nanomembrane which are detected by strongly nonlinear in-phase current oscillations.

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p-n junction in graphene nano-ribbons

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A graphene nano-ribbon (GNR) is a quasi-one-dimensional system cut out of a two dimensional graphene sheet. It is currently under extensive investigation both from a fundamental perspective and for its potential in electronics. We report on electronic transport measurements performed on quantum dot devices based on graphene nano-ribbons. Local gates on the ribbon define the desired quantum dots. We observe Coulomb oscillations through such devices, and the coulomb peak spacings correlate with the designed device area. Finally, we observe that disorder plays a significant role in the low-temperature transport. Future studies will investigate the single particle energy level spectra and spin states.

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4-terminal transport in chemically doped graphene pn-junctions

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We investigated the influence of chemical doping on the transport properties of graphene. Water for instance causes a strong hysteresis known from carbon nano tubes [1], which depends on the sweep conditions of the gate voltage and the environment. A strong asymmetry between electron- and hole mobilities can be observed in freshly prepared flakes similar to what has been seen by other groups [2]. The asymmetry always vanishes after sufficient annealing. A remarkable observation is that this asymmetry changes its sign depending on the type of the adsorbed molecule. We see clear differences between H2O, O2 and NH3 for instance. The electron mobility of p-doped graphene is always below that of holes. After n-doping the electron-mobility becomes larger. The observation is in qualitative agreement with recent numerical calculations [3] which attribute the asymmetry to the influence of surface adsorbates. In addition we never observed a lowered mobility after doping with NH3 in contrast to what has been demonstrated using low-temperature potassium doping by others [4]. We speculate that because in our experiments doping is performed at room temperature (the measurement is done at 1.5 K), the adsorbates have a chance to form some equilibrium lattice where the individual adsorbate cannot be considered as a point scatterer.

The ability to modify graphene's intrinsic doping has been exploited in a technique for spatially selective chemical doping. Using this technique we fabricated graphene pn-junctions and studied the magneto-transport behavior of those devices in 4-terminal geometry. A magnetic field asymmetry in the longitudinal resistance of opposite edges can be observed. "Fractional" resistance quanta h/e2, h/3e2, h/15e2 appear in the longitudinal resistance as a result of edge channel mixing at the pn-interface. The main advantage of graphene pn-junctions formed by chemical doping is that the mobility is not reduced like in the case of top-gated pn-devices.

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Nanowire Lithography on Graphene

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Graphene nanoribbons (GNRs) are the counterpart of nanotubes in graphene nanoelectronics. Electron confinement opens a bandgap, making them suitable for the realization of devices. Current GNRs fabrication techniques mostly rely on e-beam lithography [1]. However, the search for a cheap, parallel and deterministic technique for practical implementation of these structures is still open. Nanowire-lithography (NWL) consists in using NWs as etch masks to transfer their one-dimensional morphology to an underlying substrate [2,3]. Here, we show that oxidised silicon NWs (SiNWs) are a simple and compatible system to implement the NWL concept on graphene. SiNWs are grown by chemical methods [4], and mechanically transferred or dispersed from solution onto graphene flakes produced on SiO2 by exfoliation [5]. The NW morphology is then mirrored into the graphene flake by a low power O2 plasma in a deep-reactive-ion-etcher. The process leads to conformal GNRs with diameter comparable to the overlaying NW lateral dimensions (down to 15 nm) [6]. The diameter can be further reduced by multiple O2 etching steps. Raman spectroscopy is used to characterise the structure of the resulting GNRs. Field-effect measurements show the transition from semi-metal to semiconductor. The influence of trap states on the device performance is discussed.

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Transport in decoupled graphene layers

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Recently it was shown that it is possible to contact two decoupled monolayers of graphene on top of each other and to control carrier densities in both layers via top and bottom gates [1].

We present transport measurements through such decoupled layers of graphene as a function of backgate and topgate voltage as well as magnetic field at temperatures down to 300mK. The graphene samples were obtained by micromechanical exfoliation of small natural graphite flakes onto a SiO2 substrate. Folded monolayers are then structured and contacted by using electron beam lithography (EBL). A PMMA layer (~60nm) is deposited onto the structured part to be able to fabricate an additional local gate (LG) afterwards.

In a four terminal measurement the resistance of the device was obtained by tuning the potential of the backgate and the topgate independently. Charge neutrality points of both regions are clearly visible, separating the different charge configurations (e.g. p-n-p, n-n-n) of the graphene field effect transistor.

The magnetic field dependence of the localy gated sample shows four different oscillations in the Shubnikov-de Haas (SdH) measurement. Two of these oscillations are dependent on the potential of the applied backgate, whereas the other two oscillations changes when tuning the local topgate. SdH oscillation minima are obtained at filling factors of 4(i+1/2) which is equivalent to a Berry phase of Pi. Calculations of the carrier concentrations from SdH measurements as well as a Berry phase of Pi shows the existence of two decoupled monolayers of graphene that can be tuned by gates independently.

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Structural and electronic properties of epitaxial graphene on SiC surfaces from ab initio calculations.

The structural and electronic properties of epitaxial graphene are studied with ab initio calculations based on the density functional theory. Both SiC polar faces - that is Si (0001) and C (000-1) - are investigated and the theoretical results are compared to our STM data and ARPES spectra.
On the Si face, the first C layer do not show graphene properties : it forms a buffer layer that decouples the subsequent graphitic layers from SiC. The strong interaction with the substrate induces a nanostructuration of the buffer layer that exhibits a complex mosaic like structure in agreement with what can be seen on STM images. The covalent bonding to the substrate destroys the graphene pi states in agreement with ARPES data. The actual graphene layer is the second C layer. The small coupling to the buffer layer generates soft 6x6 ripples in this plane that otherwise shows a free graphene like linear dispersion. The doping of this graphene layer and the effect of the interface states will also be discussed.
The interface morphology is quite different on the C face. We will show that a reconstruction passivates the SiC surface dangling bonds so that no buffer layer is found. In our model based on the 2x2 reconstruction of the C terminated face, interaction with the substrate is small even for the first C layer that shows graphene electronic structure. The orientation of the graphene layer is not (or slightly) imposed by the substrate and different orientations can be found both between C layers or within one C plane. The effect of the orientation disorder in a graphene bilayer will be discussed to show that it preserves the free graphene linear dispersion.

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Growth Studies of Epitaxial Graphene on 4H SiC for nanoelectronics

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Here, graphene was grown on single-crystal 4H SiC by radiative heating to above 1250°C in UHV conditions (10-10 mbar). In-situ LEED performed after each of several annealing steps enables different reconstructions of the (0001) surface to be used to monitor growth. A 11 reconstruction can be seen following a 600°C anneal, (6√36√3+√3√3)R30 after 1275°C, and finally (6√36√3)R30 above 1300ºC, indicating the growth of a graphitic layer [1].

The samples have been further characterised ex-situ. The ratio of XPS Si to C peak intensity indicates a carbon-rich surface. Although Raman spectra are well suited to characterising exfoliated graphene flakes [2], those from graphitised SiC do not indicate layer thickness so clearly [3]. Our spectra do show the appearance of carbon peaks, with intensity rising for higher annealing temperatures. AFM/STM images show domains with a 30nm grain size.

Electrical contacts have been patterned onto samples via optical lithography and four-point I(V) measurements have been made at room and cryogenic temperatures. We measure resistance of 295Ω at room temperature and 27.4kΩ at 33K with a voltage probe separation of 20μm, within the range of resistances reported by other groups, e.g. [1,4]. More detailed I(V) measurements, and field-dependent transport measurements are in progress.

This work was supported by the EPSRC and Intel Ireland.

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Transport gap in side-gated graphene constrictions

We present measurements on side gated graphene constrictions of different geometries. We characterize the transport gap by its width in back gate voltage and compare this to an analysis based on Coulomb blockade measurements of localized states. We study the effect of an applied side gate voltage on the transport gap and show that high side gate voltages lift the suppression of the conductance. Finally we study the effect of an applied magnetic field and demonstrate the presence of edge states in the constriction.

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"Theory of ARPES and magnetooptical measurements of bilayer graphene grown on SiC"

M. Mucha-Kruczynski, E. McCann, V.I. Fal'ko
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Using the tight-binding approach we investigate the properties of bilayer graphene grown on SiC. We model interactions with the underlying substrate by including an energy difference between the layers and sublattice asymmetry in the bottom layer. We show that these
asymmetries affect the band structure and the Landau level spectrum of the system by opening a gap. In the band structure, `Mexican hat'-like structures appear. In the case of the Landau level spectrum, the Landau level valley degeneracy is lifted and the zero-energy Landau level is split into four. Finally, we predict results of angle resolved photoemission spectroscopy (ARPES) and magnetooptical measurements of bilayer graphene. For ARPES, we show that the anisotropy of constant-energy maps may be used to extract information about the magnitude and sign of
interlayer coupling as well as the aforementioned symmetry-breaking parameters. For magnetooptical measurements, we check the robustness of selection rules for inter-Landau-level transitions in the presence of the asymmetries.

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Ab initio Quantum Monte Carlo study of interlayer binding in graphitic nanostructures

The electronic structure of graphitic systems is studied using ab initio quantum Monte Carlo methods implemented in the CASINO code. The diffusion Monte Carlo method allows the exact handling the long-ranged correlations responsible for the London dispersion forces that dominate the interlayer binding. The finite size errors caused by the limited volume of the simulation cell are reduced by a careful extrapolation to infinite size giving a reliable theoretical prediction of the interlayer binding of graphite and related nanostructures.

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Raman spectroscopy studies of folded graphene

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The electronic properties of graphene are highly sensitive to the number of graphene layers and also the stacking geometry.[1] Raman spectra of graphene are very sensitive to the electronic band structure of graphene and hence can be used to investigate the electronic structure of multilayer graphene that deviates from the AB stacking.
In this work, we have successfully made the 1+1 folded graphene with different stacking order and Raman and contrast imaging were carried out to precisely locate the folded sample.[2] Raman spectroscopy was also used to determine the edge chirality of graphene [3] and hence estimate the rotational angle between the two graphene layers.
The Raman results of folded graphene include two parts: Firstly, the 2D band of folded graphene is similar to that of single layer graphene (SLG) and obvious blueshift of 2D band of folded graphene was observed. The blueshift is weakly dependent on excitation energy. These phenomena are interpreted in term of change of electronic structures of folded graphene.[4] It is proposed that the electronic structure of 1+1 folded graphene is similar to SLG but with smaller Fermi velocity. Secondly, strong resonance of G band (with intensity 10 to 50 times higher than that of SLG) was observed on some of the 1+1 folded graphene sample. First principle calculations were carried out to study the electronic band structure of such folded graphene, with orientation and rotational angle predetermined by Raman spectroscopy. It is found that the phonon energy of G band may match the small split of electronic bands of folded graphene when excited by ~2.7 eV laser energy. Therefore, both the incident and scattered photons (G band) are resonant with real electronic states and hence result in the strong G band resonance.
Our findings on folded graphene help on the better understanding of electronic structure of graphene with different stacking geometry.

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Transmission electron microscope observation of the interface between graphene and 6H-SiC (0001)

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Few-layer graphene on the SiC substrate is one of the promising materials for device integration. The opening of a gap in few-layer graphene due to the interaction with the SiC substrate is also an advantage in switching-device application. For detailed understanding of the electronic state due to the interaction between graphene and the SiC substrate, it is important to observe the cross-section directly from a perspective parallel to the interface. In this study, high-resolution transmission electron microscopic (TEM) cross-sectional observations were performed to investigate the interface structure between graphene and 6H-SiC (0001). A first principles calculation combined with high-resolution TEM allowed us to understand the interface structures together with their electronic states.

Graphene-on-SiC samples were prepared by annealing Si-terminated 6H-SiC single crystals. SiC substrates were cleaned using HF solution and then annealed at different temperatures, ranging from 1350 to 1500 ºC, in a vacuum furnace. Thin specimens for TEM observation were prepared by Ar-ion thinning method. Cross-sectional observation of the interface structure was carried out using a JEM-2010-type TEM with an accelerating voltage of 200 kV.

Our observations revealed the presence of a metastable transitional structure formed by decomposition of a single SiC bilayer as well as fully-packed honeycomb graphene as the interface structure. The results of our calculation clarified that the difference in the interface structures should strongly influence the electronic state. Our observation also revealed the process of the layer-by-layer decomposition of the SiC substrate during the formation of graphene layers. The obtained results of our observations and calculations will be reported in the conference.

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Tunning the proximity effect in graphene.

C. M. Ojeda-Aristizabal, M Ferrier, S Guéron and H. Bouchiat.

We have tuned in situ the proximity effect in a single graphene layer coupled to two superconducting electrodes. An annealing current through the device changed the transmission coefficient of the electrode/graphene interface, encreasing the probability of multiple Andreev reflections. After three annealing steps the contact was improved sufficiently for a Josephson current to be induced in graphene. Universal conductance fluctuations also depended on the annealing step.

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Title: "The insulating state of graphene nanoribbons"

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The last few years graphene -a single atomic layer of graphite- has attracted a lot of attention, because of its unusual electronic properties. Besides, the high carrier mobilities measured in graphene (up to 100,000 cm2/Vs) make it also a new promising candidate for future high-speed electronic devices. However, since graphene is a zero-gap semiconductor, electrical conduction cannot be switched off by using control voltages, which is essential for the operation of transistors.
In this presentation I will show that the conduction can be swithed off in narrow graphene ribbons. Although these ribbons are metallic at high charge densities, they become insulating at low densities. We have studied the insulating properties as a function of temperature and magnetic field. The experimental results indicate that the insulating state is a consequence of strong localization of electronic states. This result makes graphene ribbons possibly interesting for graphene-based field-effect transisors.

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Self-standing graphene sheets fabricated by a CVD growing technique

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Because of the small miss-fit of lattice constants and surface periodicity, a graphene sheet of a monolayer thickness grows in the epitaxial way to the some
substrate lattices by a CVD technique. In particular, high-quality crystalline film grew in the 1x1 structure on Ni (111) surfaces. The orbital mixing of the pai electrons anddelectrons of Ni substrate produces relatively strong inter-layer bonds, which selects with the unique position of carbon atom on the Ni substrate; they are three-hold
hollow sites and on-top sites. On the other hands, intra-layer bonds of graphene sheet became week. Since the surface free energy of Ni (111) was decreased with graphene-
coverage, the faceting phenomena results in the expansion of the (111) surfaces with the step bunching, which indicates the possibility of fabricating macroscopic graphene sheet.By solving only the Ni substrate with acids chemically, we successfully fabricated self-standing graphene sheet, which was now investigated by using TEM. We will discuss the difference between this sheet and the other ones prepared with the other technique

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Gate controlled non-volatile memory devices using graphene and ferroelectric thin films

We demonstrate a novel non-volatile memory device using a combination of graphene and a ferroelectric thin film. The binary information, i.e. “1” and “0”, is represented by the high and low resistance states of the graphene working channels and is switched by the polarization directions of the ferroelectric thin film. A highly reproducible resistance change exceeding 300% is achieved in our graphene-ferroelectric hybrid devices under ambient conditions. By avoiding the chemical modification of the unique 2D crystalline structure of graphene, this device concept utilizes the intrinsic field-dependent conductance and retains the high charge carrier mobility in graphene. All these make this new memory structure a promising candidate for the next generation of ultra-fast non-volatile memory.

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Pristine and intercalated graphite revisited: A key to graphene

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The contribution will give an overview on our current research focus on the electronic and optical properties of graphite and graphite intercalation compounds using angle resolved Photoemission (ARPES) and electron energy-loss spectroscopy (EELS) as probes. We clearly proof that we are able to unravel the complete valence band structure of both graphite and doped graphene, using KC8 as archetype for the latter. The comparison to ab-initio calculations highlights the importance of the inclusion of electron-electron interactions on the GW level in describing the electronic band structure graphite [1] and of doped graphene [2]. In addition, we also analysed the optical properties of individual large diameter single wall carbon nanotubes [3] and graphite [4] using EELS. We clearly proof that local field effects are crucial in explaining the momentum dependent optical properties of this low dimensional carbon systems. The pi plasmon dispersion of in plane graphite is fully explained by a quadratic dispersion whereas the pi plasmon of isolated SWCNT along the tube axis is strictly linear and a clear manifestation of the excitation spectrum of graphene.
In summary the detailed understanding of these fundamental electronic and optical properties of graphite, SWCNT and graphite intercalation compounds is one key to gain new insight into the underlying electronic structure of graphene.

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Title: Theory of the plasmon pole in doped graphene sheets

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Plasmons in ordinary electron liquids with standard parabolic bands are collective density oscillations whose dispersion, to leading order in momentum in the long-wavelength limit, is rigorously unrenormalized by many-body effects as a consequence of gauge, Galileian, and translational invariance. At low energies, electrons in doped graphene sheets are described by a massless Dirac fermion Hamiltonian, which is not invariant under ordinary Galileian boosts. As a consequence, the plasmon pole in doped graphene sheets is non-trivially renormalized by electron-electron interactions, even at the leading order in the long-wavelength limit. This effect is not captured by the simple Random Phase Approximation (RPA). In this talk we will present a many-body theory of this subtle effect that goes beyond the RPA. We will also discuss the implications of our findings for theories of charge transport and cyclotron resonance in graphene sheets.

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Nanoscale capacitive behaviour of graphene on SiO2

Graphene, a flat monolayer of carbon atoms tightly packed into a two-dimensional (2D) honeycomb lattice, is the object of intense theoretical and experimental investigations, due to its outstanding electronic properties, making this material the bridge between solid state physics and quantum electrodynamics. Electronic transport behaviour (extremely high mobility, ballistic transport..) and electrostatic properties (the occurrence of field effect) have been experimentally studied in graphene and/or few layer graphene (FLG) crystals obtained by mechanical exfoliation of graphite or by graphitization of SiC surface. However, no experimental investigation of the capacitive behaviour of graphene has been reported.
In this work, we present an accurate nanoscale investigation on the capacitive behavior of graphene deposited on SiO2/n+ Si substrates with different SiO2 thickness (300 or 100 nm). Graphene flakes were identified by the combination of optical microscopy and atomic force microscopy (AFM). Local high frequency capacitance-voltage measurements were carried out on an array of well defined positions both on the graphene flakes and on the bare SiO2 by a Pt coated AFM tip connected to a high sensitivity capacitance sensor. A bias Vg composed by an AC signal and a slow DC voltage ramp was applied to the macroscopic n+ Si backgate, while a nanoscale contact was obtained on graphene by the AFM tip. By comparing the C-V characteristics on the Pt tip/SiO2/Si nanoscale MOS capacitor with those on the tip/graphene/SiO2/Si capacitor, both the “effective” biased area (Aeff) on the flake and the local graphene quantum capacitance (Cq) were determined. Interestingly, the capacitor effective area Aeff responding to the AC bias is much smaller than the geometrical area of the graphene sheet. This area is related to the length scale on which the externally applied potential decays in graphene, i.e. the screening length of the graphene 2DEG. The not-stationary charges (electrons/holes) induced by the AC potential spread within this area around the contact. Aeff increases linearly with the bias (i.e. proportionally to the induced charge density in graphene) and in a symmetric way for bias inversion. For each bias Vg, the value of Aeff is related to the minimum area necessary to accommodate the not stationary charges, according to the graphene density of states (DOS) at Vg. The local quantum capacitance Cq in the contacted graphene region was calculated starting from the screening length, and the distribution of the values of Cq for different tip positions was obtained. Finally the lateral variations of the DOS in graphene was determined.

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Epitaxial graphene: a correlated system?

A single graphene layer grown on 6H-SiC(0001) exhibits an intriguing gap-like structure near the Fermi-level in scanning tunneling spectroscopy as well as an asymmetric density of states which is not well understood. Atomic-resolution tunneling-asymmetry imaging shows spatial variations at carbon sites indicative for localized Si-C electron states in both the interlayer 6sqrt3x6sqrt3R30 structure and the graphene layer formed on top. Inelastic Electron Tunneling Spectroscopy shows huge phonon contributions, with a maximum intensity near the Si-C electron states. We propose that these features can be explained in the context of electron correlation effects and disorder in a single layer of electron-doped graphene due to a strong interaction between the graphene electrons and the localized states of the interlayer.

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Tunable band structure in double gated trilayer graphene

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Graphene based materials are promising candidates for nano electronic applications. It is currently unclear which layer thickness is better suited for a given application, as only the properties of monolayers and bilayers have been investigated systematically. For the optimization of future devices, it is important to understand how the electronic properties of graphene based materials evolve from Dirac particles, in monolayer, to massive particles in bulk graphite. We experimentally address this question by investigating transport in trilayer graphene –i.e. the thinnest few layer graphene in which all the parameters determining the band structure of graphite are first found. In this talk we present the results of a systematic comparison of intrinsic electronic properties measured in several double gated structures of single, double and triple layer graphene as a function of carrier density, temperature, and perpendicular electric field. Contrary to monolayer and bilayer (which are both zero gap semiconductors), we find that trilayer is a semimetal with a finite overlap of conduction and valence bands. We show that the low energy band structure of trilayer graphene can be tuned by a large amount by means of an external perpendicular electric field, achieving 100% change in band overlap a property not known to occur in any other semimetal. The quantitative analysis of the data further allows the determination of the carrier effective mass, which accounts for large part of the observed evolution of the carrier mobility with layer thickness.

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Towards graphene epitaxy on Si

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Graphene is a single plane of sp2 carbon atoms arranged in a hexagonal lattice. Thanks to its interesting electronic properties, originating from the linear dispersion of the pi and pi* bands in the vicinity of the K point of the Brillouin zone, it represents a promising two-dimensional electron gas system for new high-speed, ballistic-transport based electronic devices [1, 6].

Using exfoliated graphene, a number of impressive results have been obtained, but it is questionable whether this preparation route is suitable for technological processes where large areas of uniform graphene would be required. Solid state graphitization of 4H or 6H silicon carbide surfaces by annealing in UHV at temperatures between 1100 and 1400 °C has been demonstrated to result in excellent quality material [4], but the large cost and limited size of SiC substrates represent a significant hurdle for industrial application of this process. If a similar process could be transferred to SiC grown epitaxially on Si, then the SiC sublimation approach could point the way to an industrial scale fabrication method for high quality graphene layers on a Si platform.

We have studied few layer graphene formation on 4H-SiC monocrystals (hexagonal C and Si faces) as well as 3C- SiC epilayers on Si(100) and Si(111). Our data suggests that few layer graphene formation on 4H-SiC requires a minimum temperature of 1350 °C and occurs preferentially by nucleation in pits or at SiC surface defects where the density of atomic steps is high, resulting in the formation of disk-shaped few-layer graphene regions, several tens of micron in diameter. These disks exhibit a negligible D peak in their Raman spectra, suggesting a low degree of structural defects, as well as a single component 2D peak, indicating single graphene layer electronic behavior. Meanwhile, for 3C-SiC layers grown epitaxially on Si, Si sublimation starts at 1300°C, opening the possibility of synthesizing few-layer graphene on a 3C-SiC/Si stack without melting the underlying substrate. Peculiar Raman features of the obtained triangular-shaped graphene regions have been investigated.

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Graphene-based terahertz lasers and detectors: Physics and feasibility of realization

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The gapless energy spectrum and possibility of bandgap engineering open up prospects of realization of novel terahertz (THz) and far infrared (FIR) devices. We consider and analyze terahertz lasers based on graphene and graphene bilayer heterostructures with optical pumping. We show that the optical pumping followed by emission of a cascade of optical phonons can result in the population inversion between the low energy states. The latter implies the negative contribution of the interband transitions to the graphene (or graphene bilayer) dynamic conductivity in the THz frequency range.
Analytical estimates and numerical simulations demonstrate that despite the intraband (Drude) absorption and the losses in the device waveguide structure, this can result in the negative net dynamic conductivity and, hence, provide an opportunity of creating graphene-based THz/FIR lasers.
We also present concepts of THz/FIR detectors with the structure of a field-effect transistor (THz/FIR phototransistors) made of graphene nanoribbon arrays as well as of a graphene bilayer and analyze their characteristics (spectral characteristics, responsivity, and detectivity) as functions of the structural parameters and applied voltages.

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Quantum Interference in Graphene Structures

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We show that quantum interference of carriers in graphene is very different from that in conventional 2D systems. This is seen both in effects of weak localisation (WL) and universal conductance fluctuations (UCF) which appear with changing the carrier concentration and magnetic field. In addition to phase-breaking (inelastic) scattering, both effects are strongly dependent on different elastic scattering mechanisms that control inter-valley scattering and intra-valley suppression of quantum interference [1-2].

By performing comparative studies of WL and UCF in different graphene samples fabricated by mechanical exfoliation, we establish the roles of this elastic scattering for a range of experimental situations. We show that the interplay between elastic and inelastic scattering controls the change of the sign of the quantum correction to the conductance and the transition from WL to anti-WL, and at the same time a noticeable change in the amplitude of UCF. The correlation properties of the fluctuations, however, can be largely independent of the details of carrier scattering [3].

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Growth and analysis of graphene on different nickel substrate surfaces

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Graphene is one of the most promising advances of the past years in condensed-matter physics. The two-dimensional graphite structure exhibits exceptionally physical and electronic properties, which offer innovative applications in future nanotechnologies. On the way to real applications one has to overcome the difficulties of a controlled synthesis and insulation as well as the difficulties in realizing an electric contact. Therefore, the main topic of this paper concerns the graphene-synthesis on real surfaces by comparing the growth on single crystalline Ni(111)-and on polycrystalline nickel-surfaces. Principle characteristics of adsorption and of the catalytic reactivity of the substrates were examined by adsorption of carbon monoxide (CO) and propene (C3H6). High Resolution Electron Energy Loss Spectroscopy (HREELS), X-ray Photoelectron Spectroscopy (XPS) and Low Energy Electron Diffraction were used to analyze the differences between the surfaces. The method of epitaxial growth supplied monolayer graphene on Ni (111) and few-layer graphene on polycrystalline nickel. Measuring the surface phonon dispersion relation revealed characteristic differences, which are discussed in detail.

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Transport measurements in width modulated graphene nanoribbons

Silvia Schmidmeier, Dieter Weiss, Jonathan Eroms

We investigate electronic transport both in graphene and graphene nanoribbons (GNRs). This allows us to determine the influence of the dimensionality on the transport properties.
The lateral confinement of the charge carriers in the quasi one-dimensional ribbons creates an energy gap near the charge neutrality point, where the gap depends on the width of the GNR. The effect of different widths has already been investigated in previous studies (Han et al. PRL 98, 206805 (2007); Chen et al. Physica E 40 (2007)). Here we are using this width dependence to create a potential modulation along the nanoribbon. To this end, the nanoribbon width is varied periodically, which we expect to affect the electronic transport in an interesting way.
Graphene nanoribbons with different width, flat as well as modulated ribbons, were fabricated by electron beam lithography and plasma etching techniques. The devices are fully tunable by two graphene sidegates and a backgate.
Here we present the first measurements on those GNRs. In order to verify the single-layer character of the investigated devices we performed quantum Hall measurements and found the characteristic half-integer quantization.
By examining the differential I-V characteristics of the GNRs at different backgate voltages a transport gap is clearly observed at the Dirac point. These measurements allow us to determine the size of the energy gap.
We also measured the magnetoconductance in a perpendicular magnetic field for different temperatures. At low magnetic fields weak localization is clearly visible, therefore the phase coherence length can be determined by 1D weak localization theory . Additionally the amplitude of the universal conductance fluctuations allows us to extract the phase coherence length in an independent way. Both measurements are in good agreement.

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Electronic Transport in Graphene Quantum Dots

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We demonstrate that excited states in single-layer graphene quantum dots can be detected via direct transport experiments. Coulomb diamond measurements show distinct features of sequential tunneling through an excited state. Moreover, the onset of inelastic co-tunneling in the diamond region could be detected. For low magnetic fields, the position of the single-particle energy levels fluctuate on the scale of a flux quantum penetrating the dot area. For higher magnetic fields, the transition of the formation of Landau levels is observed. Estimates based on the linear energymomentum relation of graphene give carrier numbers of the order of 10 for our device.

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Adsorbate-limited conductivity of graphene

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This talk presents a theory of electronic transport in graphene in the presence of randomly placed adsorbates [1].
The analysis predicts a marked asymmetry of the conductivity about the Dirac point, as well as a negative weak-localization magnetoresistivity. In the region of strong scattering, quantum corrections drive the system further towards insulating behavior. These results explain key features of recent experiments, and are validated by numerical transport computations.

[1] Adsorbate-limited conductivity of graphene
J. P. Robinson, H. Schomerus, L. Oroszlany, and V. I. Fal'ko, Phys. Rev. Lett. 101, 196803 (2008)

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Graphene Transistors - Prospects and Problems

Soon after the first realization of graphene samples by Novoselov and Geim in 2004, device engineers started to explore different options to use this material for electronic applications. Since early 2007, a limited but steadily growing number of experimental graphene transistors have been presented and, in parallel, the results of theoretical investigations on the performance of graphene transistors have been published. While most of the authors made optimistic predictions regarding the potential of future graphene transistors, a number of quite critical conclusions have been drawn as well.

The aim of the present paper is to assess the potential and the expected performance limits of future graphene-based transistors as realistically as it is possible at the present time. In particular, we will review the low-field and high-field carrier transport properties in graphene and their relation to the bandgap. It will be shown that, for a given bandgap, graphene does not provide a distinct advantage over more common semiconductors (i.e., Si, Ge, III-V compounds) in terms of the electron mobility. In connection to this, the effect of carrier mobility on the performance limits of FETs (field-effect transistor) in general will briefly be discussed.

It is important to recognize that carrier transport is only one issue relevant to the performance of transistors. Therefore, other factors strongly affecting transistor performance will be discussed. In particular, we will focus on FETs and highlight the role of electrostatics and short channel effects, and apply the concept of scale length, which is well established for Si MOSFETs (metal-oxide-semiconductor FET), to graphene MOSFETs. It will be shown that, regarding the scale length, graphene MOSFETs have a clear edge over FETs of any other material. Finally, the importance of drain current saturation for FET performance will be discussed. Based on experimental data published by other groups for graphene FETs with either metal-like or semiconducting graphene channels and results obtained in our lab we will discuss the problem of drain current saturation in graphene MOSFETs.

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Resist-free approach for contacting graphene and few-layer graphene

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Graphene has recently attracted increasing interest due to its exotic properties [1]. In particular, exceptional electronic transport properties (i.e. μ~200,000cm2/Vs in suspended annealed sample [2]), makes graphene an outstanding candidate for future high-performance robust nanoscale electronic devices. Conventional techniques currently used to fabricate graphene devices include resist-based lithographic approaches, which incidentally modify the structure and the surface of graphene, and therefore its properties by the presence of residual adsorbates. Post-fabrication treatments have been proposed to partially recover intrinsic properties of graphene [2,3]. Here, we present a simple single-step approach for contacting graphene and/or few-layers graphene by a resist-free non-invasive method. Focused ion beam-designed or microfabricated patterned membranes are used to direct masking samples laying on a substrate, followed by a metal evaporation to produce metal electrodes for electrical testings. Further, we illustrate some of our preliminary measurements of the room- and low-temperatures properties of a FLG sample contacted by such technique. This resist-free approach is of general use, including in UHV, and reveals to be extremely powerful when surface damaging and/or modification need be avoided to preserve the intrinsic properties of the material.

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Magnetoresistance in hydrogen-doped graphene nanoribbons.

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Recent works have focused on hydrogen-doped graphene, both in the diluted and highly doped concentrations. It is known that a single hydrogen atom on top of a carbon atom in graphene has a magnetic moment. In the case of a low concentration of hydrogen dopants, it is believed that the ground state features local moments with zero total spin.
Application of a strong enough magnetic field can spin polarize the system, in analogy with diluted magnetic
semiconductors. In this work we study whether this spin order changes the resistance of the system. We study the relation between conductance and spin order for hydrogen-doped graphene armchair nanoribbons. We use both mean field Hubbard model and density functional theory calculations and compare results from both approaches. For the latter one, B3LYP hybrid functional is used. The conductance is calculated for the diluted limit. We use the Landauer formalism with the Green's Function Approach for the conductance calculation. We find that the conductance in these systems is significantly affected by spin order. Thus, we predict magnetoresistance in graphene ribbons doped with Hydrogen.

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Growth, characterization, molecular doping and bandstructure engineering of epitaxial graphene on SiC(0001)

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Graphene with its unconventional two-dimensional electron gas properties promises a pathway towards nanoscaled carbon electronics. Large scale graphene layers for a possible application can be grown epitaxially on SiC surfaces by Si sublimation. In the present work we investigate the initial growth of graphene on SiC(0001) using scanning tunneling microscopy (STM), low energy electron diffraction (LEED), angle resolved ultraviolet photoelectron spectroscopy (ARUPS) and Raman spectroscopy. Using ARUPS with UV light from a laboratory based He source we can control the number of graphene layers grown by monitoring the conical bandstructure of the pi-bands around the K-point of the graphene Brillouin zone. We show that also the spot intensity spectra in LEED can be used as fingerprints for the exact determination of the number of layers for the first three graphene layers. LEED data correlated to the ARUPS results allow for an easy and practical method for the thickness analysis of epitaxial graphene on SiC(0001) that can be applied continuously during the preparation procedure. On a micrometer scale the graphene thickness can be controlled by Raman spectroscopy. By looking at graphene flakes exfoliated from the SiC surface we can isolate those properties of the graphene layers originating from their interaction with the substrate. Most importantly, epitaxial graphene layers display an intrinsic n-doping due to the interaction with the SiC substrate that can be observed by both ARUPS and Raman. We investigate the details of the electronic structure of mono- and few-layer graphene and show that by the deposition of tetrafluorotetracyanoquinodimethane (F4-TCNQ) one can neutralize the intrinsic n-doping of the graphene layers. F4-TCNQ provides a stable functionalization of graphene that is device compatible, and we show that it can even be attached from chemical solutions. On bilayer samples we show that during the progressive doping reversal also the details of the band structure are influenced and a band gap engineering seems possible. With the molecular layer the metallic graphene samples on SiC can be turned into truely semiconducting layers.

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Graphene on various substrates

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So far nearly all transport experiments on graphene have been carried out using silicon dioxide (SiO2) as a substrate. In transport experiments of suspended graphene it was shown that the substrate has a strong influence on the carrier mobility. Effects like weak localization or spin relaxation in spin injection experiments in graphene also strongly depend on the presence of charged and magnetic impurities. Hence it is of great importance to study electrical transport in graphene on substrates other than SiO2.
To clarify the influence of the substrate on visibility, morphology and all transport properties of graphene and few layer graphene (FLG), we study graphene on (001)-GaAs, manganese p-doped (001) GaAs and InGaAs. But the detection of graphene on these substrates grown by molecular beam epitaxy (MBE) is challenging as the usual method employing the interference contrast in an optical microscope gives no reliable signature. Hence we combine scanning electron microscopy (SEM) and atomic force microscopy (AFM) to detect, pattern, and study the morphology of the graphitic layers on different substrate materials.
The MBE grown substrates can be tailored in terms of morphology, polarity as well as doping and are all equipped with back-gate electrodes. From morphology and flexibility measurements we learned that graphene is quite flexible and follows continuous textures. Thin layers of carbon have the capacity to follow the morphology of the substrate from the nm- to the μm range. Low-temperature magnetotransport measurements of graphene on these substrates reveal normal electric field dependence via back gate voltages as known from reports of transport on suspended graphene or layers on SiO2. In our measurements, the charge neutrality point (CNP) appears close to zero-field indicating a low concentration of charged impurities.
In further studies, the influence of the substrate on position and sharpness of the CNP, intrinsic carrier density and mobility will be investigated.

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The non-linear optical properties of single and multilayer graphene

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After producing single and multilayer graphene samples by using the standard scotch-tape technique on transparent substrates like glass and sapphire optical experiments were performed using a homemade confocal microscopy setup with diffraction limited spot size and sub-micrometer lateral resolution.
By exciting single and multilayer graphene flakes with pico- and femtosecond pulses of different wavelength and with pulse power densities in the order of GW/cm² we can not only observe the well known G-line (1580 wavenumbers) and D’-line (2700 wavenumbers) but also the anti-Stokes G line. In addition to that, a broad background can be detected which peaks at the excitation wavelength and which extends by about 3000 wavenumbers into the red and about 2500 wavenumbers into the blue. Both, the continuum and the anti-Stokes G line were found to be of cubic dependence with respect to the incident laser power.
We can explain the occurrence of the anti-Stokes G line as a result of a stimulated Raman process due to the pulsed laser excitation.
As we will give further evidence, simple heating effects of the flakes cannot account for the broad continuum radiation; however this feature can be assigned to an electron-hole scattering mechanism which depends primarily on the number of excited charge carrier pairs. By this model it also becomes evident that the continuum is centered around the excitation wavelength and not at a material dependent fixed spectral position.
As a possible application we show that due to its higher integrated intensity and its higher order dependence on incident laser power this continuum radiation can be used to significantly improve the contrast of a confocal image compared to that mapped at the Raman lines and thereby will pave the way of a detection mechanism of high sensitivity.

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Optical Conductivity Measurements of Graphene on Glass

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The optical conductance of graphene in the visible frequency range is very nearly given by a universal value (~0.023 when normalized by the impedance of free space). We show experimentally that this universal conductance is sufficiently large that optical reflection microscopy can be used to reliably count graphene layers deposited on bulk, low-index substrates such as glass. Optical reflection microscopy on bulk substrates can be used to measure the optical conductance of graphitic flakes. We will present experimental data on the transition from graphene-like optical conductance to bulk graphite-like optical conductance versus thickness.

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Electron-Beam Irradiation Damage of Graphene and Graphene Devices

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Graphene has attracted major attention of the research community owing to a number of its unique properties. From the practical point of view, some of the most interesting characteristics of graphene are the extraordinary high room temperature carrier mobility and recently discovered high thermal conductivity [1]. Graphene characterization and device fabrication require an extensive use of the scanning electron microscopy (SEM), transmission electron microscopy (TEM) and focused ion beam (FIB) processing. The techniques involving the electron beam irradiation of the samples may result in damage and disordering leading to deterioration of the electrical and heat conduction properties. The damage to the material, which consists only of a single or few atomic layers, during its characterization can be quite significant even at low radiation doses. In this talk we report micro-Raman investigation of changes in the single and bi-layer graphene crystal lattice induced by the low and medium energy electron-beam irradiation (5 – 20 keV) typical of the electron microscopy. After that the samples were subjected to electron beam irradiation. It was found that the radiation exposures results in appearance of the strong disorder D band suggesting significant damage to the crystal lattice. The D and G peak evolution with the increasing radiation dose indicates graphene transformation to nanocrystalline form, and then to amorphous carbon. The micro-Raman spectroscopy data for the transformation of graphene lattice was independently confirmed with the measurements of the electrical resistance of graphene samples. Using the Tuinstra – Koening relation for the intensity of the D and G peaks, I(D)/I(G), we were able to determine that the grain size in graphene is on the order of ~ 2.4 – 3.5 nm after just few minutes of irradiation when graphene transforms to nanocrystalline form. The obtained results have important implications for graphene electron microscopy characterization and graphene device fabrication, which required electron microscopy and focused ion beam processing.

The work in Balandin group was supported, in part, by DARPA – SRC Focus Center Research Program (FCRP) through the Interconnect Focus Center (IFC).

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The reduction of the Lifsitz transition density in graphene bilyers due to many-body effects

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We show that the renormalization of the physical parameters of the graphene bilayer system by the electron-electron interaction near neutrality results in a logarithmically enhanced inverse effective mass and trigonal warping within the Hartree-Fock approximation. The net effect of these renormalizations in the low-energy bands is to reduce the critical density of the Lifsitz transition, the crossover between the single-pocket and four-pocket topology of the Fermi surface. This reduction is estimated both for a suspended sample and one placed on a SiO$_2$ substrate handling the screened Coulomb interaction within the random phase approximation.

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Finite difference method for transport properties of massless Dirac fermions

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We adapt a finite difference method of solution of the two-dimensional massless Dirac equation, developed in the context of lattice gauge theory, to the calculation of electrical conduction in a graphene sheet or on the surface of a topological insulator. The discretized Dirac equation retains a single Dirac point (no "fermion doubling"), avoids intervalley scattering as well as trigonal warping, and preserves the single-valley time reversal symmetry (= symplectic symmetry) at all length scales and energies -- at the expense of a nonlocal finite difference approximation of the differential operator. We demonstrate the symplectic symmetry by calculating the scaling of the conductivity with sample size, obtaining the logarithmic increase due to antilocalization. We also calculate the sample-to-sample conductance fluctuations as well as the shot noise power, and compare with analytical predictions.

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Controlled thinning of few-layer graphite to graphene

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To fulfill the many technological promises envisioned for graphene, it is detrimental to have access to a reliable method to synthesize large area graphene or manipulate graphite down to the level of single graphene layers. This work contributes to the ongoing research[1,2] on the controlled manipulation of graphite thickness with the objective to reduce it down to single graphene sheets. In this work, the few-layer graphite samples are prepared by micromechanical cleavage and transferred to a substrate such as, for example, SiO2.
We have found that layer by layer removal is possible by using successive oxidation of the samples under mild conditions. Besides the parameters like temperature and time, it seems that this oxidation mechanism is mainly controlled by the composition of the gas used during the heating cycle. Besides the subtle layer-by-layer removal, the mechanism changes if more severe oxidative conditions are used. Under these conditions, the oxidation preferably starts from edges and defect sites resulting in an increase of number and size of the defect areas. More importantly, thinning is not observed. These findings are supported by optical characterization methods such as in-situ Raman measurements, AFM analysis, and annealing experiments under inert atmospheres and with different oxygen levels. The objective is to use the controlled thinning under mild oxidations as a method to produce high quality graphene surfaces without oxide-related defect sites.
Besides oxidation, the composition of the gas in contact with the graphene surface may also alter its electronic properties under device operation. The results obtained for the different gas compositions contribute to the understanding of graphene devices for gas sensing application.

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Building a molecular detector with graphene

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A recent discovery that the conductance of graphene can be manipulated by molecules assembled on its surface opened a new direction of investigations: graphene-based sensors [1]. The reported electrical measurements on graphene devices show that the Fermi level versus the Dirac neutrality point is shifted by an amount different from one device to another. This hinders the fabrication and consistent characterization of devices relying on measuring graphene resistivity. The reason for this shift is not fully clarified, but the main influence factors can be: the doping of graphene by water molecules adsorbed from the environment, built-in electrical charges in the silicon oxide substrate or presence of impurities in/on graphene sheet. The impurities and substrate might also contribute to the lowering of the carrier mobility in graphene to room temperature values of 2000-5000 cm2/Vs, well below the theoretical expectations [2]. Therefore for the application of graphene as a sensor one should be aware of dependence of charge transport in graphene on its surface purity.

We show a method for a controlled shift of the Dirac charge neutrality point versus the applied gate voltage towards a desired value as well as an increase of carrier mobility by a factor of 6 in graphene by annealing the device at 150 oC in vacuum. We assume that such essential change in the mobility is determined by the desorbtion of the water molecules and the polymer contaminations (left behind from the lithography steps that are necessary for device application) from the graphene surface. Another issue of sensor application is an optimal sensitivity to adsorbed molecules on the graphene surface, which can be obtained by Hall type measurements in a magnetic field. However, besides the Hall resistivity, we present a non-trivial magnetic field dependence of graphene longitudinal resistance as well. This peculiar behavior is most pronounced at the charge neutrality point and in order to explain it, further experiments need to be done.

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2. K. Bolotin et al, Solid State Communications 146, 351–355 (2008).

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Title: Broadband Nonlinear Optical Response of Graphene Dispersions

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Since the discovery in 2004, GRAPHENE became one of the most prominent materials in the field of nanoscience and nanotechnology. Whereas the electronic properties of graphene have been generating much research interest, the optical properties remain largely experimentally unexplored. We studied for the first time, to the best of our knowledge, the nonlinear optical property of graphene in liquid-phase dispersions. Employing high-yield exfoliation of graphene in the liquid-phase, a series of dispersions with large populations of single and multiayer graphene was prepared. Transmission electron microscopy and Raman spectroscopy verify the high quality of the graphene flakes - unoxidized and defect-free. Nonlinear optical properties of these graphene dispersions were studied using the open aperture Z-scan technique at 532 nm and 1064 nm. The graphene dispersions exhibit broadband optical limiting. Nonlinear scattering, originated from the thermally induced solvent bubbles and microplasmas, is responsible for this nonlinear behaviour. Very different nonlinear properties were observed in various dispersions, implying an apparent solvent influence: the lower the surface tension of solvents, the better the optical limiting effect. The demonstration of the unique optical limiting property effectively extends the potential application of graphene from electronics to photonics. Part of results was submitted to Nano Letters.

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Transport properties of epitaxially grown graphene layers

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We are investigating charge transport across graphene, which is epitaxially grown on the silicon terminated side of SiC. We report on conductivity and Hall-effect measurements done both on macroscopic samples, which extend over many surface terraces with an average layer thickness of 1.2 monolayers as well as on micrometer sized hall bars, which are fully placed on atomically flat terraces. For both configurations, the mobility of ~ 1000 cm2/Vs at room temperature is very similar. We further report on field effect gating. A buried gate, provided by an implanted conducting layer, did not provide an observable charge carrier modulation. However, we present a novel method of top-level gating, which turns out to be very efficient. Both low experimental effort as well as low gate voltages are needed to drive the charge carrier concentration over the charge neutrality point.

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"Adsorbates on graphene: Impurity states and electron scattering"

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We investigate the electronic properties of graphene in presence of impurities and structural inhomogeneities by means of first principles calculations and model based approaches.
Impurities cause doping of graphene and adsorption site specific signatures in the local electronic structure. Firstly, we give a microscopic theory of doping of graphene by different types of realistic impurities. Molecular adsorbates (NO2, H2O, C2H5OH) as well as single atoms on graphene are considered and substrate effects are discussed. In general, open shell molecules are found be strong dopants, whereas the substrate turns out to be crucial for graphene's sensitivity to closed-shell adsorbates like H2O: These adsorbates do not cause any impurity states close to the Fermi level of free standing graphene but shift the substrate's impurity bands with respect to the graphene bands. In this way, H2O can lead to doping of graphene on top of a SiO2-substrate.
Furthermore, we analyze the adsorbate's impact on electron scattering in graphene. The occurrence of midgap states and their coupling to the graphene bands is discussed. H2O and C2H5OH can reduce the hybridization of graphene's electrons and impurity states of the substrate. A comparison of different sources of midgap states including static ripples, covalently bond and weakly bond impurities is given and discussed in the light of recent experiments.
Local probe techniques like scanning tunneling microscopy (STM) are powerful experimental tools to characterize the electronic structure of graphene. We give an ab-initio based guide to these experiments and explain how different types of impurities manifest in STM images and in scanning tunneling spectra. The adsorption sites of impurities can be identified in Fourier transformed STM images.

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Fabrication of graphene by bromine-intercalation and sonochemical exfoliation

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We present a method of producing suspensions of graphene sheets by combining intercalation and mild sonication. Ultrasonic treatment of graphite leads to the formation of small graphene-like flakes in solution. The delamination of the graphite is dramatically increased by intercalation of bromine. After ultrasonic treatment, large amounts of graphene-like flakes with varying thickness are observed in SEM and TEM. They can be adsorbed onto a surface of a suitable substrate by a simple dipping technique. The effect of polar and non-polar solvents as well as adsorption of the graphene on hydrophobic and hydrophilic substrates will be demonstrated and compared. Finally, the general approach of using ultrasonic treatment and intercalation as a facile route to graphene synthesis compared to other methods will be discussed.

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Quantum Hall Effect in Two-Terminal Graphene Devices

We report on transport measurements in the quantum Hall regime of two-terminal single and bilayer graphene devices. The mixture of the longitudinal and transverse conductivities in the two-terminal geometry results in departures from the expected conductance values on the Hall plateaus and are found to be device-geometry dependent. The experimental results are compared to theory and discrepancies are discussed, focusing on deviations from theory near the Dirac point.

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Electron-phonon coupling in graphene within the GW-approximation

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The phonon dispersion of graphite continues to present surprises. Up to the year 2002, new parameters for semi-empirical force constant models, fitted to selected experimental data and strongly deviating from one-another, have been put on the market. Different ab-initio calculations (using density-functional theory in the LDA or GGA) agree well with each other with experimental data. Yet, even within the ab-initio framework, some new discoveries have been made during recent years: in 2004 it was demonstrated [1] that the highest optical branch (HOB) presents two pronounced Kohn anomalies (kinks in the dispersion) around the high symmetry points Gamma and K. The slope of the HOB around K is proportional to the square of the electron-phonon coupling (EPC). According to the double-resonance Raman model, this slope is also proportional to the dispersion of the Raman D and 2D lines as a function of the laser wavelength [2]. Furthermore, it determines the splitting of the 2D line of double-layer graphene compared to single-layer graphene [3,4].
Within DFT-LDA and GGA, the slope of the HOB around K is strongly underestimated, leading to wrong quantitative predictions of the double-resonance Raman model. We evaluate the electron-phonon coupling (EPC) between the pi-bands and the HOB at K in the GW-approximation, i.e., taking into account electron-electron correlation within first-order many-body perturbation theory. Non-local exchange-correlation effects renormalize the square EPC by almost 80%, almost doubling the slope of the HOB around K [5]. This explains recent experimental results on graphite-phonons using inelastic x-ray scattering and leads to quantitative agreement between the predictions of the double-resonance Raman model and experimental data. The short-coming of LDA and GGA may be partially fixed by the use of hybrid-functionals such as B3LYP (which partially contains exact Hartree-Fock exchange). The use of pure Hartree-Fock, however, leads to an extremely strong EPC and consequently to an instability of graphene under distortion along the HOB phonon at K.

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Magnetotransport on evenly curved graphene and thin graphite

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The interesting properties of conventional two-dimensional fermions in a sinusoidally modulated magnetic field have already been studied in detail. In this context we are interested in the comparison of transport measurements of evenly curved conventional and massless dirac fermions in graphene. Moreover, the curvature should affect intervalley scattering and Rashba induced spin-orbit interaction. Additionally, an interesting feature could be the influence of a zigzag or armchair like rolling direction on the transport behaviour referring the effects of metallic or semiconducting carbon nanotubes.
To experimentally realise evenly curved graphene and thin graphite sheets we use semiconductor-graphene metal hybrid microscrolls with rolled-in contacted sheets of thin graphite. The semiconductor substrates are grown on semi-insulating (001) GaAs by means of molecular beam epitaxy (MBE). These consist of an AlAs sacrifical layer, a n-type doped InGaAs stressor and a thin dielectric GaAs or AlGaAs layer on which the graphite is deposited with the micro-mechanical cleavage method. For the preparation of the microscrolls a two step optical lithography method is used to define the length of the scroll and to selective etch the AlAs sacrificial layer. Due to the one-sided strain relaxation of the InGaAs stressor, a torque arises and the lamella is rolled up. The diameters of the scrolls depend on the indium mole fraction of the stressor and the thickness of the whole lamella and ranges from hundreds of nm to several μm. The thickness of the lamella is limited by the thickness of the dielectric GaAs layer between the doped stressor acting as back gate and the graphene sheet.
We started to optimise the layer thickness in the frame of capable field effect and reduced scroll diameter. The established method of preparation, electrical and morphological characterisation of graphene layers on SiO2 is transferred to deposit graphite on GaAs substrates. Graphene on GaAs will be characterized by scanning electron microscopy (SEM) and patterned with optical and electron beam lithography (EBL) or by local oxidation with an AFM tip. Thin graphite in two-terminal geometry is used for optimisation the fabrication process, the field effect via back-gate electrode and first investigations of a sinusoidal modulated magnetic field on the low-temperature transport behaviour. Next these experiments will be performed on patterned Hallbar devices consisting of graphene or thin graphite rolled in a GaAs microscroll including a back-gate electrode.

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Quantum transport and Klein tunneling in graphene heterojunctions

I will discuss the observation of quantum conductance oscillations in extremely narrow graphene heterostructures where a resonant cavity is formed between two electrostatically created bipolar junctions. From analysis of the observed interference pattern, it can be inferred that individual p-n junctions have a collimating effect on transmitted carriers, leading directly to the observation of resonant oscillations despite the largely diffusive carrier dynamics. The oscillatory part of the conductance is insensitive to the scattering of electrons in the individual p-n junctions, making the study of the conductance fluctuations a novel probe of the ballistic physics of graphene at the Dirac point and allowing an estimate of the electric field due to nonlinear screening. In a weak applied magnetic field, the oscillations undergo a phase shift characteristic of reflectionless normal transmission, or "Klein Tunneling," at the individual pn junctions. Finally, at high magnetic field, graphene heterostructures show modified Shubnikov de Haas oscillations due to the inhomogenous external potential.

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Engineering band structure of graphene by chemical decoration

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The fact that graphene is metallic even at the neutrality point has been a major obstacle to developing device applications based on graphene. To open a gap in the electron spectrum of graphene, theoreticians have proved that chemical decoration could be an effective way. In this work, single layer graphene (SLG), bilayer graphene (BLG) and few layer graphene (FLG) have been chemically decorated by our modified plasma treatment, particular H2 plasma treatment. Room temperature and in-situ high temperature and vacuum Raman spectroscopy and mapping have been performed and clearly reveal: (i) the reversibility of hydrogenation, (ii) two types of hydrogen-carbon bonding, and (iii) layer effects on hydrogenation. As comparison, suspended graphene has also been investigated. The transport measurements demonstrate the change of the band structures by this chemical decortion.

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Thermopower measurements on single layer graphene

We present thermopower measurements on graphene flakes in the temperature range of 77-300k. Flakes were mechanically exfoliated onto a 300 nm-thick SiO2 layer covering a p++ silicon substrate, which is used as a gate electrode. Raman spectra of all measured flakes reveal characteristic fingerprint of single layer graphene.
Thermovoltage across the flakes was generated by micrometer heaters fabricated adjacent to the flakes. Excellent correlation is obtained between the Seebeck coefficient and the conductance as a function of gate voltage through the Mott relation. The behavior of the Seebeck coefficient is also in good quantitative agreement with recently published theoretical calculations on its expected behavior as a function of temperature above 100K. Below this temperature the measurements still follow the expected theoretical behavior alas only qualitatively, with some strong deviation in terms of the absolute Seebeck values. Possible explanations to this discrepancy are discussed.