Poster Abstracts

SESSION I

(26 August)

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Roughness and Ripples of Graphene sheets

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We present a statistical point of view to study of the Graphene's surface morphology. We prepare an MD simulation of suspended Graphene using the Many-body Brenner potential. The roughness and ripples can effectively result in a random gauge field and has important consequences for Graphenes electronic structure. Our results show that its height fluctuations in small scales have scaling behavior with temperature dependent roughness exponent in the interval of $0.6 < \chi < 0.7$. The correlation function of height fluctuations depends on temperature with characteristic length scale of $\approx 90°$A (at room temperature). We can also see the ripples of graphene. We compare the correlation function of height fluctuations in rough Graphene and Graphene with ripples. The scaling behavior of $\langle|h(q)|^2\rangle$ changes for these to states. $h(q)$ is the fourier transformation of height fluctuations. Characteristic length scale of ripples are obvious from the peak in $\langle|h(q)|^2\rangle$. Rough Graphene does not have any peaks. We also show that the correlation function of the induced gauge field has a short-range nature with correlation length of about $2 - 3°$A. We also treat the problem analytically by using the Martin-Siggia-Rose method. The renormalization group flows did not yield any delocalized-localized transition arising from the Graphene roughness.

Symmetry Classes of Graphene Quantum Dots: Universal Spectral Statistics, Weak Localization and Conductance Fluctuations

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Recent experimental results on graphene quantum dots in the coulomb blockade regime showed signatures of quantum chaos [1]. Motivated by these experiments, we study both, open and closed graphene quantum dots with chaotic classical dynamics using semiclassical methods as well as numerical simulations. In this work, we consider two types of boundary: (i) sharp lattice termination that gives rise to strong inter-valley scattering and (ii) a smoothly varying mass-confinement, modeling the presence of a possible edge magnetization, for which the influence of the sharp edges and therefore intervalley scattering is suppressed. We first study the transport properties of open chaotic systems attached to two leads. By investigating the weak localization correction and the conductance fluctuations in such devices, we find, not surprisingly, a crossover from the circular orthogonal ensemble (COE) for zero magnetic field to the circular unitary ensemble (CUE) for finite magnetic field, for the case (i). More interestingly, the systems with smooth mass boundary show strongly suppressed weak localization and the magnitude of the conductance fluctuations fits well to the prediction of the unitary ensemble even in the absence of magnetic field. Next, we investigate the eigenvalue spectra of closed chaotic systems, particularly Africa billiards. Surprisingly, in small systems, we find Poissonian statistics for the level spacing, which we attribute to the localized edge-states. For large systems we find that the level spacing distribution corresponds to the Gaussian orthogonal ensemble (GOE) for zero magnetic field, and to the Gaussian unitary ensemble (GUE) if a finite magnetic field is present, *regardless of the type of the boundary*. Thus we find that the universality class of the conductance of open dots and spectra of closed dots for boundary type (ii) are different. We attribute this to the fact that even a small amount of residual intervalley scattering becomes dominant in closed systems, where the escape time is infinitely large, whereas the intervalley scattering time is always finite.

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Density-Functional Theory of Graphene Sheets

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We outline a Kohn-Sham-Dirac density-functional-theory (DFT) scheme for graphene sheets that treats slowly-varying inhomogeneous external potentials and electron-electron interactions on an equal footing. The theory is able to account for the the unusual property that the exchange-correlation contribution to chemical potential increases with carrier density in graphene. Consequences of this property, and advantages and disadvantages of using the DFT approach to describe it, are discussed. The approach is illustrated by solving the Kohn-Sham-Dirac equations self-consistently for a model random potential describing charged point-like impurities located close to the gaphene plane. The influence of electron-electron interactions on these non-linear screening calculations is discussed at length, in the light of recent experiments reporting evidence for the presence of electron-hole puddles in nearly-neutral graphene sheets.

Graphene bilayer superlattices

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We evaluate the dispersion relation for massive fermions in bilayer graphene in the presence of a one-dimensional periodic potential applied to the two layers, aswell as for a periodically biased bilayer. For zero bias the dispersion relation shows a finite gap for carriers with zero momentum in the direction parallel to the barriers in contrast with single-layer graphene. A gap also appears for a periodically baised bilayer similar as for a uniform bias. Numerical results for the energy spectrum, conductance and the density of states are presented. In addition, we evaluate the transmission through a finite number of barriers, as well constructed by a bias as by a potential barrier and relate it with that through a superlattice.

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Effect of a single impurity on the local density of states in monolayer and bilayer graphene

We have analyzed the effect of a single localized impurity on the local density of states in monolayer and bilayer graphene. We have shown that, for monolayer graphene, the Friedel oscillations generated by intra-nodal scattering of quasiparticles obey an inverse-square law, while those generated by inter-nodal scattering obey an inverse law. In the Fourier transform this translates into a filled circle of high intensity in the center of the Brillouin zone, and empty circular contours around its corners. For bilayer graphene we have found that both oscillations obey an inverse law. Recent STM experiments have confirmed our theoretical predictions, while also showing that the chirality of quasiparticles in an epitaxial graphene monolayer corresponds to the one predicted for ideal graphene. More generally, our analysis proves that STM experiments can provide information not only about the band structure, but also about the underlying Hamiltonian of two-dimensional systems.

Hall resistance plateaus in high quality Graphene samples at large currents

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In the following, we present preliminary results showing that monolayer Graphene shows robust Hall quantization at 4.2 K for large currents while contact resistance can reach very low value.

Sample fabrication

The sample is made from natural graphite mechanically exfoliated and deposited on a 340 nm thick oxidized highly doped Si wafer. Deposition is done on a pyrhana cleaned SiO2 surface, increasing the yield of high quality and, often, of very large (>400 μm^2) samples. After optical detection of f Graphene Electron lithography is carried out to deposit 60 nm TiAu contacts using electron gun evaporation. Finally, an other lithography process is performed and combined with O_2 plasma etching to define the Hall bar shape. Before mounting the sample in the cryostat, it is heated in dry atmosphere for more than 12 hours at 170 °C to avoid unintentional doping (by H_2O donors for example).

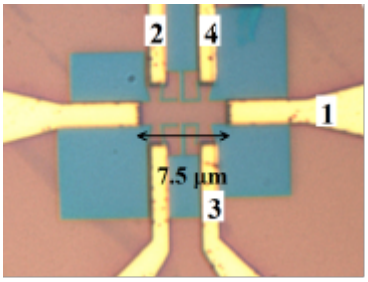


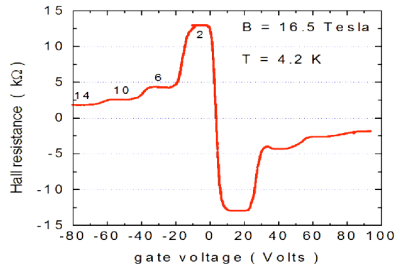
Fig.1: Optical image of the Graphene sample covered by PMMA resist. The Hall bar width is 2 µm.

Hall measurements at 4.2K

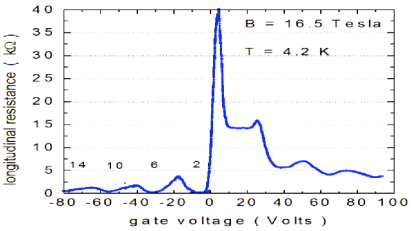
Fig. 2a shows the Hall resistance measured under low bias current (100 nA) at 4.2 K and 16.5 T magnetic flux density. The series of Hall plateaus $\pm\frac{h}{2e^2}, \pm\frac{h}{6e^2}, \pm\frac{h}{10e^2}$, and $\pm\frac{h}{14e^2}$ is shown in the range of gate voltage swept here. Negative and positive voltages correspond to the holes and electrons conduction regimes respectively. It is important to remark that zero electron density (zero Hall resistance) occurs at a gate voltage very close to zero. This indicates a very low uncontrolled doping, less than 2×10^{11} cm^{-2}. Such a low doping increases the homogeneity and quality of the sample.

Fig. 2: (a) Hall resistance $(V_3–V_4)/I$ and (b) sum of the longitudinal and contact n°2 resistances $(V_4–V_2)/I$. The current is injected in contact n°1 and returns to ground in contact n°2.

For negative voltages, holes regime, this resistance drops below 40 Ω (including 20 Ω wiring) for the first three plateaus. This gives a contact resistance as low as about



(a)

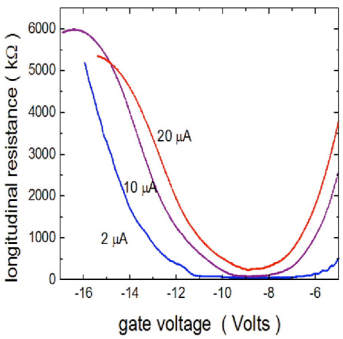


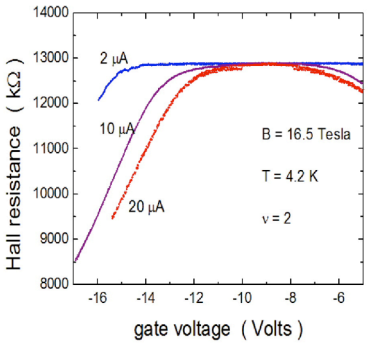
(b)

20 Ω. As no strong effort has been done yet to reduce the contact resistance, there is room for further improvements. For positive voltages, electrons regime, we remark that the Hall resistance adds to the sum of longitudinal and contact resistances. This usually occurs when changing the sign of *B* and results from the reversal of the propagation direction of electrons.

Hall quantization breakdown current

Fig. 3 shows Hall and longitudinal resistance traces of the first plateau versus gate voltage, for different currents in the holes regime. A quantized Hall plateau of finite width survives up to 10 µA and starts to close for 20 µA. Similarly, the longitudinal resistance starts to significantly increase in the middle of the plateau, only for 20 µA.





Field of improvement

We are now working for improving homogeneity of density in graphene by using different type of gate and working to avoid unintentional doping.

Charge density excitations in bilayer graphene in high magnetic field

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Recent experimental progress has allowed the fabrication and study of monolayer and bilayer graphene. The electronic band structure of these objects is gapless and have a chirality. The monolayer has dirac-type spectrum with linear dispersion and chirality exhibiting Berry phase π. In magnetic field there is zero-energy Landay level. The bilayer graphene is the unique object which combines the parabolic dispersion law of quasiparticles with their chirality exhibiting Berry phase 2π. In magnetic field there is a double-degenerate zero-energy Landay level incorporating two different orbital states with the same energy. Taking into account spin and valley degeneracies, the zero-energy Landau level in a monolayer is fourfold degenerate, whereas in bilayer the zero-energy Landau level is eightfold degenerate. This one-electron structure was confirmed in experiments of integer quantized Hall effect and Shubnikov-de Haas oscillations. These properties are understood in terms of non-interacting electrons. The influence and exhibition of electron-electron interaction is the following problem. The low-lying excitations of these systems may be sensitive to interaction.

Inter-Landau-level transitions in the bilayer graphene at high magnetic field have been studied. The charge density excitations (magnetoplasmons) are considered. These types are more useful for experimental study (it is possible to observe their energy by inelastic light scattering or microwave absorption). The charge-density excitations at small momenta are considered in the frame of the Hartree-Fock approximation. The case of filling-factor $\nu << 1$ is considered. This filling-factor means the absence of free carriers due to doping. The presence of small asymmetry of graphene layers is included. Without magnetic field, the asymmetry gives rise to the gap in the spectrum; in the presence of the field, the asymmetry splits the eightfold degenerate zero-energy Landau level into four twofold levels. The energy of the magnetoplasmon excitations is calculated and the dependence of the energy on the form of the bilayer ground state is shown. In the asymmetric case there is no splitting in transition energy. In symmetric case with half-fillind of zero-energy states the exsitation energies are splitted due to Coulomb interaction.

Pseudospin Magnetism in Graphene

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We predict that neutral graphene bilayers are pseudospin magnets in which the charge density-contribution from each valley and spin spontaneously shifts to one of the two layers. The band structure of this system is characterized by a momentum-space vortex which is responsible for unusual competition between band and kinetic energies leading to symmetry breaking in the vortex core. We discuss the possibility of realizing a pseudospin version of ferromagnetic metal spintronics in graphene bilayers based on hysteresis associated with this broken symmetry.

Hongki Min, Giovanni Borghi, Marco Polini, and A.H. MacDonald, Phys. Rev. B **77**, 041407(R) (2008).

QUASIPARTICLE CHIRALITY IN EPITAXIAL GRAPHENE PROBED AT THE NANOMETER SCALE

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Many of the tantalizing electronic properties of graphene can be understood as due to the conservation of pseudospin and quasiparticle chirality, two entities that have no equivalence in any other two-dimensional system. They are responsible, for example, of the new 'chiral' quantum Hall effects (QHE) observed for monolayer and bilayer exfoliated graphene, which are the most direct evidence for Dirac fermions in graphene. Paradoxically, the QHE has not been yet observed in epitaxial graphene, which leaves open the question about the Dirac nature of the quasiparticles in this system. Our work shows how pseudospin and quasiparticle chirality can be experimentally detected at the nanoscale by means of STM, since they are reflected in the quasiparticle interference processes that take place in graphene. Our STM data, complemented by theoretical calculations, demonstrate that the quasiparticles in epitaxial graphene on SiC(0001) have the chirality predicted for ideal (free standing) graphene, which proves the Dirac character of the quasiparticles in this system. Moreover, we go one step further and show how the direct observation of pseudospin and quasiparticle chirality can be used to determine the sublattice symmetry of graphene. This a very important issue which has originated an intense scientific dispute, since Zhou *et al* (2007) proposed the existence of a substrate induced C-C asymmetry in monolayer epitaxial graphene to explain the opening of a bandgap at the Dirac point. We demonstrate that the chirality which we measure on the monolayer discards the existence of such a C-C asymmetry.

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Surface transfer p-type doping of epitaxial graphene on 6H-SiC(0001)

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It has been demonstrated that ultrathin graphene films epitaxially grown on commercial silicon carbide substrates by thermal decomposition in vacuum can be patterned using standard nanolithography methods, making it compatible with current semiconductor technology. Recent transport measurements on ultrathin epitaxial graphene (EG) on silicon carbide (SiC) substrates have revealed the Dirac nature of the charge carriers.[1] Long phase coherence lengths of over 1 micrometer at 4 Kelvin and mobilities exceeding 2.5 square meters per volt-second have also been observed,[1] making EG a promising material for future nanoelectronics.

In this work we demonstrate a simple and effective way to non-destructively control the hole concentration in epitaxial graphene (EG) layers thermally grown on 6H-SiC(0001) by modifying the EG surface with an appropriate electron acceptor of tetrafluoro-tetracyanoquinodimethane (F4-TCNQ).[2] Synchrotron-based high-resolution photoemission spectroscopy study clearly reveals that electron transfer from graphene to adsorbed F4-TCNQ is responsible for the p-type doping of graphene. In contrast, the adsorption of a relatively weak molecular acceptor of C_{60} does not result in a significant charge transfer at the C_{60}/EG interface, and hence the absence of the surface transfer doping of the EG layers. This novel surface transfer doping scheme by surface modification with appropriate molecular acceptors has great implications for future EG-related nanoelectronic devices.

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Signature of chirality in scanning probe imaging of charge flow in graphene

We theoretically propose to directly observe the chiral nature of charge carriers in graphene mono- and bilayers within a controlled scattering experiment.
By creating a controllable scattering center with a scanning probe microscope (SPM) tip between two constrictions, the conductance of the sample shows unambiguous feature revealing chirality.
To theoretically model the scattering from the smooth potential in graphene mono- and bilayers, we calculate the real-space electron Green function, and develop the scattering formalism within first-order Born approximation.

Shot noise and evanescent wave transport in graphene

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We have investigated shot noise in graphene field effect devices in the temperature range of 4.2–30 K at low frequency (f = 600–850 MHz). We measured gate dependent current fluctuations in short graphene strips with large and small W/L. At the Dirac point, i.e. where the conduction and the valence band touch, we observed that for large W/L both minimum conductivity and Fano factor reach universal values of $\frac{4e^2}{\pi h}$ and 1/3, respectively. By increasing the gate voltage, the Fano factor decreases and tends to zero, i.e. the value expected for a ballistic system [1].

For W/L smaller than 3, the Fano factor is lowered and the minimum conductivity increases. These findings are well explained by the evanescent wave theory describing transport at the Dirac point in perfect graphene [2,3].

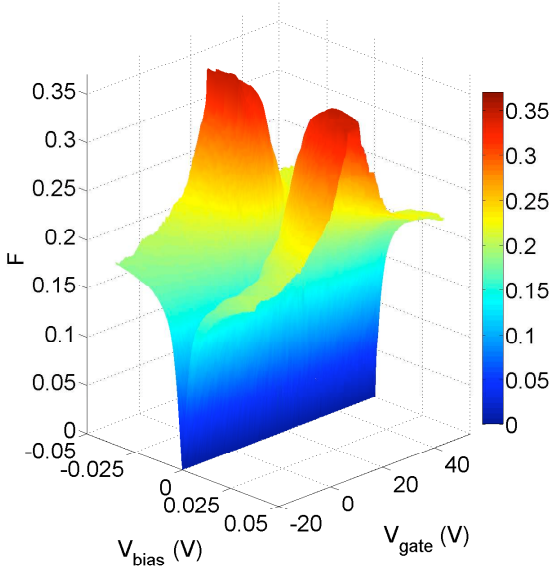

Figure 1: Mapping of the average Fano factor F as a function of gate voltage V_{gate} and bias voltage V_{bias} at T = 8.5 K.

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PHONON RENORMALIZATION IN DOPED SINGLE ALD BILAYER GRAPHENE

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The recent discovery of thermodynamically stable two-dimensional single and few layers graphene has led to many experimental and theoretical advances in two dimensional physics and devices. In particular, near ballistic transport at room temperature and high carrier mobilities (between 3000 and 25000 cm^2/Vs) make graphene a potential material for nano-electronics. Electrochemical top gating is key to enable polymer transistors. It has also been successfully applied for nanotubes. Here we demonstrate a top-gated graphene transistor able to span much higher doping levels than previously reported. Electron and hole doping up to ~ $2\text{-}5\times10^{13}$ cm^{-2} is achieved by solid polymer electrolyte gating. Such a high doping level is possible because the nanometer thick Debye layer gives a much higher gate capacitance compared to the commonly used 300 nm thick SiO2 back gate. In-situ Raman measurements monitor the doping.

The Raman G peak of single layer graphene stiffens and sharpens for both electron and hole doping, while the 2D peak shows a different response to holes and electrons. The variation of G peak position is a signature of the non-adiabatic Kohn anomaly at Γ. On the other hand, for visible excitation, the variation of the 2D peak position is ruled by charge transfer and discriminate between the electron and hole doping. The intensity ratio of G and 2D peaks shows a strong dependence on doping, making it a sensitive parameter to monitor charges. However, we show that the phonon renormalization of bilayer graphene has characteristic features compared to that of single layer graphene. Bilayer has two subbands in each conduction and valence band and the spliting depends on the interlayer coupling strength, γ_1, between the two graphene sheets. Here, we first time experimentally probe the effect on the phonons when crossing from the first to the second sub-band of bilayer graphene. This results in a change of slope in the variation of G peak position with doping, which allows a direct estimation of γ_1.

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Electrical conductivity of chemically modified graphene sheets

The study of the electronic properties of graphene and its chemical derivatives promises to open a new era of solid state electronics and of composite materials. A central challenge of rapid graphene implementation is its mass production. The chemical exfoliation of graphite through oxidation [1-3] and then dispersion in water, down to single graphene sheets [4], is one of the potential methods of achieving this goal. We use a simple, reliable, and scalable way of making chemically modified graphene (CMG) sheets with tunable electronic properties [5], which can be placed flat on any surface or homogeneously dispersed in various matrices [6-8]. CMG sheets share some similarities with pristine graphene and carbon nanotubes, e.g. tunable electron- and hole-type conductivity is observed in single CMG sheets just above the percolation threshold. CMGs may also be considered as a template for a bottom up development of a new class of materials [8,9]. We have performed and compared electrical measurements of individual CMG sheets, CMG powder samples having different chemical composition, and CMG sheets dispersed randomly or aligned inside of nonconductive matrices. We will discuss the electronic properties of individual CMG sheet and the possible mechanisms of the charge transport between the sheets in the composite materials.

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Rabi Oscillations in Landau Quantized Graphene

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Abstract

We investigate the relations between the canonical model of quantum optics, the Jaynes-Cummings Hamiltonian describing a two level atom in a cavity interacting with electromagnetic field, and Dirac fermions in quantizing magnetic field, occurring in graphene under non-relativistic circumstances. We demonstrate that Rabi oscillations, corresponding to the excitations of the atom in the former case are observable in the optical response of latter, providing us with a transparent picture about the structure of optical transitions in graphene. This opens up the exciting possibility of investigating a microscopic model of a few quantum objects in a macroscopic experiment of a bulk material with tunable parameters.

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Lateral structuring of graphene by local oxidation

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Strong charge carrier confinement as well as control over the edge configuration are highly desired features in graphene nanostructures. This is up to now hardly obtainable by the standard process of e-beam lithography followed by RIE-etching.

We investigate the feasibility of local oxidation for patterning of graphene as one approach to reach this goal. Applying voltage to an AFM-tip, which is moved above the sample, initiates the oxidation of graphene leading to the release of gaseous reaction products. Thereby trenches are formed where the tip is driven across the surface and the SPM-probe can be used as a pair of "nano-scissors" cutting the desired structure out of a graphene flake.

First proof-of-principle results show that different parts of a single layer graphene flake deposited on a SiO_2/Si substrate can be electrically isolated from each other using this technique.

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Intrinsic and extrinsic corrugation of monolayer graphene deposited on SiO_2

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Abstract

Using scanning tunneling microscopy in ultra high vacuum and atomic force microscopy, we investigate the corrugation of graphene flakes deposited by exfoliation on a Si/SiO_2 (300 nm) surface. While the corrugation on SiO_2 is long-range with a correlation length of about 25 nm, the graphene monolayer exhibits an additional corrugation with a preferential wave length of about 15 nm.
A detailed analysis shows that the long range corrugation of the substrate is also visible on graphene, but with a reduced amplitude, leading to the conclusion that the graphene is partly freely suspended between hills of the substrate. Thus, the intrinsic rippling observed previously on artificially suspended graphene exists as well, if graphene is deposited on SiO_2.

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Extremely High Thermal Conductivity of Single Layer Graphene

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We report the results of the first experimental study of the thermal conductivity of graphene. The single layer graphene flakes were obtained by the standard mechanical exfoliation technique and placed on Si/SiO_2 substrates with trenches fabricated by the reactive ion etching. The number of atomic layers and quality of graphene were verified by the deconvolution of the 2D Raman band [1]. Long graphene layers and ribbons connected to the large graphitic pieces, acting as heat sinks, were selected for the study. The measurement of the thermal conductivity was performed using an original Raman microscopy – based technique developed by us for graphene. We have recently discovered that G peak in graphene spectra manifest strong temperature dependence [2]. The G peak's temperature sensitivity allowed us to monitor the local temperature change produced by the variation of the laser excitation power focused on a suspended portion of graphene. The extremely small cross-section area of the graphene heat conduction channel made it possible to detect the local temperature rise with the Raman spectrometer. The fraction of power dissipated in graphene was determined through the calibration procedure, which used bulk graphite as a reference sample. Our measurements revealed that the single-layer graphene has an extremely high room-temperature thermal conductivity in the range 3080 – 5300 W/mK [3]. The thermal conductivity of graphene is on the high-end of the values reported for carbon nanotubes or exceeds them. The obtained experimental results for the thermal conductivity of graphene were explained with the help of the Klemens – Callaway theory and specifics of the phonon dispersion in graphene calculated from the atomistic model [4]. The extremely high thermal conductivity coupled with graphene's flat geometry and ability for functioning in Si/SiO_2-based devices make graphene an excellent material for heat removal from nanoelectronic circuits.

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Single Layer Graphene Production Exploiting PDMS Transfer Printing

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Graphene is a new candidate for micro-scale fabrication of circuits thanks to its remarkable electronic properties linked to its peculiar band structure [1,2]. Currently the only reliable method for fabricating single layer graphene is the micromechanical method commonly known as the tape method which is time consuming and impractical for manufacturing graphene based electronic devices [3]. Here we report the results of graphene production by a transfer printing approach with polydimethylsiloxane (PDMS) stamps on Si/SiO_2 substrates [4,5]. We show that the process represents a reproducible method for producing monolayer graphene with both HOPG and natural graphite. The stamps cleave single and multilayer graphene from bulk graphite and print directly onto an Si/SiO_2 substrate. This method is advantages because it does not leave any residues on the substrate as opposed to the micromechanical technique. PDMS is a transparent, silicon-based elastomer and although it is not possible to see a single layer of graphene on the surface of PDMS, multilayers are visible with the aid of an optical microscope. This property provides a level of control over the position of the deposited flakes. We also present spatially-resolved Raman spectroscopy analysis to verify the transfer of a monolayer of graphene followed by AFM imaging to analyze the quality of the graphene flakes [6,7].

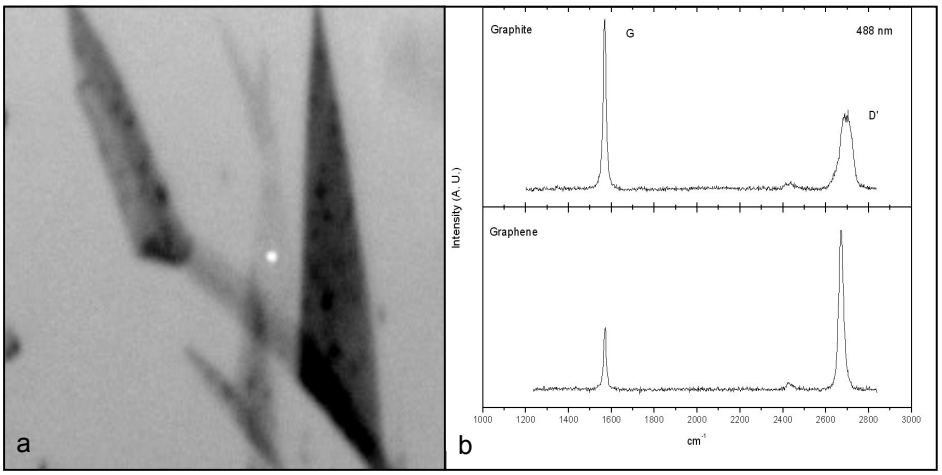

Figure 1: **a**, Image of a single layer of graphene with the laser spot on an Si/SiO_2 substrate exfoliated from bulk HOPG graphite by PDMS transfer printing. The white circle is the laser spot. **b**, Room temperature Raman spectra of graphene and graphite fabricated using PDMS transfer printing.

We also show that with PDMS we can produce areas where the single layer of graphene forms a membrane not in contact with the substrate. This effect is possibly caused by stress introduced into the graphene when it is in contact with the PDMS. AFM imaging on the surface of PDMS reveals that the graphene layers are bubbled and we propose that these deformations are directly transferred to the substrate when the graphene is printed. We have performed spatially resolved Raman spectroscopy on graphene samples on Si/SiO_2 substrates containing such bubble-shaped membranes with dimensions of the order of 200 nm in width and 10 nm in height and have observed energy shifts of the graphene Raman peaks that we link to the impact of graphene-substrate interaction.

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ELECTRONIC AND MECHANICAL PROPERTIES OF CHEMICALLY DERIVED GRAPHENE

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We report on the electronic and mechanical properties of single graphene sheets obtained via chemical reduction of graphite oxide.

We find that reduced single layers exhibit room temperature conductivity of 10 S/cm and field effect mobility up to 1000 cm^2/Vs. According to temperature dependent electrical measurements, Raman spectroscopy and scanning tunneling microscopy the structure of the sheets is best described by intact, nanometer-sized graphitic domains separated by defect clusters, which results in hopping conduction as the dominant charge-transport mechanism[1].

Towards their mechanical characterization we have prepared free-standing single layers and measured their elasticity by indenting the tip of an Atomic Force Microscope at the center of the suspended area. For single layers we find a mean elastic modulus of $0.2TPa$[2]. This outstanding stiffness, rivaling that of pristine graphene, is coupled with high flexibility. More over, the electrical conductivity of the sheets scales inversely with the elastic modulus, pointing toward a two-fold role of the remaining oxygen bridges, i.e., to impart a bond reinforcement while at the same time impeding the charge transport. Finally, built-in tensions are found to be significantly lower compared to mechanically exfoliated graphene.

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Momentum alignment of photoexcited carriers and THz detection in graphene

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Since its recent successful exfoliation from graphite [1], graphene, a single layer of carbon atoms in a honeycombed lattice, has become a favorite material for numerous device proposals, based on its unusual mechanical, thermal and, most of all, electronic properties [2]. As a gapless semiconductor with ultra-high carrier mobility, graphene is a natural material for detecting terahertz (THz) radiation. The Fermi level in graphene-based devices can be easily controlled by the gate voltage, which allows a certain degree of tunability in the lower limit of absorbed radiation frequency via the Moss-Burstein effect. An additional control can be achieved in bilayer graphene by opening an energy gap by applying an inter-layer voltage [3,4], making this material an ideal system for a THz filter. We calculate photoconductivity in single and few-layer graphene focusing on a hitherto overlooked effect of momentum alignment (anisotropy of the distribution function) of photoexcited carriers created by linearly-polarized THz excitation. Our calculations show that there is a striking difference between momentum alignment in graphene and in quantum wells based on conventional III-V semiconductors [5]. One of the most interesting latest trends in graphene research is related to p-n junctions [6, 7], which can be created using two gates placed above and below the graphene layer. In such structures, with high enough top and bottom gate voltages, THz absorption is only possible in the junction area. In conjunction with an extremely strong angular dependence of the tunneling probability for graphene p-n junctions [8], optical alignment of momenta raises the possibility of using recently fabricated graphene p-n junction structures in polarization-sensitive THz detectors. We design optimal structures for such detectors working in close collaboration with an experimental group of A. Savchenko at Exeter University, which has recently obtained interesting results on weak localization in single-layer [9] and bilayer [10] graphene, using in-house fabricated structures and currently study transport properties of bipolar graphene p-n junctions.

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Formation of Graphitic Thin Films from Nanodiamond by Laser Annealing

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A grain of ultra-nanocrystalline diamond with a diameter of 4 nm is composed of about 6,000 carbon atoms, quantitatively equivalent to ten molecules of C_{60} or to an 18 nm square sheet of graphene. The properties of nanodiamonds are intermediate between nanoparticles and molecules; e.g., they may become a colloidal dispersion in water, while they may grow into whiskers out of their aqueous colloid [1]. Another interesting nature can be found in that nanodiamonds less than about 5 nm in diameter are more stable than their graphite counterparts at ambient conditions [2], although macroscopically diamond is a metastable phase, compared with graphite.

We have investigated the graphitization of nanodiamonds by laser annealing. Commercial nanodiamonds with sizes of 4-5 nm were homogenized in ethanol by strong ultrasonication to produce a monodispersed suspension. It was deposited onto SiO_2/Si substrates to form nanodiamond thin films with thicknesses ranging from 10 nm to 1 μm. As soon as a 1064-nm laser beam scanned the nanodiamond film, the annealed nanodiamonds turned from transparent to brown or black, depending on the laser power. Four probes electrical measurements revealed that the change in sheet resistance between the unannealed and well-annealed films was more than 6 orders of magnitude. This observation implies that the nanodiamonds were transformed into graphitic counterparts or were peripherally graphitized to form surface conductive layers. The low-resistance thin films can be easily formed on various substrates, such as 15-μm thick aluminum foil, 120-μm thick cover glass and 35-μm thick Kapton film. The annealed film exhibits some transparency. Although the low resistivity is incompatible with the high visibility, the thin films formed from nanodiamonds by laser annealing could be available for some electrode applications.

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POSTER ABSTRACT

Electron transport in graphene samples

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1. Theory of mesoscopic conductance fluctuations in graphene.

Universal conductance fluctuations in graphene samples at energies not very close to the Dirac point are studied analytically. We demonstrate that the conductance variance is very sensitive to the elastic scattering breaking the valley symmetry. In the absence of such scattering (disorder potential smooth at atomic scales, trigonal warping negligible), the variance is 4 times greater than in conventional metals, which explains a recent unexpected numerical finding. Strong intravalley scattering and/or warping reduce this factor to 2 and only the intervalley scattering leads to same result as for conventional metals. Different universal values of the variance, when compared with experimental data, can provide important information about disorder in the system.

2. Quasiclassical theory of electron transport in graphene samples.

We develop a quasiclassical theory of electron transport in graphene. The conductance of a graphene sample can be expressed through the two-particle quasiclassical propagators, which satisfy certain differential equations. Within this approach both ballistic and diffusive regimes, as well as the crossover between them, can be studied, the first one is more relevant for suspended graphene devices and the latter for samples on a substrate.

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Universal conductance fluctuations in disordered graphene nano-transistors

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In a typical graphene-based field effect device phonons excited in the graphene flake are poorly coupled to environment due to a relative lightness of carbon atoms (as compared to atoms in the underlying substrate). Thus the overheating of graphene structures (with the temperature of electrons in graphene different from that in the substrate) is a likely event in transport experiments. This raises a question of how to measure this electron temperature. Since classical conductivity in graphene showed a very weak temperature dependence [1], solving this problem experimentally requires turning to more subtle quantum transport effects. Also, an analysis of the decoherence rate τ_φ^{-1} extractable from weak-localisation (WL) magneto-resistance often used to obtain information about electron temperature is hindered in graphene by a very complicated dependence of WL on the strength of inter-valley and sublattice asymmetric disorder in a particular sample [2, 3]. In this work we analyzed the universal conductance fluctuations (UCF) in disordered graphene structures and explored the possibility to use UCF to obtain information about the electron temperature. Using the diagrammatic perturbation theory we found the UCF amplitudes in the two asymptotic regimes [4]: 'low temperature' $k_BT, \hbar\tau_\varphi^{-1} \ll \hbar\tau_D^{-1}$ (where $\tau_D \equiv L_x^2/D$ and D is a diffusion coefficient) for the cases of a wide contact $L_y \gg L_x$ and narrow wire $L_x \gg L_y$,

$$\langle \delta\mathcal{G}^2 \rangle = \alpha(\tau_w, \tau_z, \tau_{iv}) \frac{3\zeta(3)}{2\pi^3} \frac{L_y}{L_x} \left(\frac{2e^2}{h}\right)^2, \quad \langle \delta\mathcal{G}^2 \rangle_{wire} = \frac{1}{15}\left(\frac{2e^2}{h}\right)^2, \tag{1}$$

and 'high temperature' $k_BT \gg \hbar\tau_\varphi^{-1}, \hbar\tau_D^{-1}$ for the cases of a wire $L_y < \sqrt{D\tau_\varphi} \ll L_x$ and wide sample $L_y \gg \sqrt{D\tau_\varphi}$,

$$\langle \delta\mathcal{G}^2(T) \rangle \approx \frac{\alpha(\tau_w, \tau_z, \tau_{iv})}{6} \left(\frac{2e^2}{h}\right)^2 \frac{L_y}{L_x} \frac{\hbar\tau_\varphi^{-1}}{k_BT} \ln\left(\frac{k_BT}{\hbar\tau_\varphi^{-1}}\right), \quad \langle \delta\mathcal{G}^2(T) \rangle_{wire} \approx \frac{\pi}{3}\left(\frac{2e^2}{h}\right)^2 \frac{\hbar\tau_\varphi^{-1}}{k_BT}\left(\frac{L_\varphi}{L_x}\right)^3. \tag{2}$$

The values of the disorder sensitive coefficient for different parametric regimes are summarized in following table,

$\alpha(\tau_w, \tau_z, \tau_{iv}) \approx 4$	$\tau_D^{-1} \gg \tau_{iv}^{-1} + \tau_z^{-1} + \tau_w^{-1}$	τ_w^{-1} - scattering rate due to trigonal warping
$\alpha(\tau_w, \tau_z, \tau_{iv}) \approx 2$	$\tau_{iv}^{-1} + \tau_z^{-1} + \tau_w^{-1} \gg \tau_D^{-1} \gg \tau_{iv}^{-1}$	τ_z^{-1} - intra-valley scattering rate
$\alpha(\tau_w, \tau_z, \tau_{iv}) \approx 1$	$\tau_{iv}^{-1} \gg \tau_D^{-1}$	τ_{iv}^{-1} - inter-valley scattering rate

In the experimentally relevant 'high-temperature' regime $k_{\mathrm{B}}T \gg \hbar\tau_\varphi^{-1}$, $\hbar\tau_D^{-1}$ the analysis of the temperature dependence of the UCF amplitude (2) which could provide information about electron temperature is complicated by the necessity to disentangle temperature dependence from that of τ_φ^{-1}. Moreover, the UCF amplitude in graphene (1) and (2) is sensitive to microscopic disorder realization in a particular sample. Therefore it does not readily offer a universal tool for thermometry. We propose a method of correlation function thermometry of mesoscopic conductors and demonstrate the applicability of this method to graphene-based micron-size devices. The method is based upon the analysis of the normalized correlation function of UCF, $F_{\mathrm{n}}(\Delta) \equiv F(\Delta)/F(0)$, in the vicinity of the Fermi energy ε_{F}, where $F(\Delta) \equiv \left\langle \delta\mathcal{G}(\varepsilon_{\mathrm{F}}) \delta\mathcal{G}(\varepsilon_{\mathrm{F}} + \Delta) \right\rangle$. We show that the correlation energy Δ_c of $F_{\mathrm{n}}(\Delta)$ in a quasi-1D mesoscopic sample (where $L_x \gg L_y$) is determined by thermal broadening of the electron Fermi step:

$$\Delta_c \approx \alpha k_{\mathrm{B}} T, \quad \alpha_{1D} \approx 2.7\,. \tag{3}$$

Thus by measuring Δ_c one can determine the electron temperature with an accuracy better than 10%. Such a determination is also possible for a $2D$ sample with an arbitrary aspect ratio, albeit with a lesser accuracy. This suggestion was tested and confirmed numerically for a wide parametric range and experimentally for several graphene-based devices [5].

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Growth of curved graphene sheets at the edges of graphene bilayer

Carbon nanostructures like fullerenes, carbon nanotubes and graphene, play a central role in nanomaterials science. Recently the interest in carbon nanostructures has been stimulated by the observation of intriguing electronic properties in planar graphene sheets [1,2]. In this work, we report the fabrication of structurally new form of graphene, namely curved graphene sheets (CGS). The structure is obtained by chemical vapor deposition (CVD) of methane on highly oriented pyrolitic graphite (HOPG), using Fe catalytic particles. The morphology is investigated by scanning tunneling microscopy (STM). A possible mechanism explaining the origin of the CGS is discussed.

The development of synthesis methods for graphene structures is still a challenging issue. To date, planar graphene has been obtained mainly by mechanical exfoliation from bulk graphite crystals [1], or thermal decomposition of SiC crystals under vacuum conditions [3]. Our approach is based on the CVD of methane using the Fe catalytic metal particles, decorating the step edges of HOPG substrate [4], and resulting in the growth of CGS at the step edges of topmost graphene bilayer. It should be noted that under the same experimental conditions we have produced CNT on the SiO_2 substrate, while on HOPG substrate no CNT has been observed. Moreover, the same CVD reaction without Fe catalysts produces amorphous carbon species located mainly at the substrate steps. The HOPG sample is cleaved in ambient conditions, immediately inserted in the vacuum chamber, and thoroughly degassed up to 900 °C. All experiments, including the deposition of Fe catalysts by e-beam sublimation, CVD of methane and STM measurements (taken at room temperature) are performed in-situ. The STM data show that the CVD reaction is localized at steps, due to their decoration by metal catalysts.

The curved structure located along the step edges of HOPG substrate, that we name CGS, is observed only at step edges of double graphene layers. Apparently the CGS is morphologically very similar to carbon nanotubes and graphene foldings [5]. However, the continuous connection of CGS to the terrace of the topmost graphene layer, clearly show the difference of grown CGS from nanotubes. Moreover, CGS follow the step edge kinks and bendings, presenting continuous tubular structures with long axis at different angles, that cannot be obtained by folding a single graphene plane.

The initial stage of CGS growth develops with the similar mechanism as in case of CVD growth of CNT. Fe particles trapped at the topmost graphene edges act as catalysts, where the decomposition of methane molecules can take place. Diffusing over the surface of the catalyst particle, the decomposed carbon atoms can meet the graphene edges, in contact with Fe particle, and create chemical bonds with the edge carbon atoms, allowing the growth of the edge. Due to the fact that the Fe particles are in contact with the edges of both stacked layers, this mechanism takes place on both graphene layers, but following the metal catalyst particle curvature, forming by this way a curved structure. Diffusion of the metal particle along the step edge during methane decomposition allows the growth of the curved structure along the entire step, hence creating the CGS by a zipper-like mechanism (slide fastener), resembling the "top" growth mode of CNT. The described growth model method may have a significant implications for fabrication of novel carbon structures, by employing for instance patterned graphene bilayer with edges connecting through curved graphene sheets.

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Nearly neutral graphene on Ir(111)

Graphene is a promising candidate for carbon-based devices due to its exceptional electronic properties at low carrier densities. These properties originate from the linear energy dispersion and particle-hole symmetry in the vicinity of the Dirac point. Thus, the nearly neutral graphene is desired for carbon-based electronics. A prerequisite for large scale applications is the epitaxial graphene, preferably of high structural quality and electronically only weakly perturbed by the substrate, so that it can be further manipulated for electronic devices.

The most prominent example of epitaxial graphene is the one grown on SiC(0001). The experimental results imply that graphene on SiC is heavily doped and its structural quality is relatively poor, with the typical domain size in the submicron range. The complexity of this system arises from the large super-cell reconstruction of the carbon-rich supporting interface, which represents a difficult problem for a quantitative comparison with theory. For experimental electronic structure investigations it thus appears useful to seek for alternative but simpler graphene-substrate systems with a very high structural quality so that the suitable method, i.e. angle-resolved photoelectron spectroscopy (ARPES) can be applied. Graphene on Ir(111) is such a system – without an intermediate layer between the graphene and the metal and with very good and well characterized structural quality. Moreover, the motivation to take a look to graphene on a metal with photoemission spectroscopy comes also from the fact that implementation of graphene devices implies contacting by metal electrodes, necessitating a profound knowledge of the graphene-metal interaction.

We have prepared graphene on Ir(111) in exceptional structural quality and have studied it by ARPES. It is found to interact only weakly with Ir(111) resulting in an intact Dirac cone with a Dirac point shifted slightly above the Fermi level. The moiré pattern resulting from the superimposed incommensurate graphene and Ir(111) surface lattice implies a superperiodic potential which gives rise to Dirac cone replicas and the opening of the corresponding band gap. Based on these findings, Ir appears to be well suited for electronic contacts to graphene. Graphene on Ir(111) is also a specifically simple epitaxial graphene system which is potentially of interest for further fundamental investigations.

High field transport and optical phonon scattering in graphene

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A thorough understanding of charge transport in graphene is of great interest with regard to the anticipated applications of this two-dimensional material in future electronic devices. This requires the investigation of the electron and the phonon structure along with their relevant interaction processes.
High field transport in carbon nanotubes is limited by scattering with optical phonons [1, 2]. Thus, also in graphene, scattering with optical phonons is expected to be significant. The low scattering rates combined with significant electric field strengths, which typically arise in modern semiconductor devices, lead to non-equilibrium charge carrier distributions that must be accounted for.
Here we investigate this regime solving the semi-classical Boltzmann equation [3, 4]. The interaction with optical phonons is modeled by taking into account results obtained by Raman spectroscopy and density functional calculations[5, 7, 1, 6]. We show that optical phonons contribute significantly to the overall phonon scattering rates and, therefore, must be treated comprehensively. The optical phonon distribution departs from equilibrium, with significant effect on the charge carrier transport. This becomes pronounced when the chemical potential is close to the Dirac-point and optical phonons are able to produce electron-hole pairs which increase the current density.

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Fabrication of Graphene *p-n-p* Junctions with Contactless Top Gates

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We developed a multi-level lithography process to fabricate graphene *p-n* junctions with the novel geometry of contactless, suspended top gates. This fabrication procedure minimizes damage or doping to the single atomic layer, which is only exposed to conventional resists and developers. The process does not require special equipment for depositing gate dielectrics or releasing sacrificial layers, and is compatible with annealing procedures that improve device mobility. Using this technique, we fabricate graphene devices with suspended local top gates, and demonstrate formation of a graphene *p-n-p* junction via control of the charge type and density of individual regions of the device.

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NMR relaxation rate and static spin susceptibility in graphene

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(Dated: June 2, 2008)

Abstract

The NMR relaxation rate and the static spin susceptibility in graphene are studied within a tight-binding description. At half filling, the NMR relaxation rate follows a power law as T^2 on the particle-hole symmetric side, while with a finite chemical potential μ and next-nearest neighbor t', the $(\mu + 3t')^2$ terms dominate at low excess charge δ. The static spin susceptibility is linearly dependent on temperature T at half filling when $t' = 0$, while with a finite μ and t', it should be dominated by $(\mu + 3t')$ terms in low energy regime. These unusual phenomena are direct results of the low energy excitations of graphene, which behave as massless Dirac fermions. Furthermore, when δ is high enough, there is a pronounced crossover which divides the temperature dependence of the NMR relaxation rate and the static spin susceptibility into two temperature regimes: the NMR relaxation rate and the static spin susceptibility increase dramatically as temperature increases in the low temperature regime, and after the crossover, both decrease as temperature increases at high temperatures. This crossover is due to the well-known logarithmic Van Hove singularity in the density of states, and its position dependence of temperature is sensitive to δ.

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Polarized Raman scattering in mono- and bi-layer graphene

Raman scattering has been a successful experimental tool to study single- and few-layer graphene samples. In this work we will present polarized Raman spectroscopy measurements in mono-, and bi-layer graphene deposited on a silicon oxide substrate. We will study the effect of the incident and scattered light polarization on Raman cross section, by controlling the angular dependence of the intensity of G and G' bands in the VV and VH scattering configurations. The results will be compared with the group theory predictions based on the determination of the Raman tensor.

Ripples in Epitaxial Graphene on the SiC (0001) Surface

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On the basis of extensive ab initio calculation supported by scanning tunneling experiments, we have elucidated the complex morphology of the graphene/SiC (0001) interface [1]. We demonstrate that a carbon buffer layer is always present at the interface. It is a key characteristic of the system because this buffer layer electronicaly decouples the graphene layer from the substrate [2]. It has a mosaic structure that is reminiscent of a graphene honeycomb lattice distorted by the formation of strong covalent bonds with the substrate. The substrate-induced nanostructuration extends up to the ontop graphene layer where it generates an incommensurate modulation of the honeycomb lattice. The possible opening of a gap induced by the substrate [3][4] in the epitaxial graphene electronic structure will also be discussed.

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Effect of trigonal warping on the minimal conductivity of bilayer graphene nanoribbons

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One of the most important observations in graphene systems is the minimal nonzero conductivity in the limit of vanishing density of carriers. This minimal conductivity also has been observed in bilayer graphene which has different dispersion relation from single-layer graphene. Fermi line of bilayer graphene at zero energy is transformed into four separated points positioned trigonally at the corner of the hexagonal first Brillouin zone. Considering this trigonal splitting, we have found that the minimal conductivity of bilayer nanoribbons varies with the length of the nanoribbons on the characteristic scale $\ell = \pi/\Delta k \simeq 50nm$ determined by the inverse of k-space distance of trigonally split Dirac points. Interestingly, the conductivity not only depends on the length, but also it is anisotropic with respect to the angle between symmetry axis of bilayer graphene lattice and the orientation of electrodes.

Our calculations show the minimal conductivity for a short strip $L \ll \ell$ has a universal isotropic value $\sigma_{\perp}^{min} = (8/\pi)e^2/h$ which is the same result in the absence of trigonal splitting. However by increasing the length of nanoribbons, the effect of trigonal splitting becomes important and the conductivity grows to a higher anisotropic value for longer strips. In the limit of $L \gg \ell$ minimal conductivity varies from $(7/3)\sigma_{\perp}^{min}$ at $\theta = 0$ to $3\sigma_{\perp}^{min}$ over an angle range $\Delta\theta \sim \ell/L$. Our result indicates the effect of both electrodes and length of junction which are present in a realistic experiment as well as the effect of trigonal splitting. This could be in particular important in graphene contacts due to the chirality of the carriers and the resulting Klein tunneling phenomena which have been believed to be the main origin of minimal conductivity.

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Magnetic field effects in graphene nanostructures

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We study the effects of a perpendicular magnetic field on graphene constrictions, quantum dots and rings.

The quantum dot consists of a graphene island, connected by narrow constrictions to source and drain contacts, and is fully tunable by three side gates. An applied perpendicular magnetic field changes the transport through the tunnel barriers, and makes them more transparent.

In the ring, we observe the Aharonov-Bohm effect, resulting from the interference between paths through the two arms of the ring. We study the influence of applied back gate and side gate voltages on the oscillations.

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Electron phonon interactions in bilayer graphene studied by Raman spectroscopy

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Graphene, the two dimensional semimetal carbon material led recent progress on devices applications and the physics underlying electronic and phonon properties to further understand the relation of electron phonon interactions (EPI) [1,2] like Kohn anomaly. Bilayer graphene, the Schrödinger equation counter part of Dirac graphene in the electronic spectrum, promises to reveal more about the EPI because of its low charge inhomogeneity when compared to graphene. In this work, we study EPI in bilayer graphene devices applying bottom gate voltage thorough the substrate in a micro Raman setup, revealing the dependence of the Raman features of bilayer graphene as function of the doping level.

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Raman spectroscopy and imaging of graphene

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Graphene, a monolayer graphite sheet, has attracted much interest since it was discovered in 2004. The exceptionally high crystallization and unique electronic properties make graphene a promising candidate for ultrahigh speed nanoelectronics and fundamental research. In this work, we have used Raman and contrast spectroscopy as a fast, non-destructive, easy-to-use, and accurate method to identify the graphene thickness below 10 layers. We also used Raman spectroscopy and image to study the effect of gate oxide deposition and annealing on graphene, mainly on two issues: the defects and strain. While defects lead to the observation of defect-related Raman bands, stress causes shift in phonon frequency. A compressive stress (as high as 2.1 GPa) was induced in graphene by depositing a 5 nm SiO_2 followed by annealing. The magnitude of the compressive stress can be controlled by annealing temperature.

By using Raman spectroscopy, the substrate effect on graphene were also studied, including micromechanically cleaved (MC) monolayer graphene on SiO_2(300nm)/Si, single crystal quartz, Si, glass, polydimethylsiloxane (PDMS) and NiFe substrates, as well as epitaxial graphene (EG) grown on SiC substrate. Our data suggests that the Raman features of monolayer graphene made by MC are independent of the substrate used; in other words, the effect of substrate on the atomic/electronic structures of graphene is negligible for graphene made by MC. On the other hand, significant blueshift of Raman bands are observed on EG which is attributed to the interaction of graphene sheet with SiC substrate, resulting in the change of lattice constant and also the electronic structure.

Finally, The 1+1 layer folded graphene sheets that deviate from AB stacking are successfully fabricated and their electronic structures were investigated by Raman spectroscopy. Significant blue shift of the 2D band of folded graphene compared to that of single layer graphene (SLG) wss observed. This is attributed to SLG-like electronic structure of folded graphene but with slowing down of Fermi velocity (as much as ~5.6%).

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Locally Gated Graphene Devices

Most graphene experiments depend on the presence of a heavily doped Si substrate which serves as a global back gate, inducing charge density via the electric field effect. Although such a global gate approach yields interesting transport phenomena, it represents only the first step towards more complex devices. Such devices require lithographically patterned locally gated graphene nanostructures; examples range from Klein tunneling and electron Veselago-lens to spin qubits. From an application point of view these new phenomena promise novel devices with strongly enhanced functionalities and novel operating principles.

I will present a simple process which combines *both* the patterning of graphene sheets into any desired planar nanostructure *and* the local top gating of the latter. Employing this method, I have fabricated graphene nanoconstrictions with local tunable transmission and characterized their electronic properties. A complete turn off of the device is demonstrated as a function of the local gate voltage. Next, Experiments with locally top gated graphene devices in the quantum Hall (QH) regime will be discussed. By independently varying the voltage on the back gate and local top gate, we have studied bipolar QH transport in graphene p-n-p heterojunctions in different charge density regimes. We find a series of fractional QH conductance plateaus as the local charge density is varied in the p and n regions. Charge transport in top gated graphene bilayer samples will also be discussed.

For a poster presentation in *"ICTP Conference Graphene Week 2008"*

Growth of periodically rippled graphene on *Ru*(0001)

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The possibility to produce single layers of graphene [1,2] has opened a fascinating new world of physical phenomena in two dimensions. Ultrathin epitaxial films of graphite and even ‘‘monolayer graphite’’ have been grown on solid surfaces by chemical vapour deposition for quite some time [3], but the degree of characterization of the films was hampered by experimental limitations [4].

In this work we report on a method to fabricate highly perfect, periodically rippled graphene monolayers and islands on *Ru*(0001) under ultrahigh vacuum conditions. We characterized by means of scanning tunnelling microscopy or spectroscopy (STM/STS) the perfection at the atomic scale and the local electronic structure of the rippled graphene monolayer. The periodicity of the ripples is dictated by the difference in lattice parameters of graphene and substrate, and, thus, it is adjustable. We observe inhomogeneities in the charge distribution, i.e., electron pockets, at the higher parts of the ripples. The graphene nanoislands display a hexagonal shape with atomically resolved zigzag edges, whose characteristic edge states allows us to determine experimentally the doping of the graphene layer.

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Structural and electronic properties of epitaxial graphene on SiC(0001)

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The controlled graphitization of SiC surfaces by high temperature annealing in ultra high vacuum (UHV) promises the preparation of large area graphene layers on a solid substrate [1-6]. The dispersion curves of the π-bands as measured at synchrotron light sources can be used for the determination of the number of graphene layers [4,5]. Of course, it would be preferable to count the number of layers in the home laboratory and even continuously during the preparation procedure. In our present work, we show that angular resolved ultraviolet photoemission spectroscopy (ARUPS) from He II excitation and low energy electron diffraction (LEED) give a solution to this problem. The graphene layer thickness determined in this way can be corroborated by Raman spectroscopy and low energy electron microscopy (LEEM). Using ARUPS and scanning tunneling spectroscopy (STS) we investigate in detail the electronic structure of mono- and few-layer epitaxial graphene. The discussion of the influence on the electronic structure by depositing metals or functional molecules on top of graphene completes our current analysis.

SiC(0001) samples (both 4H- and 6H-polytpype) were prepared by Si deposition and subsequent annealing at different temperatures to obtain graphene layers of different thickness [6]. During the graphitization procedure LEED shows the diffraction pattern of the $(6\sqrt{3}x6\sqrt{3})R30°$ buffer layer reconstruction. For a different graphene thickness the LEED pattern does not change except for the intensity spectra of the diffraction spot related to graphene. The analysis of characteristic variations in these spectra together with simultaneous measurements of the π-bands at the K-point of the Brillouin zone using ARUPS in the same UHV system allows for the determination of the number of graphene layers. The powerful combination of ARUPS and LEED fingerprints therefore facilitates a precise control of the graphene growth in the home laboratory continuously during the preparation procedure. The technique demonstrated here thus paves the way for a large variety of both easily and precisely accomplishable experiments with few layer graphene. Raman spectroscopy and core level photoelectron spectroscopy are used to study the structure of the graphene layers and their interaction with the substrate. LEEM turns out to be a quite useful technique to analyze and control the homogeneity of the graphene films. On such precisely prepared graphene samples, we investigate their electronic structure using ARUPS and STS. By the deposition of metals or functional molecules we investigate the impact on the electronic structure of epitaxial graphene such as the dispersion of the graphene π-bands.

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Weiss oscillations in the magnetoconductivity of modulated graphene bilayer

We present a theoretical study of Weiss oscillations in magnetoconductivity of bilayer graphene. Bilayer graphene in the presence of a perpendicular magnetic field and a unidirectional weak electric modulation is considered. We determine the □_{yy} component of the magnetoconductivity tensor for this system which is shown to exhibit Weiss oscillations. We show that Weiss oscillations in the magnetoconductivity of bilayer graphene are enhanced and more robust with temperature compared to those in conventional two-dimensional electron gas systems whereas they are less robust with temperature compared to monolayer graphene. In addition, we also find phase differences of □ and 2□ in the magnetoconductivity oscillations compared to monolayer graphene and conventional 2DEG system which arise due to the chiral nature of quasiparticles in graphene.

Fabrication of graphene pits and local electronic structures near graphene edges investigated by LT-STM measurement

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Abstract

In recent researches on graphene, edge state is one of the hottest and intriguing topics from the viewpoint of its fascinating features; it forms a flat band at the Fermi level with its population localized and spin-polarized at zigzag-shaped graphene edges. Among the issues on the edge state, the interaction with the Landau levels is of importance since the Landau quantization in the magnetic field enhances the density of state at the Fermi level in case of graphene. Graphene edges behave also as the potential barriers which cause the interference between incident and reflected plane waves near the edges, which is often observed on metal surfaces. We report the fabrication of graphene pits having specific edge structures by slight oxidation at high temperature, and LT-STM observations of their local electronic structures.

Cleaved HOPG samples were heat-treated in the range of 700 to 1000 °C in Ar gas flow with a trace of oxygen. The treated samples were introduced into UHV-STM chamber, degassed at 200 °C for several days at 10^{-8} Torr, and then LT-STM measurements near graphene edges were performed.

The high temperature heat-treatment with a trace of oxygen was found to be effective in fabricating graphene pits at high densities since the oxidation reaction was well controlled at the chemically active defect sites on the HOPG surface (Fig. 1). They form circular or hexagonal structures where two adjacent linear edges intersect at 120° with each other (Fig. 1, inset). By comparing the edge direction with the hexagonal network of graphene obtained from atomic STM images, armchair edges are found to dominate the step edges. Therefore, we confirm that armchair edge is more stable energetically than zigzag one and that oxidation reaction proceeds isotropically in-plane direction perpendicular to the armchair edge. In LT-STM images on a terrace near the step edge taken at 9 K, two types of superperiodic structures, $(\sqrt{3}\times\sqrt{3})R30^\circ$ and honeycomb, were observed. They are ascribed to the transition and interference between K and K´ points at the edges. Particularly, the appearance of a fine structure with three-fold symmetry was discovered on the individual bright spot in the honeycomb area. This can be explained on the basis of the wave functions having the three-fold symmetry and the preferred orientation to avoid the Coulomb repulsion. Results of LT-STM measurements on graphene edges under strong magnetic field will be also discussed.

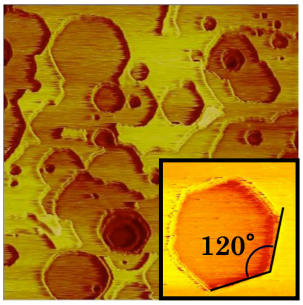

Fig. 1 Ambient-STM image of heat-treated sample at 900 °C (500 × 500 nm²). Inset: detail of a hexagonal pit.

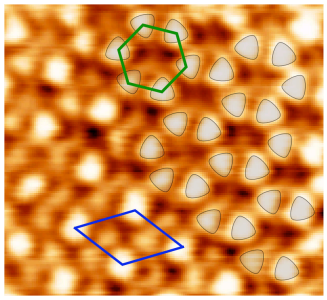

Fig. 2 LT-STM image of a terrace near the edge taken at 9 K. Diamond and hexagon represent the unit cells of $(\sqrt{3}\times\sqrt{3})R30^\circ$ and honeycomb superperiodic structures, respectively. Triangle-like shapes are the fine structures appearing in honeycomb area (1.5 × 1.4 nm²).

Magnetotransport in Graphite

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Interest in graphite has been renewed by the recent investigation of graphene, a single layer of graphite. In order to probe the dimensionality of its charge carriers, magnetotransport in Natural Graphite (NG) and Highly Oriented Pyrolytic Graphite (HOPG) in the limit of low temperatures ($T < 50$ mK) and high magnetic fields $B = 0 - 28$ T has been studied. The observed Shubnikov-de Haas oscillations reveal that the electronic transport in graphite is governed by two types of carriers with fundamental frequencies of $B \approx 5$ T and $B \approx 7$ T, ascribed to electrons and holes, respectively. A filling factor analysis of the Shubnikov de Haas features, similar to that presented in [1], shows a phase shift of π between these two types of carriers, suggesting that the electrons are massive with a Berry phase $\gamma = \pi$ and holes are massless $\gamma = 0$. A zero Berry phase can only be explained assuming that graphite is a quasi two dimensional (2D) material with a graphene like energy spectrum. Tilted field measurement of the Shubnikov de Haas oscillations and the observed quantum Hall effect at magnetic fields up to B = 3 T seem to confirm the 2D picture of loosely coupled graphene sheets.

Problems of the interpretation of magnetotransport data within the 2D model, however, arise in the explanation of the double features at magnetic field $B > 0.5$ T, which cannot be explained by a spin splitting of the Landau levels within the 2D model. Moreover, massless of charge carriers $\gamma = 0$ in graphite are not consistent with the Slonczewski-Weiss-McClure (SWM) model [2], assuming a three dimensional (3D) energy spectrum of graphite. In this model, the charge carriers at Fermi energy are massive and the oscillations are caused by a crossing of Landau bands with the Fermi energy. The SWM-model parameters were fitted to the magnetotransport data in order to calculate and the density of states at Fermi energy in the presence of an applied magnetic field. A good agreement was obtained between the simulated density of states and the main features in the magnetotransport data at high magnetic field.

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Excited States in Graphene Quantum Dots

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We have successfully patterned graphene quantum dots and report the direct measurement of excited quantum states in such dots using tunneling transport spectroscopy.

Quantum dots can be seen as small islands capable of trapping electrons. The quantization of charge and the Coulomb repulsion lead to an integer number of electrons on a dot which can in principle be reduced to just a single electron. If the size of a quantum dot is reduced below around 200 nm, quantum mechanical excitations become observable. Good characterization of these excitations is essential for the coherent manipulation of single electrons and their spin and hence for future quantum electronics based on quantum dots. Measurements of excited state are therefore a prerequisite for further experiments in this field.

A first quantum dot device made of single-layer graphene could be fully tuned using three lateral graphene gates and an additional back gate, and Coulomb blockade was observed at 1.7 K. In particular, energy scales for the tunneling gap, resonances in the constrictions, and Coulomb resonances could be extracted. In a next step, a smaller dot (diameter ~140 nm) was investigated at lower temperatures (electronic temperature ~200 mK). Quantum confinement effects could be detected in transport experiments via excited states and signatures of inelastic cotunneling.

Critical eigenstates and the splitting of the conductance peak near the Dirac point in disordered graphene

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The electronic properties of a bricklayer model which shares the same topology as the hexagonal lattice of graphene is investigated numerically. We study the influence of random magnetic field disorder, which preserves the chiral symmetry and causes similar effects as ripple-disorder[1–4] in real samples, in addition to a strong perpendicular magnetic field. From the calculation of the density of states and the two-terminal conductance, we find a disorder driven splitting of the longitudinal conductance peak within the narrow lowest Landau band at the Dirac point. The energy splitting[5–8] increases with the square root of the magnetic field as already observed in experiments, and is linear in the random magnetic field disorder strength. We calculate the scale invariant peaks of the two-terminal conductance and obtain the critical exponents as well as the multifractal properties of the chiral and the quantum Hall states. We find approximate values $\nu \approx 2.5$ for the QH states, but $\nu = 0.33 \pm 0.1$ for the divergence of the correlation length of the chiral state at $E = 0$ in the presence of a strong magnetic field. Within the central $n = 0$ Landau band, the multifractal properties of both the chiral and the split quantum Hall states are the same, showing some sub-lattice polarization and a parabolic $f(\alpha(s))$ distribution with $\alpha(0) = 2.13 \pm 0.02$, which is conspicuously distinct from the usual quantum Hall behavior.

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Electronic and Magnetic Properties of $3d$ Transition-Metal Atom Adsorbed Graphene and Graphene Nanoribbons

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Abstract

In this work [1], we theoretically studied electronic and magnetic properties of graphene and graphene nanoribbons functionalized by $3d$-transition metal (TM) atoms. The binding energies, electronic and magnetic properties have been investigated for the cases where TM-atoms adsorbed to a single side and double sides of graphene. We find that $3d$-TM atoms can be adsorbed on graphene with binding energies ranging between 0.10 to 1.95 eV depending on their species and coverage density. Upon TM-atom adsorption graphene becomes a magnetic metal. TM-atoms can also be adsorbed to graphene nanoribbons with armchair edge shapes (AGNR's). Binding of TM-atoms to the edge hexagons of AGNR yield the minimum energy state for all TM-atom species examined in this work and in all ribbon widths under consideration. Depending on the ribbon width and adsorbed TM-atom species, AGNR, a non-magnetic semiconductor, can either be a metal or a semiconductor with ferromagnetic or anti-ferromagnetic spin alignment. Interestingly, Fe or Ti adsorption makes certain AGNR's half-metallic with a 100% spin polarization at the Fermi level. Present results indicate that the properties of graphene and graphene nanoribbons can be strongly modified through the adsorption of $3d$ TM atoms.

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Effect of radiation on transport in graphene

We study transport properties of graphene-based p-n junctions irradiated by an electromagnetic field (EF). The resonant interaction of propagating quasiparticles with an external monochromatic radiation opens *dynamical gaps* in their spectrum, resulting in a strong modification of current-voltage characteristics of the junctions. The values of the gaps are proportional to the amplitude of EF. We find that the transmission of the quasiparticles in the junctions is determined by the tunneling through the gaps, and can be fully suppressed when applying a sufficiently large radiation power. However, EF can not only suppress the current but also generate it. We demonstrate that if the height of the potential barrier exceeds a half of the photon energy, the directed current (*photocurrent*) flows through the junction without any dc bias voltage applied. Such a photocurrent arises as a result of inelastic quasiparticle tunneling assisted by one- or two-photon absorption. We calculate current-voltage characteristics of diverse graphene based junctions and estimate their parameters necessary for the experimental observation of the photocurrent and transmission suppression.

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Multiple Quantum Well Structures of Graphene Nanoribbos

Based on first-principles calculations we predict that periodically repeated junctions of armchair and zigzag graphene nanoribbons of different widths can form superlattice structures. In these superlattice heterostructures the energy band gap and magnetic configuration are modulated in real space. Orientation of constituent nanoribbons, their width and length, the symmetry of the junction are some of the structural parameters to engineer electronic and magnetic properties of these quantum well structures. The edge states of zigzag graphene nanoribbons for specific spin directions can also be confined in these wells. In specific geometries, the absence of reflection symmetry causes the magnetic ground state of whole heterostructure to change from antiferromagnetic to ferrimagnetic. Not only the structural modulation, but also composition modulation, such as periodically repeated, commensurate heterojunctions of BN and graphene honeycomb nanoribbons result in a multiple quantum well structures. We showed that these graphene based quantum structures can introduce novel concepts to design nanodevices.

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CONDUCTIVITY OF GRAPHENE: HOW TO DISTINGUISH BETWEEN SAMPLES WITH SHORT AND LONG RANGE SCATTERERS

To understand the spectacular transport properties of single graphite layers [1] one has to know which kind of scatterers dominates in a given sample. Indeed, theory predicts the electrical conductivity to be strongly dependent on the particular type of the scatterers being present in the system [2]. We demonstrate that the diversity of the conductivity behaviour observed in graphene (cf. [3] and [4]) can be naturally described employing the concentrations of long and short range scatterers as parameters. According to our microscopic model, the conductivity measurements upon potassium doping [3] obviously suggest a strong domination of the long range scattering potential, whereas the conductivity of suspended graphene after annealing [4] is governed by short range scatterers such as nano-sized ripples and other imperfections. In the first case, the width of the minimum conductivity region is rather broad, with a well defined plateau, the residual conductivity defined by the linear fit keeps constant near $2e^2/h$, and the conductivity minimum itself is around the universal value $4e^2/h$. In the opposite limit, the conductivity demonstrates very sharp dip at zero carrier concentrations (i. e. no plateau is unambiguously visible), and the residual conductivity can acquire a wide range of values depending on the scattering parameters. Our semiclassical approach [5] fully incorporates the chiral nature of electronic states in graphene which is crucial for a correct description of transport properties mentioned above.

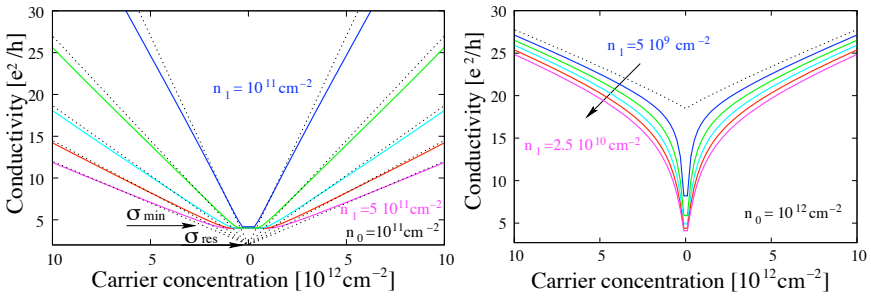

Figure 1: Our prediction for the conductivity vs. carrier concentration for different relation between the renormalised concentrations of long n_1 and short n_0 range scatterers. Left panel: Long range scatterers dominate, cf. Ref.[3]. Right panel: Short range scatterers dominate, cf. Ref.[4].

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Plasmon modes in graphene

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The spectrum of 2D plasma waves in graphene have been studied recently by [1, 2] in the Dirac fermion model, which is valid when the plasmon wave vector $\mathbf{q}$ is small as compared to the size of the Brillouin zone (BZ). This model neglects transitions with large $\mathbf{q}$ inside the BZ. To study these effects we consider electromagnetic response of graphene to a longitudinal electromagnetic radiation (described by a scalar potential ϕ) for $\mathbf{q}$ lying in the whole BZ. We take into account the whole dispersion relation for graphene electrons in the tight binding approximation and the local field effects in the electro-dynamical response. In the presented approach retardation effects are ignored. In the limit of small $\mathbf{q}$ our results coincide with [1, 2]. Near the wavevectors close to the corners of the hexagon-shaped BZ we find new low-frequency 2D plasmon modes, weakly damped, with the spectrum $\omega \sim |\mathbf{q} - \mathbf{K}_i|$, i=1,...,6. These modes are related to the transitions between K and K' cones (K and K' are "Dirac" points with conical singularities) in the electron spectrum, and we call them *inter-valley plasmons*. The inter-valley plasmons could be experimentally observed by Raman spectroscopy.

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Nonequilibrium Carriers in an Intrinsic Graphene

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We examine the non-equilibrium electron-hole pairs in an intrinsic graphene under heating by the steady-state electric field and under far/mid IR excitation. At low temperatures, one can disregard the Coulomb scattering processes (because a low carrier concentration) taking into account the intraband quasielastic energy relaxation caused by the acoustic phonon scattering and the generation-recombination processes due to interband transitions caused by thermal radiation. At high temperatures, where the quasi-equilibrium distribution takes place due to strong carrier-carrier scattering, the effective temperature and concentration of carriers are determined from the balance equations. We also discuss the case of acoustic phonons and thermal radiation at different temperatures, when non-equilibrium electron-hole pairs are connected with two thermostats. The momentum relaxation is assumed to be caused by the elastic scattering [1].

The pertinent collision integrals [2] are adapted for the case of the massless energy spectrum of carriers (the neutrinolike Weyl-Wallace model) which are interacted with the longitudinal acoustic phonons and the thermal radiation [3]. Both electron-hole dispersion laws and scattering processes under consideration are symmetric, so that the non-equilibrium distributions of electrons and holes are identical ones. The shape of the energy distribution of carriers is determined by the interplay between the radiative generation-recombination processes and the quasielastic energy relaxation moreover the styles of distributions are different for the excitation mechanisms considered. The calculations were performed with the use of the Fokker-Planck quasielastic collision integral, interband photogeneration rate, and the non-linear generation-recombination term.

Finally, we analyze the following responses of nonequilibrium carriers:
(a) the current-voltage characteristics of hot carriers,
(b) the nonlinear interband far/mid IR absorption,
(c) the photoconductivity under a probe dc electric field, and
(d) the effect of thermal radiation on conductivity.

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Quantum oscillations in coherent graphene heterojunctions

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The gapless spectrum in graphene [1–3] allows the fabrication of adjacent regions of positive and negative doping. The study of such graphene pn junctions [4–6] has attracted interest lately both for its potential device applications as well as its role as a table top laboratory to study the tunneling of massless fermions through a potential barrier [7]. Here we report transport measurements in locally gated graphene heterostructures which reveal quantum oscillations in the conductance across the barrier as a function of both magnetic field and density. This effect is explained using a simple model analogous to the optical etalon, or Fabry Perot cavity, and is shown to rely on the selection of forward moving electrons passing through a single pn junction, as previously predicted theoretically [7, 8].

However, as noted in [9], such resonances cannot be generated by exactly normally incident electrons due to the absence of backscattering [10], in contrast with conventional resonant tunneling experiments. In fact, the resonant conduction is dominated by electrons incident at the angle where the probability of transmission through the individual pn junctions is $\sim \frac{2}{3}$. This angle θ^*, along with the width of the junction L, determines the period of the oscillations and can thus be determined from the transport experiments. In addition, detailed analysis of the oscillation period and overall resistance of the pnp junction allows us to estimate the influence of disorder on conduction through the pnp region.

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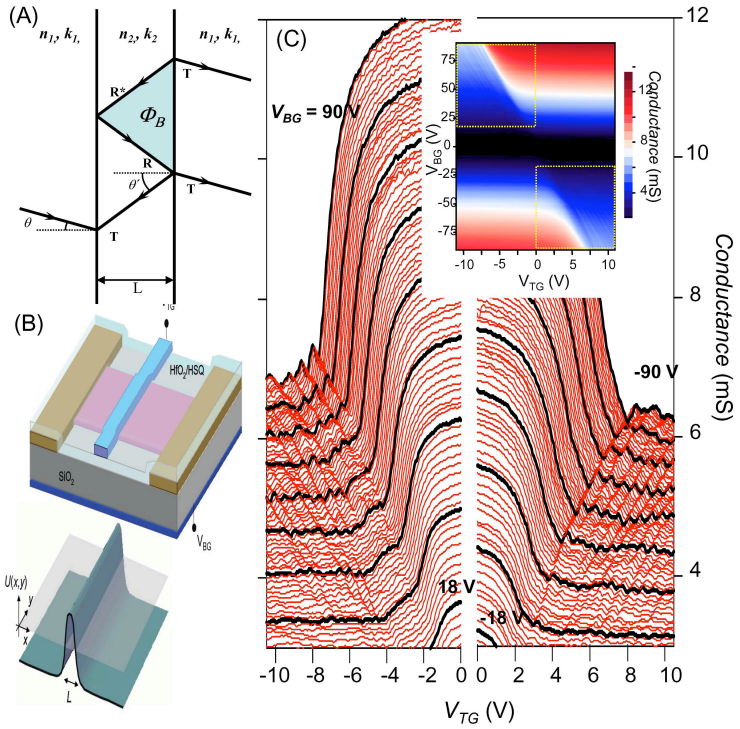

FIG. 1: Graphene heterojunction device schematics and conductance measurements. (a) Schematic picture of electron transmission through graphene etalon. (b) Schematic diagram of the device structure and the electric potential distribution in the graphene. (c) The inset shows the conductance of device as a function of the top gate and back gate voltages V_{TG} and V_{BG}. The main panels show line cuts through this color map in the region indicated by the dotted lines in the inset, showing the conductance as a function of V_{TG} at fixed V_{BG}. These traces are separated by a constant V_{BG} shift, where some representative curves are highlighted by black color. The numbers in the graph indicate V_{BG}.