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Logarithmic renormalization of interactions and disorder in graphene.

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The fact that the Coulomb interactions induces logarithmic anomalies in the spectrum of the clean gapless semiconductors is known for almost four decades [1]. Recent explosive interest in graphene called for revisiting and refining of old results. In my talk I will review:

1. Renormalization of the one particle spectrum (including trigonal warping) in a clean graphene [2];
2. Renormalization of the short range and umklapp interactions by the Coulomb interaction in a clean graphene [2];
3. Renormalization of the electron-phonon couplings by the Coulomb interaction in a clean graphene [3];
4. Effects of the Coulomb interaction [4] on the logarithmic correction due to the multiple impurity scatterings [5].

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Electric and thermoelectric properties of graphene

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In this presentation, we will review some of recent experimental studies to investigate electric and thermoelectric properties of graphene. First, we will discuss the enhancement of carrier mobilities in suspended graphene samples and the strong temperature dependent conduction in the samples. Second, the nature of these QH states near the charge neutral Dirac point will be discussed as a single particle theory breaks down. We will discuss the transport and IR measurement results that reveal the role of the many-body effects due to the electron-electron interaction in graphene near the Dirac point. In addition, the role of disordered edges in graphene nanostructures will be discussed in the context of localization and variational range hopping conduction. Finally we will discuss thermoelectric power measurement in graphene under magnetic field.

Current-induced cleaning of graphene

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(Dated: June 6, 2008)

By nature, all the carbon atoms that compose graphene samples are exposed to the surrounding environment. As a result, the electronic properties of graphene depend crucially on the molecular species adsorbed on its surface: adsorbates may act as dopants and scattering centers, and may lower the mobility of charge carriers. Thus, identifying the nature of adsorbates and controllably obtaining adsorbate-free surfaces are essential steps towards improving transport performances of graphene devices.

In this talk, we will first present a study of the electrostatic environment of graphene samples prepared with the micromechanical exfoliation technique [J. Moser, *et al.*, Appl. Phys. Lett. **92**, 123507 (2008)]. Using electrostatic force microscopy, we detect the electric dipole of residues left from the adhesive tape during graphene preparation, as well as the dipole of water molecules adsorbed on top of graphene. Water molecules form a dipole layer that can generate an electric field as large as 10^9 V/m. We expect that such a strong electric field significantly modifies the electrical properties of graphene devices.

Further adsorbates are inevitably introduced during nanofabrication, in the form *e.g.* of resist residues. We will describe a simple, yet highly reproducible method to remove those adsorbates from the surface of graphene samples inside a cryostat. Our method is based on the application of a large dc bias across the graphene sample, thereby generating a large current and correspondingly a thermal power of several tens of milliWatts over an area of a few micrometer squares. Remarkably, graphene can sustain such extreme conditions while adsorbates get removed. We employ atomic force microscopy to visualize this effect in the case of nanofabrication residues and in the case of intentionally deposited CdSe nanoparticles. We show that our cleaning method both suppresses extrinsic doping [J. Moser, *et al.*, Appl. Phys. Lett. **91**, 163513 (2007)] and strongly enhances the mobility of our graphene samples [A. Barreiro, *et al.*, work in progress]. The mobility typically reaches 25,000 $\mathrm{cm}^2/\mathrm{Vs}$ for graphene samples in a Hall bar geometry. In addition, the quality of our current-cleaned graphene samples is high enough for us to routinely observe the anomalous quantum Hall effect (σ_{xy} plateaus at $\pm 2\,\mathrm{e}^2/\mathrm{h}$, $\pm 6\,\mathrm{e}^2/\mathrm{h}$, as the carrier density is varied), as well as the quantum Hall plateau at $\sigma_{xy} = 0\,\mathrm{e}^2/\mathrm{h}$ at moderate field strength (B=9 T).

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Nonlinear screening in graphene nanostructures

Unique properties of graphene promise a variety of novel applications and raise new fundamental questions concerning the physics that governs interacting Dirac fermions in a solid-state environment. I will present our recent theoretical work that examines how electrons in graphene respond to strong external potentials. I will discuss two specific examples where such a problem is topical: (a) a graphene *p-n* junction, where the potential is created intentionally by control gates and (b) a charge-neutrality ("Dirac") region where the potential is due to random Coulomb impurities. Our nonlinear screening approach enables us to derive new results for ballistic transport in *p-n* junctions and also sheds light on the issue of the "universal" conductivity at the charge-neutrality point.

This work is supported by NSF and ASC UCSD.

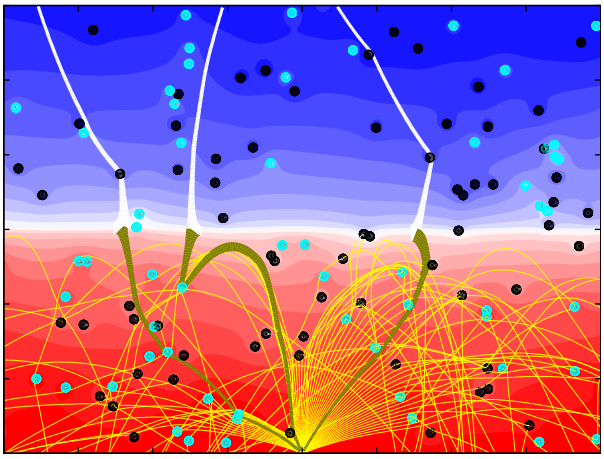

Fig. 1: Electron trajectories in a disordered graphene *p-n* junction

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Electrical Transport in Graphene p-n-p Junctions with Suspended Top Gates

High quality graphene *p-n-p* junctions with suspended top gates are fabricated using a multi-level lithography technique. This fabrication procedure minimizes damage or doping to the single atomic layer, and is compatible with annealing procedures that improve device mobility. We demonstrate individual control of charge density and type in different regions of the device, and device quality is established by the presence of the $2e^2/h$ conductance plateau at high magnetic fields. In the long term, combination of this technique with suspended graphene may enable experimental realization of novel phenomena such as the Veselago lensing effect.

Graphene single electron transistor with integrated charge detection

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We report measurements on a graphene single electron transistor (SET) with an integrated graphene charge detector. The device consisting of a graphene island (diameter approx. 185 nm) connected to source and drain contacts via two narrow graphene constrictions is tunable by lateral graphene side gates. The charge detector is based on a 45 nm wide graphene nano ribbon placed approx. 60 nm from the SET island. From Coulomb diamond measurements on the SET a charging energy of 4.3 meV is extracted. Each charging event on the SET causes a step-like change of the current through the charge detector. This allows us to study the SET behavior without measuring the current through the device. Such a charge detector can be utilized as a least invasive readout of SET's or quantum dot's charge states. The mutual interaction between the SET and the constriction is further used to study the properties of the graphene nano ribbon.

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Unconventional electronic and magnetic properties of nanographene

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The electronic structure of nanographene having open edges crucially depends on its edge shape. The circumference of an arbitrary shaped nanographene sheet is described in terms of a combination of zigzag and armchair edges. According to theoretical suggestions, nanographene has unconventional magnetic nonbonding π-electron state (edge state) localized in zigzag edges. This is reminisecent of the non-Kelulé structure of condensed aromatic hydrocarbon molecules. We investigate the structure of nanographene sheets, the electronic structure of graphene edges and unconventional magnetism of the edge-state spins in nanographite, which is a stacked nanographene sheets.

Nanographene is prepared by heat-induced conversion of nanodiamond particles. Nanographene ribbons are found by chance around step edges of graphite. The detailed structures of individual nanographene ribbons thus found are characterized by resonance Raman experiments, in which the graphitic *G*-band is used as a fingerprint. UHV-STM/STS investigations of well defined graphene edges which are hydrogen terminated confirm the presence of edge states around zigzag edges, in good agreement with theoretical works. Zigzag edges are short and defective in general in spite that armchair edges tend to be long and defect free. Edge states placed at the Fermi level are responsible for the less stabilized feature of zigzag edges. The feature of the edge state depends on the detailed geometry of the edge structures. The edge state in a short zigzag edge embedded between armchair edges becomes less localized due to state mixing with the adjacent armchair edges. The electrons in the edge state in a finite-length zigzag edge are subjected to electron confinement effect.

Host-guest interaction can modify the magnetic features of the edge-state spins in nanographite domains in nanoporous activated carbon fibers (ACFs), which consist of 3D disordred network of nangraphite domains. Physisorption of guest species such as water, organic molecules, rare gas in the nanopores of ACFs shows a high-spin/low-spin magnetic switching phenomenon, in which a discontinuous reduction of the magnetic moment takes place upon the adsorption of guest molecules. This is explained in terms of the mechanical compression of nanographite domains by the internal pressure of condensed guest molecules, which strengthens the inter-graphene-sheet antiferromagnetic interaction. The magnetic switching phenomenon is a unique magnetic feature which has never been observed.

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Fabrication and Chemical modification of Nanographene

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The reduction in the crystal size into nano-dimensions often involves novel electronic properties, which is unknown for bulk systems. Graphene is no exception. Interestingly, nano-sized graphene (nanographene) has been known to have enhanced magnetism [1, 2]. When a graphene sheet is cut along the zigzag direction, strongly spin-polarized non-bonding π-state (edge state) appears along the created edges, in spite that cutting along the armchair direction produces no such state. Meantime, the presence of edges gives graphene the potential to control its electronic properties through the chemical modification. According to the ab initio calculation [3], The fluorine-termination of the zigzag edge vanishes magnetism, while the combination of the mono-hydrogenated and di-hydrogenated zigzag edges gives rise to strong ferromagnetism, where ferromagnetic spin polarization is distributed homogeneously in the entire area of the nanographene. Here, we present the fabrication of novel nanographene by using EB-lithography, and tuning its electronic properties though chemical modification.

Nanographene were fabricated by using two methods. First, the nano-patterned resist mask was fabricated by the electron beam lithography, followed by the lift-off and post annealing process after carbon deposition by laser ablation. On the other method, gold mask nano-pattern was fabricated on graphene sample prepared by cleaving method, where oxygen plasma was used for etching process. Both methods successfully yield nanographene with the size down to 50 nm (Fig.1).

Effect of chemical modification on magnetism of graphene was examined by using nanographene network material (activate carbon fibers; ACFs). In the initial stage of fluorination of nanographene in ACFs up to a fluorine concentration of F/C~0.4 (Fig. 2), the reaction with fluorine atoms takes place mainly around the edges due to the relatively strong chemical activity of edge carbon atoms, resulting in the formation of difluorinated edge carbon sites. In this fluorination process, the concentration of edge state spins tends to decrease as the fluorine concentration is elevated. This means that the edge state is destroyed by chemical modification with fluorine atoms. After the fluorination is completed at the edges, fluorine attacking the interior of nanographene sheet, creates a σ-dangling bond having a localized spin through breaking the π-bond, and terminates them, which causes a maximum in the spin concentration at F/C~0.8, and complete vanishment at F/C~1.2.

The present study is partially supported by by MEXT Nanotechnology Network Project in the Tokyo Institute of Technology.

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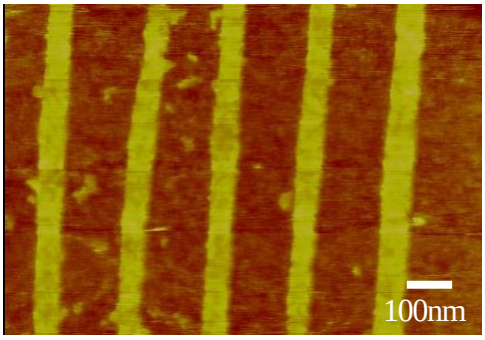

Fig. 1: AFM image of Nanographene Ribbons with 50 nm width.

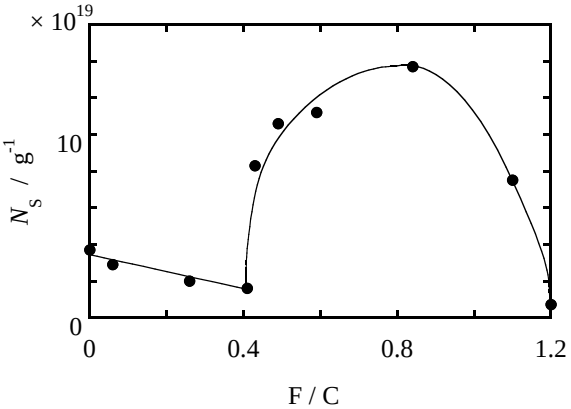

Fig. 2: The F / C dependence of the localized spin concentration for fluorinated ACFs.

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Title:
STM investigation of Few Layers Graphene (FLG) grown on the 6H-SiC(000-1) surface.

Abstract:
After the discovery of the fascinating properties of graphene [1, 2] the search for mass production techniques began. Graphitization of the surface of hexagonal SiC substrates by high temperature treatments is a promising way to fabricate large size FLG samples for possible applications for instance in microelectronics [3]. It also allows the use of the full power of modern surface science techniques for studying the structure and electronic properties of the material. Up to now, these investigations have concentrated on the so-called Si face of the SiC substrates, where signatures expected for single and bi-layer graphene have been reported (although some points remain controversial). It turns out however that most of the magneto-transport [3, 4] (and optical [5]) experiments have been performed on the (000-1) face of hexagonal samples, the so-called C-face, which show better electrical characteristics. It is therefore desirable to apply the surface characterization techniques to this face also.

Quite surprisingly, single layer graphene behaviour has been found in FLG films grown on 4H-SiC(000-1) substrates in a secondary vacuum furnace [3-5]. This behaviour has been ascribed to the presence of stacking faults in the films [6]. Analytical [7] and ab-initio calculations [6] have confirmed that a twist between adjacent carbon planes leads to an effective electronic decoupling of the layers which restores a graphene-like (single layer) behaviour. We have investigated by STM the early stages of graphitisation of the C terminated face of SiC in ultra-high vacuum (UHV) conditions [8]. For 3-5 layers thick samples, we observe superlattices with periods in the nanometer range on the FLG. We show that these superstructures arise from “Moiré patterns” -well documented for graphite surfaces-, which directly demonstrates the presence of stacking faults in the layer. Moreover, we have found that a twist can influence the apparent sublattice asymmetry in agreement with theoretical results. Measurements performed for one single graphene on the C face indicate that the graphene-substrate interaction is quite different on the Si and C faces of the substrate. In particular, atomic resolution images show that this interaction depends sensitively on the atomic structure of the substrate. Our data additionally reveal significant differences between furnace and UHV grown samples.

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Growth and structure of epitaxial graphene on Iridium

The epitaxial growth of high quality graphene is a promising route towards potential applications [1]. While SiC has attracted interest as a support already at the initial stages of graphene research, metallic substrates are a promising alternative and allow one to address fundamental issues such as the substrate-graphene interaction. Understanding the graphene metal interaction is also of importance for the practical issue of contacting graphene to metallic electrodes. We will deal with epitaxial graphene on an Ir(111) surface, which exhibits remarkable structural properties [2], together with electronic features indicating a weak interaction with the substrate [3]. We will present a scanning tunnelling microscopy analysis of the structure of graphene grown on Ir(111) through thermal decompostion of hydrocarbon molecules [4,5]. It will be shown how this approach allows to tailor the morphology of graphene monolayers, from full sample coverage down to nanosized graphene structures with well defined carbon edges. We will also focus on the structural coherency of graphene on Ir, which is preserved across the substrate step edges as a result of overstep growth, or through heptagon-pentagon pairs in graphene which we directly revealed at atomic scale. Such qualities make graphene/Ir(111) a model system, especially suited to probe the electronics of graphene and its interaction with a support (see the contribution of Pletikosic, Kralj, et al.).

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Raman Nanometrology of Graphene: Temperature and Substrate Effect

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It was recently established that micro-Raman spectroscopy is an effective tool for graphene characterization. However, most of the Raman spectroscopy studies of graphene reported to date were limited to graphene layers on Si/SiO_2 substrates with a carefully selected thickness of SiO_2 layer. The latter is due to the fact that the single-layer graphene becomes visible in an optical microscope when placed on top of Si wafer with 300-nm thick oxide layer. For graphene device applications it is important to investigate how the Raman signatures from graphene are affected by different substrates. In this talk we report our results for the Raman nanometrology of graphene on different substrates. The number of atomic layers in the examined samples was independently confirmed by the atomic force microscopy, analysis of the 2D-band in Raman spectrum and quantum Hall measurements [1]. We investigated Raman spectra from graphene layers on GaAs, sapphire and amorphous glass substrates and compared them with those from graphene on the standard Si/SiO_2 substrate and graphene flakes suspended over trenches in Si wafers. The influence of the substrates on the Raman spectra was explained by the polarization and dispersion features of the main phonon branches in graphene. We also studied the effect of temperature on the most characteristic peaks in the Raman scattering spectra of graphene. The measurements were carried out over the temperature range from ~80 K to ~370 K with the external control of the sample temperature. We observed the red shift of G peak of graphene with increasing temperature despite anomalous temperature expansion of the graphene crystal lattice. The values of the temperature coefficients for the G and 2D-band frequencies extracted from Raman spectra of the single-layer graphene are $-1.6\times10^{-2}cm^{-1}/K$ and $-3.4\times10^{-2}cm^{-1}/K$, respectively [2]. The obtained temperature coefficients of graphene Raman peaks allowed us to carry out the first measurements of the thermal conductivity of graphene [3].

The work in Balandin group has been supported by the DARPA – SRC funded FCRP Center on Functional Engineered Nano Architectonics (FENA). C.N.L. and A.A.B. acknowledge support from the UCR – UCLA – UCSB Center for Nanoscience Innovations for Defense (CNID).

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Novel Graphene-based Materials

Our top-down approaches [1,2] inspired physicists to study individual layers of graphite obtained by micromechanical exfoliation, and our current approach has been to convert graphite to graphite oxide (GO), generate aqueous colloidal suspensions containing individual layers of GO (we call them 'graphene oxide'), and to use these 'graphene oxide sheets' in a variety of ways. For example, we have embedded individual and reduced graphene oxide sheets in polymers such as polystyrene and evaluated their dispersion, morphology, and the electrical percolation and thus conductivity of the resulting composites. In parallel paths, we have: (i) undertaken studies of individual graphene oxide and reduced graphene oxide sheets, to elucidate their chemical, optical, and electrical properties, (ii) embedded graphene oxide sheets in glass by a sol-gel route and made electrically conductive and transparent glass coatings, and (iii) produced 'graphene oxide paper', a material with intriguing mechanical properties. *Support of our work by the NSF, ONR/NRL, NASA, and DARPA is appreciated.*

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Characterization of graphene through anisotropy of constant-energy maps in angle-resolved photoemission

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We show theoretically [1] how constant-energy maps of the angle-resolved photoemission intensity can be used to test wave function symmetry in graphene. For monolayer graphene, we demonstrate that the observed anisotropy of ARPES spectra is a manifestation of electronic chirality. Whereas the chirality of a relativistic particle is defined by its spin, chirality in graphene refers to the sublattice composition of plane-wave states of Bloch electrons. The eigenstates Ψ, within a single valley, have different amplitudes on adjacent A and B sites, and, following the example of relativistic physics, they may be written as a two-component "spinor" $\Psi = (\psi_A,\psi_B)$. The relative phase ϕ between the wave function on sublattice atoms indicates the "isospin" vector $\boldsymbol{\sigma} = (\cos\phi,\sin\phi, 0)$ of the chiral state $\Psi = (e^{-i\phi/2}, e^{i\phi/2})$ of quasiparticles in graphene. ARPES [2,3] is exactly the tool to visualize this state through the angular dependence of the emitted photoelectron flux.

Our analysis [1] is based upon the standard theory of angle-resolved photoemission [2,3]. In an ARPES experiment, incident photons with energy ω produce photoelectrons whose intensity I is measured in a known direction as a function of kinetic energy. Conservation of momentum ensures that the component of the momentum parallel to the graphene surface $\mathbf{p}_\parallel$ is equal to the quasi-momentum of Bloch electrons in graphene to within a reciprocal lattice vector. As graphene has two inequivalent atomic sites, the angular dependence of the intensity may be accounted for by considering two-source interference (à la Young's double slits). Outside the sample, at a position $\mathbf{R_0}$ relative to the midpoint of the two sources, electronic waves $\exp[i\mathbf{p}.(\mathbf{R_0}+\mathbf{u}/2)-i\phi/2]$ and $\exp[i\mathbf{p}.(\mathbf{R_0}-\mathbf{u}/2)+i\phi/2]$ from adjacent A and B sites combine. This yields the intensity I of the two-source interference pattern, $I \sim \cos^2[\mathbf{p}_\parallel.\mathbf{u}/2-\phi/2]$ where $\mathbf{u}$ is the separation of the adjacent sites. The first term in the argument of the cosine is a phase difference due to the different path lengths of electron waves emitted from two sublattices, while the second term, $-\phi/2$, arises from the relative phase of the electronic Bloch states on A and B sublattices determined by the quasiparticle chirality. Figure 1 shows a typical calculated dependence of the intensity of the photoemission from states (here, at energy 1.45eV below the charge-neutrality point) plotted as a function of wave vector $\mathbf{p}_\parallel$, in agreement with the qualitative prediction of the two-source interference picture. The numerical results of calculations appear to be consistent with experimentally measured constant-energy maps [4].

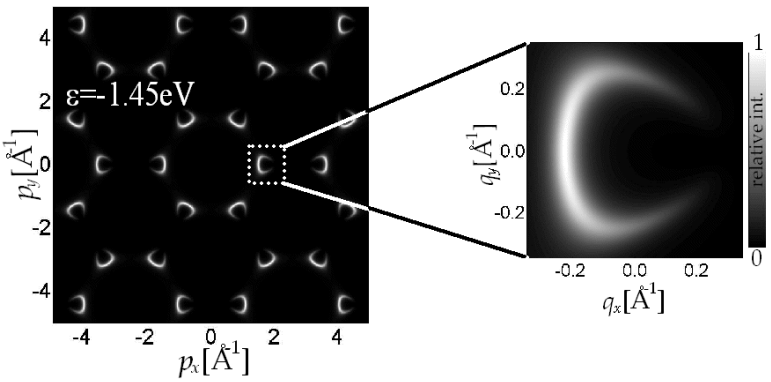

Figure 1 The intensity of photoemission from states at a constant energy 1.45eV below the charge-neutrality point in monolayer graphene, plotted as a function of photoelectron wave vector $\mathbf{p}_\parallel$ parallel to the surface of graphene for $\mathbf{p}_\parallel$ covering several Brillouin zones (left) and plotted as a function of photoelectron wave vector $\mathbf{q}$ in the vicinity of valley K_+ (right).

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Atmospheric pressure graphitization of SiC(0001) – a route towards large scale production of graphene films

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Graphene, a single monolayer of graphite, has recently attracted considerable interest due to its novel magneto transport properties, high carrier mobility, and ballistic transport up to room temperature. It has technological applications as a potential successor of silicon for the post Moore's law era, as single molecule gas sensor, in spintronics, in quantum computing, or as terahertz oscillators. For applications, uniform ordered preparation of graphene on an insulating substrate is necessary. Exfoliation of graphene from graphite yields high quality crystals, but this route for producing such isolated samples with dimensions in the micrometer range is unsuitable for large-scale device manufacturing; the vacuum decomposition of SiC, on the other hand, yields wafer-sized samples, yet with small grains (30-200nm) that are equally unsuitable. Here we show that the ex-situ graphitization of Si-terminated SiC(0001) in an argon atmosphere produces high quality monolayer graphene films with much larger domains than previously attainable. We characterize the samples by means of low energy microscopy (LEEM), atomic forces microscopy (AFM), and valence level photoemission. Our data show that domain size is presently limited only by the extent of the SiC substrate terraces, i.e. several tens of micrometers in the direction along the terraces and about 2-3 É m in the perpendicular direction. This method provides a path towards the synthesis of graphene films in a technologically viable manner.

Raman Investigation of Electric Field Effect in Graphene Layers(*†)

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Electric field effect in monolayer and bilayer of graphene thin films was studied by gate modulation of the long wavelength optical phonon (the G-band). Low-temperature Raman spectra reveal that the life time of the G-band phonon can be tuned by turning on and off with a gate electrode a phonon-decay channel, in which the phonon is annihilated by creating an electron-hole pair across the Dirac point.

The G-band energy evolution with charge doping in bilayer graphene reveals a phonon anomaly due to a resonant coupling of electron-hole pairs with the phonon mode. Similar to the better known Kohn anomaly, this phonon anomaly is a quite general phenomenon.

The phonon anomaly is also expected in monolayer graphene. Experimentally, however, it has not been observed so far. We believe that the phonon anomaly features in monolayer graphene are washed out by impacts of disorder linked to the charge density non-uniformity in the sample. The non-uniformity, however, has a smaller impact in bilayer graphene due to the interlayer coupling that has changed the low energy dispersion of carriers drastically from that in the monolayer, resulting in a much larger density of electronic states.

(*) Collaboration with Y. Zhang, E. Henriksen, P. Kim and A. Pinczuk
(†) Supported by ONR, NSF and DOE
A 20-minute talk is preferred

Phonon renormalisation and electron-phonon coupling in doped single and bilayer graphene

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Graphene's electronic structure is uniquely captured in its Raman spectrum, that evolves with increasing number of layers. Raman fingerprints for single-, bi- and few-layer graphene reflect changes in the electronic structure and electron-phonon interactions and allow unambiguous, high-throughput, non-destructive identification of graphene layers [1].

Here we report the evolution of the Raman spectra of single [2,3] and bi-layer [4] graphene as a result of doping. Doping is induced either by applying a bottom gate [2], or by a polymeric top gate [3,4], or naturally happens as a result of charged impurities [5].

We observe that in both single and bilayer graphene, while the G peak stiffens and sharpens for both electron and hole doping, the 2D peak shows a different response to holes and electrons. The ratio of the intensities of the G and 2D peaks shows a strong dependence on doping. The phonon renormalization of bilayer graphene has characteristic features compared to single layer. The bilayer has two conduction and valence subbands, with splitting dependent on the interlayer coupling strength. This results in a change of slope in the variation of G peak position with doping, which allows a direct estimation of the interlayer coupling.

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Studying electrons and phonons in graphenes by resonance Raman scattering.

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Resonance Raman spectroscopy is a very useful tool to investigate electrons and phonons near the Dirac point of graphenes due to the specific double resonance (DR) Raman process that occur in these materials. By changing the energy of the incident excitation laser, it is possible to probe different points within the interior of the Brillouin zone of graphenes. We have performed recent investigations of monolayer and bilayer graphene using this methodology and we were able to determine the tight-binding parameters that describe the electronic dispersions of these materials [1,2]. Our results reveal a significant asymmetry between the electronic dispersion in the valence and conduction bands of bilayer graphene. We are currently using this technique to study graphenes subjected to a gate voltage, and we will show the effect of the applied electric field on the Raman spectra of bilayer graphene. Raman results of graphene samples subjected to thermal treatment with different atmospheres will be also presented.

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Non adiabatic vibrations in doped graphene and graphite: measuring the doping with Raman spectroscopy

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Raman spectroscopy is a very valuable tool to characterize graphene samples and in particular to measure in-situ the doping level. For positive and negative doping, we predicted by theory a stiffening of the Raman G peak (i.e. the zone-center E_{2g} optical phonon) [1], which was then observed experimentally [2]. Such a shift is not described by the adiabatic Born-Oppenheimer approximation but requires the use of time-dependent perturbation theory to explore dynamic effects beyond this approximation. The adiabatic approximation is considered valid in most materials but it miserably fails in doped graphene. Interestingly, we also found a similar but much larger failure in graphite intercalated compounds, where the error of the Born-Oppenheimer approximation can be as large as 20% of the phonon frequency [3].

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Title:

"What can we learn from the intensities of multiphonon Raman scattering peaks in graphene?"

Abstract:

The focus of the present work is the calculation of integrated intensities of two-phonon Raman peaks in monolayer graphene. It is shown that they carry information about (i) electron-electron collisions, and (ii) electron-phonon coupling constants. The latter result does not agree with that of earlier calculations performed in the framework of the density-functional theory. It is shown how this discrepancy can be explained by Coulomb renormalizaion of electron-phonon coupling constants.

Magneto-phonon resonance in graphene

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In graphene the distance between Landau levels grows very quickly with magnetic field. As a result, the frequency of one of inter-Landau-level transitions can be brought into resonance with the frequency of an optical phonon mode. According to our prediction, this gives rise to a peculiar fine structure acquired by the zero frequency in-plane optical phonon mode (this mode is associated with the G-band Raman spectrum in graphene) brought into such a resonance. Our estimate of magnetic field required for the resonance is 30T.

Infrared conductance of graphene: universality versus interplane hopping

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In monolayer graphene, the transitions between the hole and the electron Dirac cones are expected to result in an energy independent optical conductance of $e^2/4\hbar$. However, in graphene multilayers the c-axis coupling ($\sim$ 0.3 eV) may break this 'universality' in the infrared range. To study this issue, we experimentally obtained optical conductivity of bilayer graphene flakes on top of SiO_2/Si and the one of bulk graphite (HOPG). In bilayer graphene, we observe a sharp peak due to the transition between the bands split by the interlayer coupling, which yields the precise value of the c-axis hopping $t_\perp = 0.38$ eV. The position and the shape of the peak are highly sensitive to the gate voltage that reflects a strong modification of the low-energy bands of graphene in a field effect transistor (GraFET). Surprisingly, in bulk graphite, the infrared conductance is very close to the universal value of $e^2/4\hbar$ and it shows only a weak energy variation [1]. Our calculations show that this can be explained by the c-axis band dispersion within the Slonczewski-Weiss-McClure model using almost the same value of $t_\perp$.

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Spectral properties of gated graphene

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The single-particle spectral function captures the influence of Coulomb and phonon-mediated interactions on the energy band properties of crystals. In this talk we present the results of a recent theoretical study [1] of the influence of electron-electron interactions on the one-particle Green's function of a doped graphene sheet based on the random-phase-approximation and on graphene's massless Dirac equation continuum model. We find that states near the Dirac point interact strongly with plasmons with a characteristic frequency that scales with the sheet's Fermi energy and depends on its interaction coupling constant, partially explaining prominent features of recent angle-resolved photoemission spectroscopy data [2-4].

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"Spin-orbit modulated transport in graphene and carbon nanotubes"

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In this talk, the effect of spin-orbit coupling on the spin transport in graphene and carbon nanotubes will be discussed. In the first part we will show that local curvature of the graphene sheet induces an extra spin-orbit "Rashba-like" coupling term[1]. We estimate that such curvature spin-orbit coupling is the dominant one for the values of doping and curvature reported in actual samples of graphene and carbon nanotubes[2].

In the second part, we will discuss the effect of the curvature spin-orbit coupling on both the quasiparticles' zitterbewegung and as a mechanism of spin relaxation due to its interplay with the different scattering mechanisms present in samples of graphene and carbon nanotubes.

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Theory of the valley-valve effect in graphene nanoribbons

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A potential step in a graphene nanoribbon with zigzag edges is shown to be an intrinsic source of intervalley scattering — no matter how smooth the step is on the scale of the lattice constant a. The valleys are coupled by a pair of localized states at the opposite edges, which act as an attractor/repellor for edge states propagating in valley K/K'. The relative displacement Δ along the ribbon of the localized states determines the conductance G. Our result $G = (e^2/h)[1-\cos(N\pi + 2\pi\Delta/3a)]$ explains why the "valley-valve" effect (the blocking of the current by a p-n junction) depends on the parity of the number N of carbon atoms across the ribbon.

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Entangled spin-valley texture states in graphene in the quantum Hall regime

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Abstract

Graphene reveals, due to its fourfold spin-valley degeneracy, an intrinsic SU(4) symmetry. This symmetry may be partially broken by intervalley scattering processes or else external fields that couple to the spin degree of freedom. In a strong magnetic field, when the electrons are restricted to a single partially field Landau level, it has been shown that processes that lift the valley degeneracy are supressed by the small parameter a/l_B when compared to the leading interaction energy $e^2/\epsilon l_B$. Here, $a = 0.14$ nm is the distance between neighbouring carbon atoms, and $l_B = 26/\sqrt{B[\mathrm{T}]}$ nm is the magnetic length [1,2]. Because also the Zeeman effect is small with respect to the leading interaction energy scale, one may expect SU(4)-related physics to be relevant in graphene, when the electrons are organised in a spin-valley ferromagnetic state at Landau-level filling factors such as $\nu = \pm 1$.

We develop a theory which treats the spin and valley-isospin on a manifestly equal footing, which may also be of help in visualising the relevant spin textures [3]. In particular, the spin-isospin entanglement survives in a wide temperature range even in the presence of symmetry-breaking anisotropies, such as the Zeeman effect. In order to characterise the spin-isospin entanglement, we introduce an entanglement operator which generates families of degenerate skyrmions with different degree of entanglement, which are the natural charged excitations of the ferromagnetic ground state. We finally comment on the possibility of detecting entangled skyrmions in magnetisation measurements.

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prefer Oral talk

Th5

Bulk-edge correspondence in graphene with and without magnetic field: Topological aspects of Dirac fermions in real materials

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Graphene as the condensed matter realization of massless Dirac fermions is one of the most active research elds in condensed matter physics. The graphene is fundamental and idealistic as a two dimensional zero gap semiconductor which can be understood as a typical quantum liquid with and even without magnetic eld. The quantum liquid, I mean here, is characterized by the absence of classical local order parameter which is realized in low dimensional quantum system where strong quantum e ects and low dimensionality prevent from developing order formation accompanied by symmetry breaking.

Its characteristic feature is its quantum e ects themselves. A bulk-edge correspondence is a typical such e ect, that is, the bulk is featureless but governs the characteristic e ects with topological (geometrical) perturbation as the existence of boundaries and impurities[1]. One of such examples is an appearance of edge states in the quantum Hall e ects[2] and zero bias conductance peaks in anisotropic superconductors[3]. The ground state of the graphene is also characterized by this bulk-edge correspondence with[4,5] and without[3] magnetic eld. This bulk-edge correspondence gives a topological description for the zero mode edge states originally found at the zigzag edge of graphene without magnetic eld[6].

We point out here that there are two types of edge states for graphene under a magnetic eld. One is a class of usual edge states between the (Dirac fermions') Landau levels and the other is a class of special edge states within the $E = 0$ Landau level[5]. The latter gives a signi cant contribution for the localized charge density at the $E = 0$ Landau level which can be experimentally observed by the STM image with energetic resolution. This boundary charge is characterized by the magnetic length scale as expected. However only the $E = 0$ edge states are not enough to explain this behavior where the bulk also supplies signi cant contribution as topological compensation [5].

Also e ects of randomness, interaction[7] and multiband structure will be discussed from topological point of view.

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Klein Backscattering and Fabry-Perot Interference in Graphene Heterojunctions

We present a theory of quantum-coherent transport through a lateral p-n-p structure in graphene, which fully accounts for the interference of forward and backward scattering on the p-n interfaces [A. V. Shytov, M. S. Rudner, L. S. Levitov, arXiv:0808.0488]. The backreflection amplitude changes sign at zero incidence angle because of the Klein phenomenon, adding a phase pi to the interference fringes. The contributions of the two p-n interfaces to the phase of the interference cancel with each other at zero magnetic field, but become imbalanced at a finite field. The resulting half-period shift in the Fabry-Perot fringe pattern, induced by a relatively weak magnetic field, can provide a clear signature of Klein scattering in graphene. This effect is shown to be robust in the presence of spatially inhomogeneous potential of moderate strength. We shall conclude by discussing relation with recent experiment that reported Fabry-Perot inteference in a p-n-p structure at zero magnetic field and a crossover to Shubnikov-deHaas oscillations at high field [A. F. Young, P. Kim, arXiv:0808.0855].

Shot noise in graphene

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Recent measurements [1,2] of the low-temperature electrical noise in graphene have found a shot noise power which is three times smaller than the value expected for a Poisson process of independent current pulses. Two theoretical explanations are discussed, the first [3] in terms of the shot noise of evanescent modes, the second in terms of the shot noise of fractal diffusion [4].

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Shot noise in ballistic and disordered graphene

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We have studied shot noise in graphene strips (width/length = W/L = 1.8 – 24; L = 0.2 – 1 micron) at microwave frequencies over the temperature range T = 4.2 - 30 K. We find that the Fano factor ($F = S_I/2e\langle I\rangle$) is independent of temperature but varies as a function of the carrier density and as a function of the width to length ratio [1].

At the Dirac point, the measured Fano factor F = 0.338 is close to the universal value of 1/3 that is theoretically predicted for ideal graphene samples with $W/L > 3$ [2,3]. At large gate voltages, we find small noise (F = 0.02) which indicates that the transport is ballistic in our short samples. Contrary to the predictions by theory [2], no oscillations in the Fano factor were found as a function of the gate voltage. For samples with W/L = 1.8 and 2, we find F = 0.1 and 0.19, respectively, at the Dirac point.

In samples with L = 0.5 – 1 micron, no universal behavior of F has been found yet in our work at 4.2 K. Measured conductivities in this case are much larger than the universal value of $4e^2/\pi h$, and it appears that disorder plays a role in these measurements.

We will briefly review the main experimental results and discuss the nature of the transport in graphene, as well as how disorder affects the Fano factor and the conductivity when the dimensions and the aspect ratio of graphene strips is varied.

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Abstract for Graphene Week 2008

Transport properties in disordered single-layer graphene sheets and nanoribbons

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Using the recursive Green's function method, we study the problem of electron transport in disordered single-layer graphene sheet [1] and nanoribbons[2]. For graphene sheets, the conductivity is of order e^2/h and its dependence on the carrier density has a scaling form that is controlled solely by the disorder strength and the ratio between the sample size and the correlation length of the disorder potential. The shot noise Fano factor is shown to be nearly density independent for sufficiently strong disorder, with a narrow structure appearing at the neutrality point only for weakly disordered samples. Our results are in good agreement with experiments and provide a way for extracting microscopic information about the magnitude of extrinsic disorder in graphene. We also study the effects of edge and bulk disorder on the conductance of graphene nanoribbons. We compute the conductance suppression due to localization induced by edge scattering. We find that even for weak edge roughness, conductance steps are suppressed and transport gaps appear. These gaps are approximately inversely proportional to the nanoribbon width. On/off conductance ratios grow exponentially with the nanoribbon length. Our results impose severe limitations to the use of graphene in ballistic nanowires.

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Quantum Transport in Graphene Structures

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We perform a comparative study of weak localisation (WL) in bilayer [1] and monolayer graphene [2]. Although the two systems are different in their energy spectrum (massive fermions in bilayer and massless in monolayer), they have a common feature: the chirality of charge carriers. This makes WL in both systems very different from that in conventional 2D structures. Notably, it becomes controlled not only by inelastic scattering but also by a number of *elastic* scattering mechanisms. By changing the geometry and quality of samples (obtained by mechanical exfoliation [3]) we demonstrate that WL in graphene can take a variety of forms described by theory [4]. We show that WL does exist at different carrier densities, including the electro-neutrality region, and determine the temperature dependence of the de-phasing time as well as the dependence of elastic times on the density of charge carriers.

The studies of WL are complemented by the analysis of conductance fluctuations in both systems. They have the same physical origin as WL – quantum interference – and are controlled by the same scattering mechanisms, both inelastic and elastic. Using information obtained from WL, we show that the amplitude of the fluctuations depends on *elastic* scattering, in particular the *inter-valley* scattering rate.

Using 'air-bridge' top gates, we have realised high-mobility *p-n-p* graphene structures [5]. Calculating the band-structure profile of the samples allows us to determine unequivocally the expected resistance of ballistic graphene *p-n* junctions [6] and show that in high-mobility structures ballistic p-n junctions have selective transmission for chiral carriers.

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Scanning tunneling spectroscopy and transport measurements in graphene.

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I will describe low temperature high magnetic field scanning tunneling spectroscopy and transport experiments that give access to the Dirac fermion quasiparticles in graphene. Our scanning tunneling spectroscopy experiments reveal the energy dependent density of states, dispersion relation and the Fermi velocity. In the presence of a magnetic field, we observe the Landau levels, a gap at the Dirac point and evidence for interactions including electron-phonon and electron-electron interactions. Our low temperature transport studies on suspended graphene reveal nearly ballistic transport with a minimum conductivity that increases roughly linearly with increasing temperature.

Theory of induced superconductivity in graphene

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We propose a way of making graphene superconductive by putting on it small superconductive islands which cover tiny fraction of graphene area. Cooper pairs which penetrate from the islands induce superconducting correlations in graphene rendering the system macroscopically superconductive at low temperatures and magnetic fields. We show that the critical temperature, T_c, can reach several Kelvins at experimentally accessible range of parameters. Contrary to conventional BCS superconductors, the zero-temperature energy gap in proximity-induced superconducting graphene, E_g, is smaller than T_c, leading to a number of unusual phenomena. At the smallest temperatures, $T < E_g$, the system behaves like a nearly uniform superconductor with some effective coupling constant, while at higher temperatures, $E_g < T < T_c$, the system can be described in terms of proximity-coupled islands. Finite magnetic field which destroys the spectral gap E_g does not drive graphene in the normal state. Instead, it produce a kind of a superconductive glass with higly frustrated Josephson couplings between the islands.

Andreev-Klein reflection in graphene ferromagnet-superconductor contacts

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In this talk we demonstrate the unusual features of Andreev reflection in a ferromagnet(F)-superconductor(S) junction which is realized in a grapheme sheet [1]. We show that for a weakly doped F graphene with an exchange field h larger than its Fermi energy E_F, the superconducting electron-hole conversion of massless Dirac fermions at FS junction is associated with a spin Klein tunnelling through an exchange field p-n barrier between two spin-split conduction and valance subbands. This Andreev-Klein process results in an enhancement of the subgap conductance of FS junction by h up to the point at which the conductance at low voltages is greater its value for the corresponding non-ferromagnetic junction. This effect is in striking contrast to the common view that the ferromagnetic ordering and the spin-singlet superconducting correlations are exclusive phenomena. We further present a map of angle of Andreev reflection showing that depending on the value of h/E_F, the spin and energy states of the incident electron the reflection can be retro or specular types in both convergent and divergent ways with the reflection direction aligned, respectively, closer to and farther from the normal to the junction as compared to the incident direction.

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Superconductivity in the Intercalated Graphite Compounds C_6Yb and C_6Ca

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Low dimensionality is generally considered as a necessary ingredient for high superconducting transition temperatures. Surprisingly, perhaps, systems based on graphite have received little attention in this context. Introducing metal atoms between the carbon layers can tune the interlayer spacing and charging of the graphite host through a variety of electronic ground states. One such ground state is superconductivity, which is not present in pure graphite. Our discovery of superconductivity in the intercalation compounds C_6Yb and $C6_6Ca$, with transition temperatures of 6.5 and 11.5 K, respectively has reissued the debate on such systems. These critical temperatures are unprecedented in graphitic systems and have not been explained by simple mechanisms for the superconductivity. This discovery has already stimulated several proposals ranging from exotic superconducting mechanisms to new structural phases. We will present an overview with particular emphasis on recent results from high-pressure experiments.

Electronic properties of graphene multilayers

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The optical and magnetic properties of AB-stacked multilayer graphenes are theoretically studied within the effective mass approximation. We show that the Hamiltonian of multilayer graphene with any numbers of layers, can be decomposed into sub-systems effectively identical to monolayer or bilayer graphene. We use this to systematically study the orbital diamagnetism and the optical absorption of multilayer graphenes.

Since the recent experimental realization of atomically thin graphene films,[1–3] the graphene multilayers have attracted broad interest as well as monolayer.[2,4,5] It is known that the interlayer coupling drastically changes the relativistic dispersion of monolayer graphene, leading to various band structures depending on the number of layers.[6–10]

Here we show that the effective mass Hamiltonian of multilayer graphene can always be decoupled into sub-Hamiltonians equivalent to monolayer or bilayer, and thus physical quantities can be calculated by summing up contributions of every sub-systems. When the number of layers N is odd, the system has one effective monolayer and $(N-1)/2$ bilayers, while when N is even, it has just $N/2$ bilayers. The effective bilayer-type subsystems differ from the real bilayer graphene in that the inter-layer coupling strength is modified.

We calculate the diamagnetic susceptibility as a function of N. We find that the monolayer-type subband, appearing only in odd-N graphenes, contributes to a large diamagnetism at zero Fermi energy as in the real monolayer graphene.[11] The effective bilayer subband basically gives less singular, logarithmic tail in the susceptibility, while the trigonal warping structure gives rise to a magnetic singularity at zero energy. We also study the optical absorption of multilayer graphenes in magnetic field B. Every absorption peaks are labeled by the subband (monolayer/bilayer) index and the Landau level index. The monolayer-type subband always exhibit absorption peaks which shifts in proportion to $\sqrt{B}$, while the bilayer-type subbands gives a set of peaks which exhibits a crossover from linear in B to $\sqrt{B}$. We propose a possibility of observing the monolayer-like spectrum even in a mixture of multilayer graphene films with various layer numbers.

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Landau level spectroscopy of multi-layer epitaxial graphene in the immediate vicinity of the Dirac point

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Multi-layer graphene on a SiC substrate [1] is studied in far infrared transmission experiment [2] in two different limits, in low magnetic fields and at high temperatures. To probe the nearest vicinity of the Dirac point, we focus on the optical response of the almost neutral graphene layers not affected by the SiC surface, having a density as low as 5×10^9 cm^{-2} per single sheet. At low temperatures, the cyclotron-resonance-like absorption line is present in spectra down to magnetic fields of 40 mT, showing no deviation from the expected $\sqrt{B}$-scaling of its energy. The observation of a clear Landau level quantization at such low magnetic fields gives the lower bound for the mobility in the investigated graphene layers 250 000 cm^2/(V.s). An estimate of the graphene conductivity in the limit of vanishing magnetic field gives the value of $10e^2/h$. In the limit of high temperatures, well-defined Landau level quantization is observed up to room temperature at magnetic fields below 1 T, phenomenon never observed in any other solid state system. A negligible increase in the width of the cyclotron resonance indicates that no important scattering mechanism is thermally activated, supporting recent expectations of extremely high room-temperature mobility in graphene.

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Theory of Quantum Transport in Graphene and Naotube

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The graphene consisting of a monolayer graphite sheet was fabricated [1], and the conductivity modulation by the gate was demonstrated and the quantum Hall effect was observed [2,3]. Since then, various experimental and theoretical investigations have been performed to reveal its exotic electronic and transport properties. Actually, graphene has been a subject of theoretical study prior to the experimental realization because of the peculiar electronic structure also responsible for intriguing properties of carbon nanotubes [4,5]. The purpose of this paper is to give a brief review on characteristic features of electronic states in graphene and nanotube mainly from a theoretical point of view, together with topics on roles of electron-phonon interactions studied recently [6,7].

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Electronic properties of corrugated graphene

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Elastic strains and lattice defects in graphene lead to perturbations in the electronic structure similar to those induced by a gauge field. In a graphene sheet with random corrugations, the effects of the strain field on the electrons is characterized by the parameter b h^2/(l a) , where b = d log (t) / d log (a) sim 2-3, h is the average height fluctuation, a is the lattice constant, and l the extension of the ripple. When this parameter is of order unity, the low energy spectrum is strongly modified. Long wavelenght lattice strains also exist in suspended graphene samples, due to slack, and to the electric field needed to induce carriers. Deformations in the height of 20-40nm in samples of 1micron of length can change significantly the transport properties.

Type of presentation: 20-minutes talk preferably.

Abstract: see below:

Band-gap engineering and quantum dots on graphene

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We experimentally demonstrate two methods of band gap engineering in graphene, which is normally a zero-gap semiconductor. Such bandgaps can be used in field-effect transistors, as well as in tunable electrostatically defined structures such as quantum point contacts and quantum dots, with possible applications as spin qubits.

First, in bilayer graphene, a finite band gap can be induced by an out-of-plane electric field. In our experiments, the electric field was provided by two external gates. We observe insulating behavior of the conductance in the bilayer device at nonzero electric field. At low temperature (50mK), the conductance is suppressed by several orders of magnitude at the highest electric fields used. In contrast, similar measurements on devices with monolayer graphene show a conductance that is independent of the electric field, and hardly changes with temperature, pointing at the absence of a gap, as expected. [1]

In a second method, we use graphene nano-ribbon devices. Here a nano ribbon is a quasi one-dimensional system etched into the 2D graphene sheet, where the confinement is expected to open a band gap that is inversely proportional to the ribbon width for monolayer graphene. In graphene nano-ribbon devices, we also see that the conductance is suppressed by several orders of magnitude at low temperature, and the conductance is much lower than that of the insulating bilayer devices. We observe Coulomb oscillations as a function of local gates in the nano-ribbon devices, and the coulomb peak spacings correlate with the designed device area. [2] Finally, we observe that disorder plays a significant role in the low-temperature transport, both for nano-ribbons and bilayer devices. Future studies will investigate the single particle energy level spectra and spin states.

Reference,

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Uniaxial strain on graphene: bandgap opening

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Graphene consists of one layer of carbon atoms arranged in a honeycomb lattice, it has attracted intensive interest since experimentally discovered in 2004. Due to its special properties such as the massless relativistic Dirac fermions, the quantum Hall effect, and the ballistic transport even at room temperature, graphene provides a promising future for fundamental studies and practical applications.

In order to make graphene a real technology, a special issue must be solved: creating an energy gap at K and K′ points in the Brillouin zone. Different attempts have been made by researchers, such as patterning graphene into nanoribbon, forming graphene quantum dots, making use of multilayer graphene sheets, and applying an external electrical field. Here, we propose an practical way to open the bandgap on graphene: application of uniaxial strain.

Our first principle calculation predicted a bandgap opening of ~300 meV for 1% uniaxial tensile strained single layer graphene, mainly due to the breaking of sublattice symmetry under uniaxial strain. Experimentally, we have also deposited monolayer graphene on a transparent and flexible substrate and uniaxial tensile strain up to ~1.5% was loaded by stretching the substrate in one direction. The Raman spectroscopy results clearly indicate that uniaxial strain has been successfully applied on graphene. Significant red shifts of Raman 2D band (-27.8 cm^{-1}/%strain) and G band (-14.2 cm^{-1}/%strain) were observed for single layer graphene under strain. This can be understood as due to the elongation of the carbon-carbon bonds, which weakens the bonds and therefore lowers their vibrational frequency. Our results on strained graphene suggest that (1) band gap engineering is possible by applying uniaxial strain on single layer graphene. (2) graphene on flexible substrate is ready for strain process and other applications. (3) Raman spectroscopy can be used an ultra-sensitive way to determine the strain in graphene.

Opening a Gap in Graphene

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The exceptional electronic properties of graphene with its charge carries mimicking relativistic quantum particles and its formidable potential in various applications have ensured a rapid growth of interest in this new material. I will discuss transport characteristics of quantum dot and quantum point contact devices etched entirely in graphene. At large sizes (>100nm), the quantum dots behave as conventional single-electron transistors, exhibiting periodic Coulomb blockade peaks. For quantum dots smaller than 100 nm, the peaks become strongly non-periodic indicating a major contribution of quantum confinement. Random peak spacing and its statistics are well described by the theory of chaotic neutrino billiards. Furthermore, short constrictions of only a few nm in width remain conductive and reveal a confinement gap of up to 0.5eV, demonstrating the possibility of molecular-scale electronics based on graphene.