Electronic Devices from Nano-patterned Epitaxial Graphite

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The exceptional electronic transport properties of low-dimensional graphitic structures have been amply demonstrated in carbon nanotubes and nanotube-based transistors. Ballistic transport has been observed up to room temperature, and quantum interference effects at cryogenic temperatures.Simple nanotube transistors, and interconnected logic gates have been demonstrated, which rely on the ability to control the nanotube conductance via an electrostatic gate. The basic transport parameters of these devices are so compelling that nanotubes are considered to be a candidate material system to eventually supplant silicon in many electronic devices.

An under-appreciated fact is that most electronic properties of carbon nanotubes are shared by other low-dimensional graphitic structures. For example, planar nanoscopic graphene ribbons (i.e., ribbons of a single sheet of graphite) have been studied theoretically, and they exhibit properties that are similar to nanotubes. Graphene ribbons with either metallic or semiconducting electronic structure are possible, depending on the crystallographic direction of the ribbon axis. Thus, if suitable methods were developed to support and align graphene sheets, it would be possible to combine the advantages of nanotube-like electronic properties with high-resolution planar lithography to achieve large-scale integration of ballistic devices.

An essential difference between nanotubes and planar graphene ribbons is the presence of dangling bonds at the edges. Normally these would be hydrogen-terminated, with little influence on the valence electronic properties. However, edge atoms could be passivated with donor or acceptor molecules, thus tuning the electronic properties without affecting the graphitic backbone of the device.

We recently showed the two-dimensional nature of electrical transport in ultrathin graphite (multilayered graphene) grown epitaxially on SiC(0001) [1]. 6HSiC is a large band gap (3 eV) semiconductor, which provides an insulating substrate at temperatures below 50 K for the n-type (nitrogen) doping employed here. We use magnetoconductance measurements and the physics of weak localization to determine transport parameters of the graphite 2D electron gas (2DEG), and we show that the character of the magnetotransport/ localization spans a wide range of behaviors, depending on the amount of disorder in the film or substrate. Quantum oscillations in the magnetoconductance and in the Hall resistance are found for the most ordered samples. The character of these features suggests that the quantum Hall effect could be observed at lower temperatures, higher fields, or in ultrathin graphite films of only slightly higher mobility. To our knowledge, these are the first transport measurements on oriented and patterned graphite films of only a few monolayers thickness (hence "graphene" films. Given the large mean free paths measured in high-quality graphites, the unusual electronic dispersion of graphene, and the fact that the carriers lie near an air-exposed surface, this unique 2DEG system holds great scientific potential. Furthermore, with sufficiently high-quality material, ballistic and coherent devices analogous to nanotube designs would be would be possible. This goal requires that the epitaxial graphene can survive the processing necessary for creation of submicron ribbons, and that the 2DEG can be gated electrostatically. We succeeded to demonstrate these critical elements for the realization of electronic devices based on nanopatterned epitaxial graphene (NPEG).

Our current efforts focus improving the quality of the graphene and to investigate the properties of patterned structures. We are specifically interested to produce high mobility material and to demonstrate quantum confinement effects of patterned graphene structures .at low temperatures.

This work has been highly successful. Over the course of a year:

- We have increased the mobility by more than an order of magnitude (from 400 to 10,000 cm^2/Vs).
- X-ray diffraction measurements show that the structural coherence of the graphene exceeds 3 μm.
- From the Shubnikov de Haas oscillations in patterned graphene ribbons we have found phase coherence lengths exceeding 1 μm and that the effective mass is 0.02 m (see Figure)$_e$.
- We have demonstrated quantum confinement effects which are evident from the systematic departure from the inverse field dependence of the positions of the Shubnikov de Haas oscillations: a phenomenon which is well understood in confined 2D electron gas systems.
- A variety of mesoscopic transport phenomena are observed including weak localization and universal conductance fluctuations, which provide further important clues concerning transport in these systems (as they do in 2D electron gases in general). Some peculiar systematic patterns observed in the magneto transport measurements suggest fractal like behavior, which in fact has been predicted for this system.
- Finally, an unusual first order magnetically electronic phase transition is observed at about T=2 K. The transition manifests as an abrupt change in the magnetoresistive properties of the samples accompanied with a slight change in carrier density.

The project has greatly benefited from several ongoing, active external collaborations. These include:

- Didier Mayot and Cecile Naud of LEPES, the CNRS low temperature facility at Grenoble France, where much of the transport measurements are currently made
- Alessandra Lanzara: UC Berkeley, Angular resolved photoemission (ARPES) who demonstrated that the Dirac particle behavior of the electron carriers in our samples.
- Intel Research; who supplies some funding and with whom we have monthly meetings, to discuss progress and future directions.
- Argonne National Labs, where under the supervision of Edward Conrad, the X-ray diffraction measurements are made.

[1] **Ultrathin Epitaxial Graphite: 2D Electron Gas Properties and a Route toward Graphene-based Nanoelectronics** Berger, C.; Song, Z.; Li, T.; Li, X.; Ogbazghi, A. Y.; Feng, R.; Dai, Z.; Marchenkov, A. N.; Conrad, E. H.; First, P. N.; de Heer, W. A.; *J. Phys. Chem. B. ;* **2004**; *108*(52); 19912-19916.

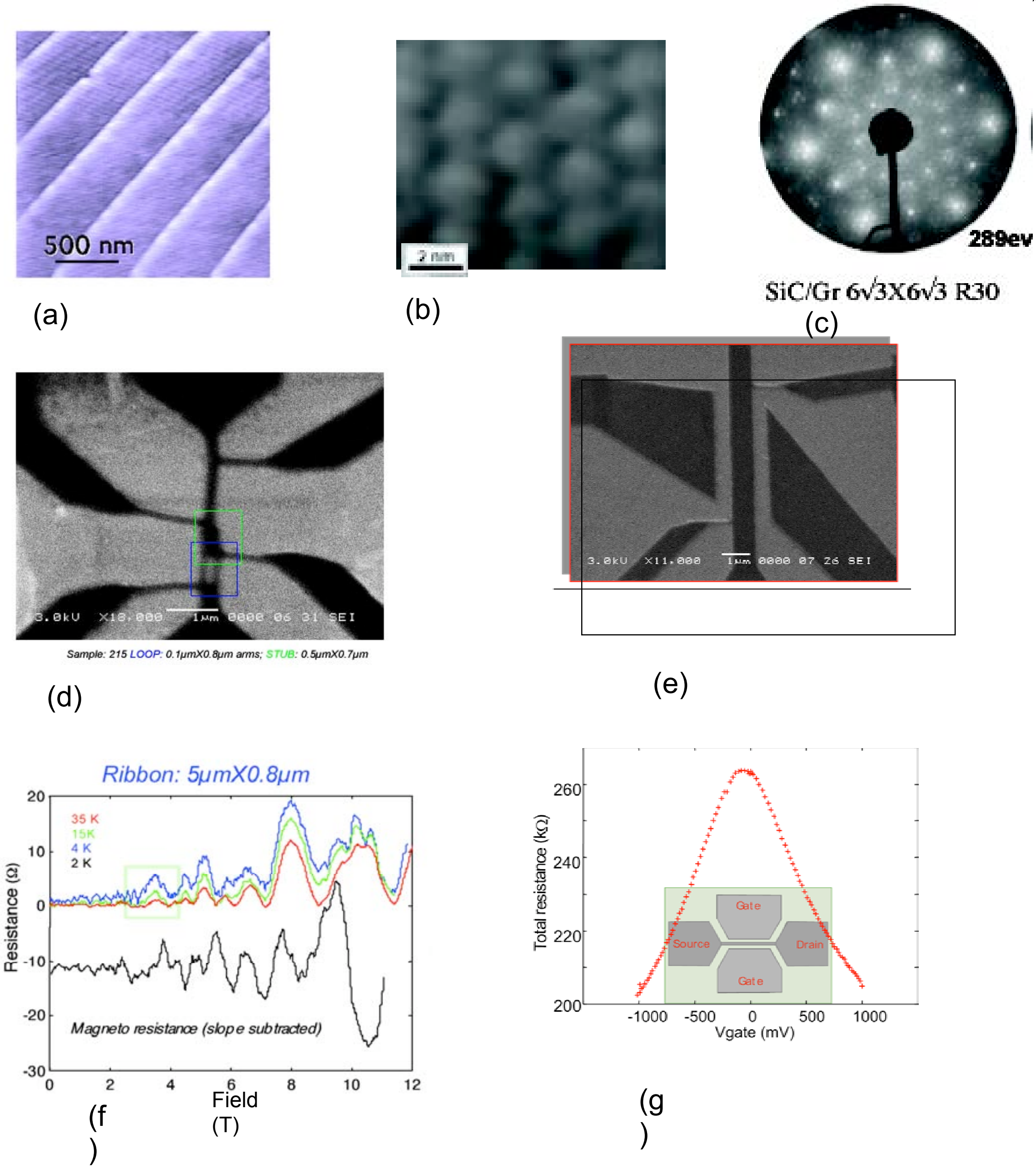

Figure 1. Nanopatterned epitaxial graphite (NPEG). (a) AFM of graphitized silicon carbide surface (thermal graphitization after H_2 etching.) The steps correspond to unit cell steps on the underlying SiC substrate. (b) STM of a graphite on SiC showing the corrugation due to the 6√3X 6√3 reconstruction. (c) LEED of a graphitized sample showing both the SiC spots superimposed on the graphite spots, clearly demonstrating the epitaxial growth (i.e. the two lattices are mutually registered.) (d) A complex NPEG sample (produced by e-beam lithography) consisting of a loop connected to a ribbon. Current contacts are at the top and bottom and there are four voltage leads on the sides. (e) Side gated FET geometry: the side gates are the two large structures flanking the ribbon, which functions as the channel.(f) Example of the low temperature magnetoresistance of a NPEG ribbon at four temperatures. Note the Shubnikov de Haas oscillations and the mesoscopic fine structure (i.e. reproducible mesoscopic fingerprint). The 2 K data are different reflecting the electronic phase transition. (g) The resistance versus gate voltage characteristics of the FET shown in (e).