Tuesday Morning, October 21, 2008

Graphene Topical Conference
Room: 306 - Session GR+EM+NC-TuM

Graphene and Carbon Electronics

Moderator: B.D. Schultz, International Technology Center

8:00am **GR+EM+NC-TuM1 Two Dimensional Plasmon Behavior in Graphene Sheets on SiC(0001)**, ***Y. Liu***, The Pennsylvania State University, *K.V. Emtsev, Th. Seyller*, University Erlangen-Nurnberg, Germany, *R.F. Willis*, The Pennsylvania State University

Using High Resolution Energy Loss Spectroscopy (HREELS), we compare experimental results for the wavevector-dependent behavior of plasmons in a graphene sheet on SiC(0001), with that due to a filled band of surface states on semiconducting silicon. There are significant diffences in behavior between the two systems, and the behavior predicted for a classical two-dimensional sheet of electrons. In particular, the damping increases with wavevector beyond the critical momentum for Landau damping by electron-hole pairs. This unusual behavior is compared with that due to the filling of two dimensional surface states on a metallized silicon surface. The graphene results are a consequence of the unusual collective behavior of Dirac fermions. The effect of adding additional graphene layers is discussed.

8:20am **GR+EM+NC-TuM2 Furnace Growth of High Quality Epitaxial Graphene on 4H-SiC(000-1)**, ***M. Sprinkle***, *F. Ming*, Georgia Institute of Technology, *D. Martinotti*, CEA Saclay, France, *P.G. Soukiassian*, Université de Paris-Sud/Orsay and CEA Saclay, France, *C. Berger, E.H. Conrad, W.A. de Heer*, Georgia Institute of Technology

Multi-layer graphene grown epitaxially on the C-terminated (000-1) surface of 4H-SiC in a high vacuum (~10^{-5} Torr), high temperature (~1420 °C) induction furnace environment has been shown to be of extremely high quality[1,2] and mobility.[3,4] Though multi-layered, the material exhibits electronic properties similar to those of isolated graphene.[1,3,4,5] Here, we characterize the material by atomic force microscopy (AFM), low energy electron microscopy (LEEM), and ellipsometry, and gain insight into growth mechanisms, highlighting growth on 4H-SiC(000-1) in comparison to 4H-SiC(0001), 6H-SiC(000-1), and 6H-SiC(0001). AFM and LEEM images demonstrate μm-scale graphene terraces. Ellipsometry and LEEM data show that graphene thickness is quite uniform over mm and μm scales.

[1] J. Hass et al., Phys. Rev. Lett. 100, 125504 (2008).
[2] J. Hass et al., J. Phys. Cond. Matt. 80, (in press)
[3] C. Berger et al., Science 3012, 1191 (2006).
[4] W. A. de Heer et al., Solid State Comm. 143, 92-100 (2007).
[5] M. Sadowski et al., Phys. Rev. Lett. 97, 266405 (2006).

8:40am **GR+EM+NC-TuM3 Toward Carbon Based Electronics**, ***K. Bolotin***, Columbia University **INVITED**

Carbon based graphitic nanomaterials such as carbon nanotubes and grpahene have been provided us opportunities to explore exotic transport effect in low-energy condensed matter systems and the potential of carbon based novel device applications. The unique electronic band structure of graphene lattice provides a linear dispersion relation where the Fermi velocity replaces the role of the speed of light in usual Dirac Fermion spectrum. In this presentation I will discuss experimental consequence of charged Dirac Fermion spectrum in two representative low dimensional graphitic carbon systems: 1-dimensional carbon nanotubes and 2-dimensional graphene. Combined with semiconductor device fabrication techniques and the development of new methods of nanoscaled material synthesis/manipulation enables us to investigate mesoscopic transport phenomena in these materials. The exotic quantum transport behavior discovered in these materials, such as ballistic charge transport and unusual half-integer quantum Hall effect both of which appear even at room temperature. In addition, I will discuss electronic transport measurements in patterned locally gated graphene nanoconstrictions with tunable transmission and bipolar heterojunctions. We observe various unusual transport phenomena, such as energy gap formation in confined graphene structures which promise novel electronic device applications based on graphitic carbon nanostructures.

9:20am **GR+EM+NC-TuM5 Spectro-Microscopy of Single and Multi-Layer Graphene Supported by a Weakly Interacting Substrate**, ***K.R. Knox***, *S. Wang*, Columbia University, *A. Morgante, D. Cvetko*, Laboratorio TASC-INFM, Italy, *A. Locatelli, T.O. Mentes, M.A. Niño*, Elettra - Sincrotrone Trieste S.C.p.A., Italy, *P. Kim, R.M. Osgood*, Columbia University

While graphene's distinctive Dirac-cone electronic structure and simple 2D atomic structure have attracted major interest in the physics community, inherent limitations in the size of available exfoliated graphene samples have made it difficult to study this system with conventional UHV probes such as photoemission and low energy electron diffraction (LEED). Thus, previous photoemission and LEED studies of graphene have probed films grown on SiC.[1,2,3] While graphene grown on SiC can form large area sheets, exfoliated graphene on SiO_2 continues to be the system of choice for transport experiments as it is relatively easy to gate and has shown the most interesting and impressive electrical properties.[4,5] Using the high spatial resolution of the Nanospectroscopy beamline at the Elettra synchrotron light source, we have overcome these size limitations by utilizing micro-spot low energy electron diffraction (μLEED) and micro-spot angle resolved photoemission (μARPES) to study exfoliated graphene. In this talk, we will discuss our measurements of the electronic structure and surface morphology of exfoliated graphene using low energy electron microscopy (LEEM), μLEED and μARPES. Our LEEM data can be used to unambiguously determine the film thickness of graphene sheets by means of a quantum size contrast effect; a well understood effect in which modulations in the electron reflectivity arise due to quantum well resonances above the vacuum level.[6] Our diffraction measurements provide information about the surface morphology of monolayer and multilayer graphene sheets, which are not atomically flat, but microscopically corrugated. This corrugation increases with decreasing film thickness, reaching a maximum for monolayer graphene. Our photoemission measurements probe the unique massless fermionic dispersion of monolayer graphene, to confirm that the electronic structure of the valence band is well described by the one-orbital tight binding model.

[1] T. Ohta et al., Science 313, 951 (2006).
[2] A. Bostwick et al., Nature Phys. 3, 36 (2007).
[3] S.Y. Zhou et al., Nature Phys. 2, 595 (2006).
[4] K.S. Novoselov et al., Science 306, 666 (2004).
[5] Y.B. Zhang et al., Nature 438, 201 (2005).
[6] M.S. Altman, et al. App. Surf. Sci. 169, 82 (2001).

9:40am **GR+EM+NC-TuM6 Intercalation and Ultrasonic Treatment of Graphite – a New Synthetic Route to Graphene**, ***E. Widenkvist***, Uppsala University, Sweden, *R.A. Quinlan*, The College of William and Mary, *S. Akhtar, S. Rubino*, Uppsala University, Sweden, *D.W. Boukhvalov, M.I. Katsnelson*, Radboud University of Nijmegen, the Netherlands, *B. Sanyal, O. Eriksson, K. Leifer, H. Grennberg, U. Jansson*, Uppsala University, Sweden

We will demonstrate that ultrasonic treatment of a graphite crystal in water can lead to the formation of small graphene-like flakes in solution. The delamination of the graphite can be increased dramatically by intercalation of bromine from a Br_2-saturated water solution. After ultrasonic treatment, large amounts of graphene-like flakes with varying thickness are observed in SEM and TEM. They can be adsorbed onto a surface of a suitable substrate by a simple dipping technique. The effect of polar and non-polar solvents as well as adsorption of the graphene on hydrophobic and hydrophilic substrates will be demonstrated and compared. DFT calculations of the intercalation process have been carried out using the SIESTA package and the effect of bromine intercalation on cohesive energy and electronic structure will be discussed and compared with experimental data. Finally, the general approach of using ultrasonic treatment and intercalation as a facile route to graphene synthesis compared to other methods will be discussed.

10:40am **GR+EM+NC-TuM9 Graphene: Exploring Carbon Flatland**, *E.W. Hill*, ***A.K. Geim***, University of Manchester, UK **INVITED**

Graphene is now a bright and still rapidly rising star on the horizon of materials science and condensed matter physics, revealing a cornucopia of new physics and potential applications. We will overview our experimental work on graphene concentrating on its exotic electronic properties and speculate about potential applications.

11:20am **GR+EM+NC-TuM11 The Mechanism of Graphene Growth on Metal Surfaces**, ***E. Loginova***, *N.C. Bartelt, K.F. McCarty, P.J. Feibelman*, Sandia National Laboratories

The structure and defects of graphene sheets have been characterized on many different surfaces, but the mechanisms of graphene growth largely remain unknown. Although simulations have been reported, how carbon atoms attach to the edge of a graphene sheet has not been experimentally determined, owing to limitations of the available experimental techniques. We have used low-energy electron microscopy (LEEM) to study the epitaxial growth of graphene on a representative metal, Ru(0001). The unique capabilities of LEEM allow us to measure simultaneously the growth rate of individual graphene islands and of the local, absolute concentration of vapor-deposited, mobile carbon adatoms. Combining this information, we have learned what controls the nucleation and growth rate of graphene on Ru(0001), and what species transport carbon over the metal surface. Graphene growth differs strikingly from the well-studied case of metal epitaxy: 1) the growth rate is limited by C-atom attachment, not by C-atom diffusion, and 2) the absolute value of the supersaturation required for appreciable growth rates is comparable to that required to nucleate new islands. Thus, a large barrier must exist for monomers to attach to the graphene step edge. We have also discovered that the growth rate as a function of supersaturation is highly nonlinear. Such behavior can be explained if carbon clusters must form, as precursors to carbon attachment. As experiment and theory reveal, this could arise from strong bonding of individual monomers to the metal substrate. We will discuss a model that explains all these observations, and thus provides insight into the molecular processes by which graphene grows. Lastly, we will show that our understanding and ability to monitor the carbon supersaturation allow the shape and position of the growing graphene sheets to be controlled. This research is supported by the Office of Basic Energy Sciences, Division of Materials Sciences, U. S. Department of Energy under Contract No. DE-AC04-94AL85000.

11:40am **GR+EM+NC-TuM12 Conformal Dielectric Layers Deposited by ALD (Atomic Layer Deposition) for Graphene-based Nanoelectronics**, ***B. Lee***, *S.Y. Park, H.Y. Kim, K.J. Cho, E.M. Vogel, M.J. Kim, R.M. Wallace, J. Kim*, The University of Texas at Dallas

To make use of top-gated graphene devices, uniform and thin dielectrics on top of graphene is required. However, the chemically inert nature of graphene basal planes inhibits deposition of high quality and atomically uniform gate dielectric films. Here, we present characteristics of dielectrics employed by atomic layer deposition on top of a highly oriented pyrolytic graphite (HOPG) surface for localized gate applications. It was found that TMA/H_2O process shows selective deposition of Al_2O_3 only along with step edges which have high chemical reactivity. Therefore, it is critical to provide uniform and dense nucleation sites on the basal plane in order to achieve conformal deposition of dielectric. In this presentation, we will demonstrate a facile route providing atomically smooth and uniform Al_2O_3 layers on top of a HOPG by atomic layer deposition (ALD). The physical properties of the deposited Al_2O_3 layer will be also studied using various characterization techniques including HR-TEM, XPS, and AFM. Acknowledgements: We acknowledge financial supports by KETI through the international collaboration program of COSAR (funded by MKE in Korea) and the SWAN program funded by the GRC-NRI.

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