

Tuesday Afternoon, November 10, 2009

Graphene Topical Conference
Room: C3 - Session GR+TF-TuA

Graphene: Characterization, Properties, and Applications

Moderator: M. Fuhrer, University of Maryland, College Park

2:00pm **GR+TF-TuA1 Graphene Atomic Membranes, P.L. McEuen, Cornell University** **INVITED**

Atomically thin graphene membranes have exceptional electronic, optical, thermal and mechanical properties. Here we discuss our group's measurements on graphene membranes made by either exfoliation, epitaxial growth on SiC, or chemical vapor deposition growth on Ni or Cu. For example, we demonstrate that a monolayer graphene barrier is impermeable to standard gases, including helium. By applying a pressure difference across the membrane, we measure both the elastic constants and the mass. We also discuss mechanical resonators made from graphene, as well as the photocurrent response of graphene optoelectronic devices. We find the photoresponse at a graphene interface junction is photo-thermoelectric, i.e. the laser locally heats the graphene, giving rise to a thermoelectric response. This is in contrast to previous interpretations based on photovoltaic charge carrier separation at local potential variations in the sample. The photo-thermoelectric model accurately describes the temperature and laser power dependence, and also provides a simple way to probe the thermal conductivity of graphene membranes. Work done in collaboration with Scott Bunch, Arend van der Zande, Scott Verbridge, Xiaodong Xu, Nathaniel Gabor, Shriram Shivaraman, Xun Yu, Robert Barton, Jonathan Alden, Lihong Herman, MVS Chandrashekhar, Jiwoong Park, Jeevak Parpia, Harold G. Craighead, and Michael G. Spencer

2:40pm **GR+TF-TuA3 Impact of Argon on the Growth of Epitaxial Graphene, J.L. Tedesco, R.L. Myers-Ward, G.G. Jernigan, U.S. Naval Research Laboratory, J.A. Robinson, The Pennsylvania State University, J.C. Culbertson, P.M. Campbell, J.K. Hite, C.R. Eddy, Jr., D.K. Gaskill, U.S. Naval Research Laboratory**

Epitaxial graphene (EG) grown *in vacuo* on semi-insulating, on-axis 4H- and 6H-SiC substrates has demonstrated morphological problems [1], such as pitting in C-face substrates during *in vacuo* growth. In order to reduce the nonuniformities present in the EG, films were grown in an Ar ambient and compared to *in vacuo* films using substrates sourced from the same wafers. The growths took place in a commercial Aixtron VP508 hot-wall epitaxial SiC growth reactor. The Ar growths were performed using temperatures ranging from 1,500°C to 1,600°C and pressures ranging from 50 to 200 mbar. The *in vacuo* growths took place for temperatures ranging from 1,225°C to 1,700°C and pressures ranging from 10^{-3} to 10^{-6} mbar. The resulting films were characterized with Nomarski and atomic force microscopies, Raman and x-ray spectroscopies, and Hall effect measurements.

Si-face EG films did not form under Ar at temperatures $\leq 1,500^\circ\text{C}$, yet *in vacuo* films formed for temperatures above $\sim 1,400^\circ\text{C}$. At temperatures $> 1,500^\circ\text{C}$ under Ar, graphene was successfully grown and, while the morphology was not significantly different from *in vacuo* films, Raman spectroscopy measurements indicated that EG films with improved thickness and strain uniformity were realized. At an Ar growth pressure of 50 mbar, resulting Si-face EG was mostly bilayer graphene, while at 200 mbar, the resulting EG films were predominantly monolayer graphene. X-ray photoelectron spectroscopy measurements indicated that argon-grown EG was thinner than *in vacuo* EG grown at the same temperature.

The morphology of argon-grown C-face films was markedly different from *in vacuo* films. Under Ar, graphene did not grow below $1,500^\circ\text{C}$, while *in vacuo* films began to grow at $1,225^\circ\text{C}$. For growths at temperatures $> 1,500^\circ\text{C}$, the density of substrate pits was reduced significantly and was eliminated in half of the argon-grown films. Furthermore, at temperatures between $1,500^\circ\text{C}$ and $1,600^\circ\text{C}$, ambient-controlled films were incomplete, and the percentage of the substrate covered by graphene increased with growth temperature.

Growth under Ar improved the electrical properties for films on both faces. Mobilities increased by up to 4 times relative to *in vacuo* films, while carrier densities decreased by ~ 10 times. For both *in vacuo* and argon-grown EG, the carrier densities of Si-face EG were at least an order of magnitude less than those of C-face EG films. Furthermore, Hall effect measurements showed that, while *in vacuo* EG films on both faces were

divided between n-type and p-type, argon-grown Si-face EG was generally n-type while argon-grown C-face EG was generally p-type.

[1] B.L. VanMil, *et al.*, Mater. Sci. Forum **615-617**, 211 (2009).

3:00pm **GR+TF-TuA4 Mapping the Electronic Surface Potential of Graphene Grown on Ir(111) and Ru(0001), S. Barja, B. Borca, Universidad Autónoma de Madrid, Madrid, Spain, M. Garnica, IMDEA Nanociencia, Spain, F. Hermanns, J.J. Hinarejos, Universidad Autónoma de Madrid, Madrid, Spain, A.L. Vazquez de Parga, R. Miranda, UAM & IMDEA Nanociencia, Spain**

Moiré patterns are generated by the superposition of two periodic structures with a lattice mismatch. They have been observed by means of Scanning Tunneling Microscopy (STM) on different systems and their interpretation, in some cases, is not straightforward. The influence, at the atomic scale, of these patterns in the local density of states of the overlayer is not clear and can be studied by STM.

The growth of graphene on metallic substrates allow us not only control the periodicity of the Moiré pattern but also tailor the interaction strength between the carbon atoms and the metallic substrate [1]. In this work we compare the results obtained on graphene overlayers grown on two different metallic substrates. We studied graphene/Ir(111) and graphene/Ru(0001) in the former there is a weak interaction between the graphene overlayer and the substrate and in the later the strength of the chemical interaction is modulated by the Moiré pattern.

Field Emission Resonances (FERs), which are detected by STM when applying voltages larger than the work function, can be used to explore with nanometer resolution, the inhomogeneities in the local surface potential landscape. Operating the STM in constant current mode implies a constant electric field between tip and sample and the expected energy position for the FERs is given by the expression founded by Gundlach some time ago [2]. From that expression it is possible to determine experimentally the local work function of the surface. We applied this method to the Moiré pattern formed by graphene grown on Ir(111) and Ru(0001). For graphene on Ir(111) we did not find any modulation in the work function due to the Moiré pattern. On the contrary for graphene on Ru(0001) we have found a difference of 0.25 eV in the work function values depending on the position on the Moiré pattern. For graphene on Ru(0001) we also found that the energy position of the first FER presents strong spatial variations that can be measured by scanning tunneling spectroscopy. In fact, for the graphene/Ru(0001) system, the energy position of the first FER is not easily related with the local work function and is modified by the interaction between graphene and the Ruthenium underneath. The energy position of the higher FERs is only influenced by the variations in the local work function.

[1] A.B. Preobrajenski *et al.*, Phys. Rev. B **78**, 073401 (2008)

[2] K.H. Gundlach, Solid State Electron. **9**, 949 (1966)

4:00pm **GR+TF-TuA7 Graphene Electronics and Optoelectronics, P. Avouris, IBM T.J. Watson Research Center** **INVITED**

Graphene is a single atomic layer, 2-dimensional zero band-gap semiconductor with a high Fermi velocity and a huge electrical mobility approaching $200,000 \text{ cm}^2/\text{V}\cdot\text{s}$ for a free sheet. The photonic properties of graphene are equally remarkable: the strength of light-graphene interaction over a very wide range of photon energies is 10 to 100 times stronger than that in conventional semiconductors. These unique properties can be employed in both electronic and photonic applications. In my talk I will discuss the basic device physics, fabrication and operating characteristics of high frequency, single layer graphene transistors. Devices with gain up to 50GHz will be demonstrated. I will also present the physics and device results on single and few layer graphene ultra-high bandwidth photodetectors appropriate for optical communications, imaging and other applications.

4:40pm **GR+TF-TuA9 Graphene Growth on Metal Surfaces, E. Loginova, N.C. Bartelt, P.J. Feibelman, K.F. McCarty, Sandia National Laboratories**

Previous work has shown that when elemental carbon is deposited on the Ru(0001) surface, graphene forms from a dense, tightly-bound carbon-adatom gas. Nonlinearity of the graphene growth rate with carbon adatom density suggests that growth proceeds by addition of carbon atom clusters to the graphene edge [1,2]. In this talk, we present the results of low-energy electron microscopy (LEEM) observations of graphene formation when Ru(0001) and Ir(111) surfaces are exposed to ethylene. We find that graphene growth velocities and nucleation rates on Ru have precisely the same dependence on adatom concentration as

in elemental carbon deposition [3]. Thus, hydrocarbon decomposition only affects graphene growth through the rate of adatom formation; for ethylene, that rate decreases with increasing adatom concentration and graphene coverage. Graphene growth on Ir(111) is similar to that on Ru: the growth velocity is the same nonlinear function of adatom concentration (albeit with much smaller equilibrium adatom concentrations, as we explain with DFT calculations of adatom formation energies). When graphene is exposed to oxygen at high temperatures, it is etched. We observe the etching to proceed by the inverse of the graphene growth mechanism, i.e., by cluster detachment.

[1] E. Loginova, N. C. Bartelt, P. J. Feibelman, and K. F. McCarty, *Evidence for graphene growth by C cluster attachment*, *New Journal of Physics* 10 (2008) 093026

[2] K. F. McCarty, P. J. Feibelman, E. Loginova, and N. C. Bartelt, *Kinetics and thermodynamics of carbon segregation and graphene growth on Ru(0001)*, *Carbon* doi:10.1016/j.carbon.2009.03.004

[3] E. Loginova, N. C. Bartelt, P. J. Feibelman, and K. F. McCarty, *Factors influencing graphene growth on metal surfaces*, submitted to *New Journal of Physics* (2009).

5:00pm **GR+TF-TuA10 The Reduction Kinetics of Graphene Oxide Determined by Temperature Programmed Desorption**, *C.A. Ventrice, N.J. Clark, D.A. Field*, Texas State University, *I. Jung, D. Yang*, University of Texas, *H. Geisler*, Texas State University, *R.D. Piner, R.S. Ruoff*, University of Texas

Graphene oxide, which is an electrical insulator, shows promise for use in several technological applications. For instance, individual, monolayer, graphene oxide platelets could be used as dielectric layers in nanoscale electronic devices. Since the electrical, optical, and mechanical properties of graphene oxide can be controlled by chemical modification, films composed of layers of graphene oxide platelets may be used as the active region of chemical sensors. In principle, graphene oxide films could also be used as a precursor for the formation of large-scale graphene films by either thermal or chemical reduction of the graphene oxide. In order to determine the thermal stability and reduction kinetics of graphene oxide, temperature program desorption measurements have been performed on multilayer films of graphene oxide deposited on SiO₂/Si(100) substrates. The graphene oxide was exfoliated from the graphite oxide source material by slow-stirring in aqueous solution, which produces single-layer platelets with an average lateral size of ~10 μm. From the temperature programmed desorption measurements, it was determined that the primary desorption products of the graphene oxide films for temperatures up to 300 °C are H₂O, CO₂, and CO, with only trace amounts of O₂ being detected. Since carbon is lost during the reduction process in UHV, the addition of other carbon containing reactants during the thermal reduction will be needed to regain the electrical and mechanical properties of pristine graphene. An activation energy of 32 ± 4 kcal/mol (1.4 eV/molecule) was determined by assuming an Arrhenius dependence for the decomposition process.

5:20pm **GR+TF-TuA11 Covalently Immobilized Graphene: Fabrication, Characterization, and Applications**, *M. Yan, L.-H. Liu, G. Nandamuri, R. Solanki*, Portland State University

We developed a simple method for the covalent immobilization of graphene films on solid substrates using a heterobifunctional coupling agent. The films were robustly attached to the substrate, withstanding extensive solvent extraction and sonication. Large sheets of single and few-layer graphene films were fabricated and characterized with Raman, AFM, and XPS. The method is readily applicable for the fabrication of graphene microarrays. Transistors were also constructed with these materials. The device performance with regard to surface and interface properties will be discussed in this presentation.

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