Tuesday Afternoon, October 29, 2013

Graphene and Other 2D Materials Focus Topic
Room: 104 B - Session GR+AS+NS+SP+SS-TuA

Characterization including Microscopy and Spectroscopy of 2D Materials
Moderator: P.W. Sutter, Brookhaven National Laboratory

2:00pm **GR+AS+NS+SP+SS-TuA1 Intercalation of SiC(0001) with Silicon**, ***S. Oida***, *J. Hannon, R.M. Tromp*, IBM T.J. Watson Research Center

Graphene growth on SiC is of interest, in part, because the synthesis takes place directly on an insulating substrate. Because of strong electronic coupling to the substrate, the first graphene layer (called the "buffer layer") does not have the unique electronic properties of graphene . The second layer has much weaker coupling to the substrate and exhibits the high carrier mobility associated with monolayer graphene. However, the synthesis of exactly two monolayers of graphene is difficult, and is usually accompanied by increased surface roughness. Therefore, it would be advantageous to electronically "decouple" the buffer layer and avoid the need to synthesize thicker layers. Here we show that by exposing a buffer layer surface to disilane in ultra-high vacuum it is possible to form Si-rich structures underneath the buffer layer domains. We do this by imaging the surface during disilane exposure using low-energy electron microscopy (LEEM). Furthermore, spatially-resolved electron-energy loss spectroscopy (EELS) shows that the intercalated Si strongly modifies the electronic coupling to the SiC substrate, effectively decoupling the graphene. Finally, we show that the intercalation is fully reversible. That is, with annealing in ultra-high vacuum, the intercalated silicon will desorb from the surface.

2:40pm **GR+AS+NS+SP+SS-TuA3 Imaging the Local Electronic Properties of Graphene**, ***B.J. LeRoy***, University of Arizona **INVITED**

Scanning probe microscopy is a powerful tool to probe low-dimensional systems. The local information provided by scanning probe microscopy is invaluable for studying effects such as interactions and scattering. Using this approach, we have probed the local electronic properties of graphene. The honeycomb lattice in graphene creates a unique linear dispersion relation and the charge carriers behave as massless fermions near the Dirac point. We have studied the effect of charged impurities and the underlying substrate on the local density of states. We find that long-range scattering from charged impurities locally shifts the charge neutrality point leading to electron and hole doped regions. By using boron nitride as a substrate, we observe an improvement in the electronic properties of the graphene as well as a moire pattern due to the misalignment of the graphene and boron nitride lattices [1]. We find that the periodic potential due to the boron nitride substrate creates a set of 6 new superlattice Dirac points in graphene [2]. The ultraflat and clean nature of graphene on boron nitride devices allows for the observation of scattering from buried step edges, which is used to map the dispersion relation [3]. More complicated graphene heterostructures can be created by adding additional layers or other two-dimensional materials. Our latest results with trilayer graphene and rotated bilayers will also be discussed.

[1] J. Xue et al., *Nature Materials* **10**, 282 (2011).

[2] M. Yankowitz et al., *Nature Physics* **8**, 382 (2012).

[3] J. Xue et al., *Phys. Rev. Lett*. **108**, 016801 (2012).

4:00pm **GR+AS+NS+SP+SS-TuA7 Tunable Optical Properties of Graphene**, ***F. Wang***, University of California at Berkeley **INVITED**

Graphene, a single layer of carbon atoms, exhibits novel tunable optical properties. In this talk, I will describe electrical control of interband and intraband optical transitions in graphene and modification of graphene optical transition in a graphene-boron nitride heterostructure. I will also discuss how we can realize other tunable nanophotonics by combining graphene with plasmonic structures and photonic crystals.

4:40pm **GR+AS+NS+SP+SS-TuA9 Purity, Structure and Electronic Properties of Graphene Studied by Low Energy Ion Scattering**, *S. Prusa, P. Prochazka, P. Babor*, Brno University of Technology, Czech Republic, *P. Bruener*, ***T. Grehl***, ION-TOF GmbH, Germany, *R. ter Veen*, Tascon GmbH, Germany, *H. Brongersma*, ION-TOF GmbH, Tascon GmbH, Germany

Based on the unique electronic properties and high chemical stability of graphene, a number of exciting applications are generated. However, since graphene films are only one or a few atomic layers thick, chemical analysis is hampered by the much larger information depth of most techniques. This leaves a gap which can be filled by Low Energy Ion Scattering (LEIS). LEIS is known for its extreme surface sensitivity. It gives a quantitative analysis of the outer atomic layer of a surface as well as in-depth information [1]. It can thus be used to selectively analyze a graphene layer. In general [2], the atomic sensitivities are independent of the neighboring atoms (no matrix effects), so a quantitative elemental characterization is feasible. Since carbon is a common contamination in surface analysis, it is crucial to distinguish such contamination from the carbon in graphene.

In an earlier LEIS study [3] of carbon segregation in C-doped rhenium it was shown that by varying the temperature the carbon species can be altered reversibly into a carbidic or graphitic state. The graphitic layer was one or a few atoms thick (depending on the temperature). A strong matrix effect was observed in LEIS, which is believed to be typical for graphene. The sp-band of graphitic carbon is so wide that it extends to the He 1s level. This gives a strong quasi-resonance neutralization of the scattered He^+ ions.

In the present study graphene layers were grown on copper foils and then transferred to an oxidized Si wafer [4]. The samples were analyzed with a dedicated high-sensitivity LEIS instrument. As reference for a carbon containing material without a wide conduction band, silicon rubber was chosen.

It was found that the neutralization of He^+ by graphene is much stronger than by the rubber. For example, the neutralization of 1.5 keV He^+ ions is almost 100x more effective for graphene.

It will be shown how it is possible to quantify the amount of carbon contamination (hydrocarbons, alcohols, etc.) on graphene using the differences in neutralization. Thus LEIS cannot only be used to verify the closure of the graphene layer, its thickness and purity, but also to check its (wide band) electronic structure.

[1] H.H. Brongersma, *Low-Energy Ion Scattering*, in: Characterization of Materials, J. Wiley & Sons (2012). DOI: 10.1002/0471266965.com144

[2] H.H. Brongersma, M. Draxler, M. de Ridder, P. Bauer, Surf. Sci. Repts 62 (2007) 63-109.

[3] L.C.A. van den Oetelaar, S.N. Mikhailov, H.H. Brongersma, Nucl. Instrum. Meth. B85 (1994) 420.

[4] Xuesong Li et al., Science 324, 1312 (2009). DOI: 10.1126/science.1171245

5:00pm **GR+AS+NS+SP+SS-TuA10 Nanoscale Tribological Characteristics of Epitaxial Graphene on SiC: The Effect of Hydrogen Intercalation**, ***S. Kwon***, *J. Ko*, KAIST, Republic of Korea, *G.E. Yang, W. Kim*, KRISS, Republic of Korea, *Y. Kim, J.Y. Park*, KAIST, Republic of Korea

Atomically-thin graphene is the ideal model system for studying nanoscale friction due to its intrinsic two-dimensional anisotropy. Here, we report the reduced nanoscale friction of epitaxial graphene on SiC, investigated with conductive-probe atomic force microscopy/friction force microscopy in ultra-high vacuum. The measured friction on a buffer layer was found to be 1/8 of that on a monolayer of epitaxial graphene. Conductive probe atomic force microscopy revealed a lower conductance on the buffer layer, compared to monolayer graphene. We associate this difference in friction with the difference in total lateral stiffness. Because bending stiffness is associated with flexural phonons in two-dimensional systems, nanoscale frictional energy should primarily dissipate through damping with the softest phonons. We investigated the influence of hydrogen intercalation on the nanoscale friction. We found that the friction decreased significantly after hydrogen intercalation, which is related to loose contact between the graphene and the substrate that results in a lower bending stiffness.

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