Tuesday Afternoon, November 1, 2011

Graphene and Related Materials Focus Topic
Room: 208 - Session GR+MI-TuA

Graphene: Magnetic Properties and Spin-Dependent Phenomena

Moderator: A.C. Ferrari, University of Cambridge, UK

2:00pm **GR+MI-TuA1 Magnetic Impurities on Graphene**, ***K. Kern***, Max Planck Institute for Solid State Research, Germany **INVITED**

Hybrid systems consisting of transition metal (TM) atoms in contact with graphene are expected to show outstanding magnetic effects, from Kondo screening to long range ferromagnetism due to the large Fermi wavelength in graphene. First recent experimental evidence supports this scenario, however, little is known about the nature of the chemical interaction between TM atoms and graphene, which is the necessary starting point for any advanced application. Here we present recent X-ray Absorption Spectroscopy (XAS) and X-ray Magnetic Circular Dichroism (XMCD) experiments probing the electronic configuration and magnetism of Fe, Co and Ni impurities on graphite and various graphenes. We find a rich physical scenario with marked differences between graphite and silicon oxide supported graphene on one hand and few layer epitaxial graphene on the C-face of silicon carbide on the other hand.

2:40pm **GR+MI-TuA3 Electron Spin Transport in Exfoliated and Epitaxial Graphene Grown on SiC**, ***J. Abel***, *A. Matsubayashi, J.J. Garramone,* University at Albany, *C. Dimitrakopoulos, A. Grill, Sung,* IBM T.J. Watson Research Center, *V.P. LaBella,* University at Albany

Graphene is an ideal candidate for the transport channel in future spintronic devices due to its long spin lifetimes at room temperature. The long lifetime arises due to the small intrinsic spin orbit coupling and low hyper-fine interaction of the electron spins with the carbon nuclei. Non-local Hanle measurement devices were fabricated on epitaxially grown graphene on SiC, provided by IBM, and multi-layer exfoliated flakes. Spin injection and detection were achieved in these devices using cobalt nano-magnets directly deposited on the graphene. Spin precession was observed and the spin lifetimes for the epitaxial graphene were found to be comparable to those found in the exfoliated multi-layer flake. We will also present our measurements of spin relaxation as a function of temperature. The temperature dependence in the spin lifetime observed in the exfoliated flake show a coupling between the magnetic contacts and graphene channel. This is expected due to the lack of a tunnel barrier contact. The comparable spin relaxation times measured in epitaxial graphene fabricated with similar contacts and the multi-layer flake is believed to be caused by a large contact induced relaxation due to the contacts coupling with the graphene channel. The strong coupling effectively removes the spin from the channel.

3:00pm **GR+MI-TuA4 Landau Levels of Dirac Fermions Observed at Zero External Magnetic Fields on Modified Graphite by STS**, ***T. Kondo***, *D. Guo, T. Machida, T. Suzuki, K. Iwatake, S. Okada, J. Nakamura,* University of Tsukuba, Japan

Under the external magnetic field, carriers of graphene are quantized to show an unusual Landau level (LL) energy spectrum due to mass-less Dirac fermions (DFs).[1] The LL energies are not equally spaced and include a characteristic zero-energy state (the n = 0 LL) contrary to the case of normal metals or two-dimensional electron gases. As a result, anomalous quantum Hall effect of graphene has been observed.[2, 3] The quantization of the graphene carrier also occurs without external magnetic field if the appropriate strain is induced.[4,5]Here, we report spontaneous LLs formation of mass-less DFs on potassium intercalated graphite (K-Graphite) and nitrogen-doped graphite (N-Graphite) under zero external magnetic field with the use of scanning tunneling spectroscopy (STS). On the basis of the calculation with the density functional theory, the top-most graphene layer is found to be decoupled with the graphite due to the partial intercalation of potassium atom or nitrogen-doping on graphite. Partially decoupled graphene layer has a sufficient strain to generate the pseudo-magnetic field with about 280 T and 60 T for K-Graphite and N-Graphite, respectively, leading to the LLs formation on the top-most graphene layer on graphite.

1. A. H. Castro Neto et al., Rev. Mod. Phys. 81 (2009) 109.

2. K. S. Novoselov et al., Nat Phys. 2 (2006) 177.

3. K. S. Novoselov et al., Science. 306 (2004) 666.

4. F. Guinea et al., Nat Phys. 6 (2010) 30.

5. N. Levy et al., Science. 329 (2010) 544.

4:00pm **GR+MI-TuA7 Tunneling Spectroscopy of Adsorbed Iron Phthalocyanine on Epitaxial Graphene on SiC(0001)**, ***A.A. Sandin***, *D.B. Dougherty, J.E. Rowe,* North Carolina State University

Graphene may be an ideal material for spin field effect transistors because of its high charge carrier mobility and long spin relaxation times due to small spin-orbit coupling.[1] However, efficient spin injection into graphene requires overcoming conductivity mismatch through the use of tunnel barriers and/or spin filters.[2] It is possible that organic films can serve as tunnel barriers/spin filters with highly tailorable properties. In particular, metal phthalocyanines have recently been shown to exhibit spin dependent interfacial coupling on magnetic electrodes.[3] A study of the coupling and morphology of such molecules on graphene is a crucial first step to understand potential spin enhanced interfaces.

We deposit monolayer iron phthalocyanine (FePc) on both single layer and bilayer epitaxial graphene on the Si-terminated polar face of SiC, named SiC(0001). Scanning tunneling microscopy reveals an adsorbed molecular lattice periodicity of 1.8 nm, close to that of the graphene/SiC buffer layer corrugation periodicity. This lattice spacing is larger than that of FePc adsorbed on a graphite surface that shows a smaller spacing of ~1.4 nm. This implies a stronger interaction of the FePc with epitaxial graphene than expected and is possibly due to the modification of graphene by the SiC substrate. Tunneling spectroscopy has been used to study the occupied and unoccupied electronic states of the absorbed monolayer FePc. Broad unoccupied states indicate significant electronic coupling between the molecules and the graphene and suggest a promising future for molecular strategies for spin injection.

*Supported by the NSF Center for Chemical Innovation: Center for Molecular Spintronics under CHE-0943975.

1. Y. G. Semenov, K. W. Kim and J. M. Zavada, Appl. Phys. Lett. 91 (15), 3 (2007).

2. W. Han, K. Pi, K. M. McCreary, Y. Li, J. J. I. Wong, A. G. Swartz and R. K. Kawakami, Phys. Rev. Lett. 105 (16), 4 (2010).

3. C. Iacovita, M. V. Rastei, B. W. Heinrich, T. Brumme, J. Kortus, L. Limot and J. P. Bucher, Physical Review Letters 101 (11), 116602-116604 (2008).

4:20pm **GR+MI-TuA8 Atomic Scale Determination of the Bilayer Graphene Energy Gap**, ***S. Jung***, *N.N. Klimov, D.B. Newell, N.B. Zhitenev, J.A. Stroscio,* NIST

We have performed scanning tunneling spectroscopy measurements on a gated bilayer graphene device. In graphene bilayer, a potential asymmetry between the layers induces an energy gap in the electron spectrum. The formation of the energy gap is investigated as a function of carrier density and magnetic field. We found that in zero magnetic field, the reliable determination of the gap can be complicated because of disorder scattering. However, in the quantum Hall regime, the energy gap can be quantitatively determined by measuring the layer-polarized low index Landau levels.

Our scanning tunneling spectroscopy measurements reveal that the microscopic nature of the bilayer gap is very different from what was observed in previous macroscopic measurements or expected from current theoretical models. The potential asymmetry varies spatially in both magnitude and sign on a nanometer length scale, showing strong correlation with the disorder potential. This random pattern of alternating dipole fields is qualitatively consistent with the reduced disorder-induced density fluctuations in the top layer.

4:40pm **GR+MI-TuA9 Atomic, Electronic, and Magnetic Properties of Metal-Graphene Interfaces**, ***I.I. Oleynik***, *L. Adamska, Y. Lin,* University of South Florida, *A. Ross,* Saint Anselm College, *M. Batzill,* University of South Florida

Metal/graphene interfaces play an important role in both surface science studies of the epitaxial growth of graphene on metallic substrates, as well as in metal/graphene contacts in graphene nanoelectronic devices. We present results of first-principles density functional theory (DFT) investigations of structural, electronic, and magnetic properties for graphene/Ni(111) and graphene/Cu(111) interfaces relevant to experimental studies of graphene growth on metallic substrates. The favored interface geometries and binding sites for different interface configurations were identified. Additional adlayers of Ni and Cu were either adsorbed on top of the graphene/metal interface, or placed between the graphene and substrate to model processes of metal intercalation. It was also found that the interaction between graphene/Ni(111) and the top Cu adlayer is much weaker compared to that for a Ni adlayer. The atomic, electronic, and magnetic properties of these

interfaces, including induced magnetic moments in graphene/Ni(111), Ni/graphene/Ni(111) systems, are also discussed.

5:00pm **GR+MI-TuA10 Spin-Dependent Scattering from Gated Potential Obstacles in Graphene Systems**, ***M. Asmar***, *S. Ulloa*, Ohio University

We study the scattering of Dirac fermions in a sheet of graphene from potential obstacles created by external gates in the presence of both intrinsic and extrinsic spin-orbit (SO) interactions [1]. Obtaining analytical solutions in a real-space representation for the eigenvectors allows us to calculate the phase shifts generated by a finite-size obstacle in the presence of SO interactions [2]. From the phase shifts extracted from these solutions we can calculate the differential, total and transport cross sections. The knowledge of these quantities allows us to obtain the spin-flip and momentum relaxation times. The dependence of both relaxation times on the strength of the SO interaction was analyzed showing comparable relaxation times for relatively large values of energy, while displaying a big difference for small values of energy. The relaxation times of the injected electrons exhibit a number of resonances in energy associated with the structure of the scattering obstacle. In the presence of SO, new resonances appear at energies that depend on the strength of the SO interactions, and as such contain spectroscopic information on the system. It has been shown that the main scattering mechanism in graphene is due to strong defects [3]. Therefore, the analysis performed in our work can help understand the role of SO interactions in the scattering processes in these and related experiments.

[1] C. L. Kane and E. J. Mele, PRL 95, 226801 (2005).

[2] A. H. Castro Neto and F. Guinea, PRL 103, 026804 (2009).

[3] M. Monteverde, C. Ojeda-Aristizabal, R. Weil, K. Bennaceur, M. Ferrier, S. Gueron, C.Glattli, H. Bouchiat, J. N. Fuchs, and D. L. Maslov, PRL 104, 126801 (2010).

5:20pm **GR+MI-TuA11 Suppression of Weak-Localization Effect in Strained CVD –grown Graphene**, ***X. Miao***, *S. Tongay, M. Lemaitre, B.R. Appleton, A.F. Hebard*, University of Florida

We investigate the magnetic field and temperature-dependent transport properties of CVD-grown graphene subjected to different strains. The graphene is transferred to kapton substrates to which a blending force can be applied. In zero magnetic field, the prefactor to the logarithmic-in-temperature conductivity correction decreases by an approximate factor of 3 for strains as high as 0.6 %. There is also a concomitant decrease in diffusivity by a factor of 6. At 5 K we observe negative magnetoresistance for fields up to 0.5 Tesla followed by positive magnetoresistance at higher fields. We attribute the low field negative magnetoresistance to weak-localization and find that it is well described by theory. The strains resulting from the applied blending force inhibit the intervalley scattering more than an order of magnitude and decrease the phase coherence length, thereby leading to a suppression of weak-localization.

5:40pm **GR+MI-TuA12 Simulation of Electron-Ion Dynamics in Pristine and Functionalized Graphene in External Fields**, ***S. Bubin***, *K. Varga*, Vanderbilt University

In the framework of real-time real-space time-dependent density functional theory (TDDFT) we have studied coupled electron-ion dynamics in small fragments of graphene, graphane, and fluorinated graphene subjected to short (a few femtoseconds) intense laser pulses or irradiated by energetic ions. The goal of this study is to investigate the possibility of defect creation in graphene and desorption of hydrogen/fluorine from graphene surface. We will present the results of our simulations, discuss the mechanisms that take place, and identify the parameters of the laser or energetic ions necessary for those processes to occur.

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