Graphene and Related Materials Focus Topic
Room: 208 - Session GR+MS+EM-FrM

Graphene Device Physics and Applications
Moderator: M. Arnold, University of Wisconsin-Madison

8:20am **GR+MS+EM-FrM1 Fabrication and Characterization of Graphene p-n Junction Devices**, ***J.U. Lee***, University at Albany-SUNY **INVITED**

Graphene is a newly discovered material composed of two-dimensional array of hexagonal carbon atoms. It has a number of unique electronic properties, the most remarkable of which is the zero band-gap light-like linear electronic dispersion, giving rise to Dirac fermions. This feature can be used to make devices based on previously unexplored physical properties. For example, in analogy to optics, we describe new devices based on *optics-like manipulation of electrons*.

Our devices are based on graphene and bi-layer graphene *p-n* junctions doped using electrostatic doping techniques from buried split gates. In the present context, graphene *p-n* junctions do not rectify, i.e. behave as semiconductor diodes. Instead, in graphene p-n junctions, carriers launched from a point contact from one side of the junction are able to refocus back to a point on the other side of the junction. This behavior, known as the Veselago effect, can be the basis for new logic devices for replacing Si CMOS. In addition, using the same platform, we describe interconnect structures that can be reconfigured. Together, we envision a new circuit paradigm based on components that seamlessly reconfigure between devices and interconnect components.

In this talk, we describe the details of graphene *p-n* junction fabrication and characterization, and circuits that are enabled by the *p-n* junction devices. The devices are fabricated at CNSE's state-of-the-art 300mm Si wafer fabrication line using processing techniques that leave atomically flat top oxide surface above the patterned split gates. For characterizing the p-n junctions, we perform transport and SPM measurements.

9:00am **GR+MS+EM-FrM3 Assembled Bilayer Graphene for Electronic Applications**, ***G.G. Jernigan***, *T.J. Anderson, J.T. Robinson, J.D. Caldwell, M.D. Ancona, V.D. Wheeler, L.O. Nyakiti, J. Culbertson, A.L. Davidson, A.L. Friedman, P.M. Campbell, D.K. Gaskill*, U.S. Naval Research Laboratory

Graphene has shown successful application in RF transistors and frequency doublers where its high mobility and high saturation velocity translate into operation at high frequencies while utilizing little power. However, a major detraction to graphene development for other device applications is that it does not have a band gap. The lack of a band gap means that graphene's current cannot be turned off. Bilayer graphene is regarded as one possible solution to this problem, since bilayer graphene is capable of developing a band gap if the symmetry of the system can be broken. That said, bilayer graphene (from exfoliation or growth) forms a highly ordered A-B stack of the two graphene sheets resulting in little to no band gap, unless a high electric field can be applied.

In this presentation, we will demonstrate a novel method for creating bilayer graphene where a single layer of CVD graphene grown on Cu is bonded to a single layer of epitaxial graphene grown on Si-face SiC. This process results in a bilayer system that has a built-in asymmetry that yields unique physical and electrical properties not previously observed. For example, we demonstrate that the transfer of CVD graphene to epitaxial graphene results in a smoother morphology than transfer onto SiO2 and that bonding of CVD graphene to epitaxial graphene can avoid the damage caused by the drying step necessary in the poly (methyl methacrylate) transfer method. X-ray photoelectron spectroscopy and Raman microscopy demonstrate that the sheets are coupled together but strained differently, in contrast to a naturally formed bilayer. Electrical characterization of Hall devices fabricated on the novel bilayer show higher mobilities and lower carrier concentrations than the individual CVD graphene or epitaxial graphene sheets alone. Modeling of the electric field produced by opposite doping in the graphene sheets will also be presented, as CVD graphene is typically p-type and epitaxial graphene is typically n-type.

10:00am **GR+MS+EM-FrM6 Rectification at Graphene / Semiconductor Junctions: Applications Beyond Silicon Based Devices**, ***S. Tongay***, *X. Miao, K. Berke, M. Lemaitre, B.R. Appleton, A.F. Hebard*, University of Florida

Schottky barriers are crucial and necessary device components of metal-semiconductor field effect transistors (MESFETs) and high electron mobility transistors (HEMTs). Here, we report on the formation of Schottky barriers at graphene-multilayer graphene/semiconductor junction interfaces which have been characterized by current density vs. voltage (J-V) and capacitance vs. voltage (C-V) measurements. After graphene transfer onto various semiconductors such as Si, GaAs, GaN and SiC, we observe a strong rectification at the interface, i.e., high (low) resistance in the reverse (forward) bias directions. The J-V characteristics have been analyzed using thermionic emission theory and the extracted barrier height values are consistent with the Schottky-Mott model. When capacitance is plotted as $1/C^2$ vs V, a linear dependence is observed, which by extrapolation to the intercept identifies a built in potential that is consistent with the Schottky barrier height extracted from J-V measurements. Graphene's low Fermi energy together with its robust thermal, chemical, structural and physical properties provide numerous advantages when used to form Schottky barriers in device applications: namely, voltage tunability of the Schottky barrier height, stability to high temperatures, resistance to impurity diffusion across the interface, and the use of absorbates to chemically tune the Fermi energy and hence the Schottky barrier height.

10:20am **GR+MS+EM-FrM7 Imaging of Electron Beam Induced Current in Epitaxial Graphene**, ***S. Mou***, *J. Boeckl, W.C. Mitchel, J.H. Park,* Air Force Research Laboratory, *S. Tetlak,* Wyle Laboratories, *W. Lu*, Fisk University

It has been known and observed that there forms a Schottky junction between graphene and SiC in epitaxial graphene due to the work function difference and the charge transfer between them. As a result, it is viable to apply the electron beam induce current (EBIC) technique on the epitaxial graphene directly due to the fact that it needs a built-in field and ample electron generation volume to generate EBIC. EBIC is an important characterization technique, which identifies electrically active impurities/defects, detects local built-in field, and measures minority carrier diffusion length. In this paper, we use a FEI SEM equipped with a current amplifier to investigate the spatial mapping of EBIC generation and collection in a two terminal geometry. The incident electron beam generates excited electron-hole pairs in SiC and the minority carriers are collected through the Schottky junction before flowing into graphene. EBIC imaging reveals mesoscopic domains of bright and dark contrast areas due to local EBIC polarity and magnitude, which is believed to be the result of spatial fluctuation in the carrier density in graphene. We also investigate the electron energy dependence, which modulates the EBIC magnitude. With an analytical drift-diffusion current model, we are able to extract the minority carrier diffusion length in the SiC, which is on the order of micro meter and agrees well with other published data.

10:40am **GR+MS+EM-FrM8 Potassium-Ion Sensors Based on Valinomycin-Modified Graphene Field-Effect Transistors**, ***Y. Sofue***, *Y. Ohno, K. Maehashi, K. Inoue, K. Matsumoto*, The Institute of Scientific and Industrial Research, Osaka University, Japan

Highly sensitive ion sensors based on valinomycin-modified graphene field-effect transistors (VGFETs) have been developed to selectively detect K ions, which are an essential element for biological activity including human life. Graphene single-layers were obtained by mechanical exfoliation. Graphene FETs were fabricated by conventional e-beam lithography and lift-off method on a thermally grown SiO_2 layer. To demonstrate selective detection of K ions, the graphene channels were covered with ion selective membrane, which consisted of polyvinyl chloride and valinomycin. Transfer characteristics of VGFETs in a 100 mM Tris-HCl buffer solution with various KCl concentrations over the range from 10 nM to 1.0mM. With increasing K ion concentration, the solution-gated voltage at the Dirac point shifted toward negative direction. The shifts are due to the accumulation of positively charged K ions surrounded by valinomycin on the graphene surfaces. The electrostatic potential of graphene surfaces exhibit a rather linear dependence on log[K]. These results indicate that VGFETs effectively detected K ions with concentration from 10 nM to 1.0 mM. To investigate selectivity in VGFETs, Na-ion concentration dependence was also measured. The transfer characteristic in VGFETs remained almost constant over the Na ion concentration range between 10 nM and 1.0 mM. These results indicate that VGFET selectively detected K ions with high sensitivity.

11:00am **GR+MS+EM-FrM9 Band-gap Generation by using Ionic-Liquid Gate in Bilayer Graphene**, ***Y. Yamashiro***, *Y. Ohno, K. Maehashi, K. Inoue, K. Matsumoto*, Osaka University, Japan

Electric fields were applied to a bilayer graphene to generate a band gap using an ionic-liquid gate instead of the general top-gate structures. The ionic-liquid gate can apply higher electric field than other type of the gates because of its large capacitance and electric strength. In this abstract, the

graphene layers were extracted from kish graphite by a mechanical exfoliation and were put on highly *n*-doped Si substrates covered with a 300-nm-thick SiO_2 layer. Side-gate electrodes were patterned approximately 20 mm away from the channels. An ionic liquid (DEME-TFSI) was put on the bilayer graphene and the side-gate electrode. Electrical characteristics at 300 K revealed that the electrical double layer in the ionic-liquid, which works as a very thin insulator, had 200 times larger capacitance than a 300-nm-thick SiO_2 layer. The thickness of electrical double layer was estimated to be 3.75 nm. In electric field dependence measurements, an increase in a sheet resistance of the bilayer grapheme channel was clearly observed with increasing the magnitude of electric field in bilayer graphene. On the other hand, the increase in the sheet resistance didn't appear in the monolayer- and trilayer- graphene. That is why the increasing of the sheet resistance was caused by a band gap generated in ionic-liquid gated bilayer graphene by the electric field.

11:20am **GR+MS+EM-FrM10 Electronic Transport in Hydrogenated Graphene Films**, ***B.R. Matis***, *J.S. Burgess,* NRC/NRL Postdoctoral Associate, *A.L. Friedman, J.T. Robinson,* Naval Research Laboratory (NRL), *F.A. Bulat,* Sotera Defense Solutions, Inc., *B.H. Houston, J.W. Baldwin*, Naval Research Laboratory (NRL)

Graphene films grown by chemical vapor deposition on copper foils and exfoliated graphene flakes were hydrogenated using low kinetic energy plasma processing. The film sheet resistance can be tuned over a wide range (1 kΩ/square – 300 kΩ/square), increasing proportionally with hydrogen coverage. Variable temperature measurements demonstrate a transition from semi-metallic behavior for graphene to semiconducting behavior for hydrogenated graphene. Sheet resistance measurements as a function of temperature also suggest the emergence of a band gap in the hydrogenated graphene films. Interesting surface doping effects will be discussed in conjunction with the location of the charge neutrality point. This work was supported by the Office of Naval Research.

11:40am **GR+MS+EM-FrM11 First-principles Study of Electronic Properties of Two Dimensional Carbon and Boron Nitride Nanomaterials**, ***S. Mukherjee***, S.N. Bose National Centre for Basic Sciences, India

First principles pseudopotential plane wave method was used to study ground state electronic properties of Graphene, hexagonal Boron Nitride (h-BN), Graphene doped with Boron and Nitrogen, and multilayers of Graphene and h-BN. Our results on doped Graphene indicate that upon electron (hole) doping, the Dirac-point in the electronic bandstructure shifts below (above) the Fermi level and a gap appears at the high-symmetric K-point. Upon co-doping of Graphene by both Boron and Nitrogen a small energy gap between the conduction and valence band appears at the Fermi level, making the CBN nanomaterial a narrow band semiconductor. The energy gap depends sensitively on the degree of doping and on the thickness of CBN layer. These results are in agreement with recent experimental measurements [1,2]. Our bandstructure calculations on the multilayers of Graphene and h-BN indicate that these nanostructured multilayers exhibit semiconducting behaviour with band gap in the range 60-600 meV depending on the relative orientation and thickness of the layers. (Author: Sugata Mukherjee, work done in collaboration with T.P. Kaloni)

1. X. wang et al, Science **324**, 768 (2009)

2. L. Cie et al, Nature Materials **9**, 430 (2010).

Authors Index

Bold page numbers indicate the presenter

— A —

Ancona, M.D.: GR+MS+EM-FrM3, 1
Anderson, T.J.: GR+MS+EM-FrM3, 1
Appleton, B.R.: GR+MS+EM-FrM6, 1

— B —

Baldwin, J.W.: GR+MS+EM-FrM10, 2
Berke, K.: GR+MS+EM-FrM6, 1
Boeckl, J.: GR+MS+EM-FrM7, 1
Bulat, F.A.: GR+MS+EM-FrM10, 2
Burgess, J.S.: GR+MS+EM-FrM10, 2

— C —

Caldwell, J.D.: GR+MS+EM-FrM3, 1
Campbell, P.M.: GR+MS+EM-FrM3, 1
Culbertson, J.: GR+MS+EM-FrM3, 1

— D —

Davidson, A.L.: GR+MS+EM-FrM3, 1

— F —

Friedman, A.L.: GR+MS+EM-FrM10, 2; GR+MS+EM-FrM3, 1

— G —

Gaskill, D.K.: GR+MS+EM-FrM3, 1

— H —

Hebard, A.F.: GR+MS+EM-FrM6, 1
Houston, B.H.: GR+MS+EM-FrM10, 2

— I —

Inoue, K.: GR+MS+EM-FrM8, 1; GR+MS+EM-FrM9, 1

— J —

Jernigan, G.G.: GR+MS+EM-FrM3, **1**

— L —

Lee, J.U.: GR+MS+EM-FrM1, **1**
Lemaitre, M.: GR+MS+EM-FrM6, 1
Lu, W.: GR+MS+EM-FrM7, 1

— M —

Maehashi, K.: GR+MS+EM-FrM8, 1; GR+MS+EM-FrM9, 1
Matis, B.R.: GR+MS+EM-FrM10, **2**
Matsumoto, K.: GR+MS+EM-FrM8, 1; GR+MS+EM-FrM9, 1
Miao, X.: GR+MS+EM-FrM6, 1
Mitchel, W.C.: GR+MS+EM-FrM7, 1
Mou, S.: GR+MS+EM-FrM7, **1**
Mukherjee, S.: GR+MS+EM-FrM11, **2**

— N —

Nyakiti, L.O.: GR+MS+EM-FrM3, 1

— O —

Ohno, Y.: GR+MS+EM-FrM8, 1; GR+MS+EM-FrM9, 1

— P —

Park, J.H.: GR+MS+EM-FrM7, 1

— R —

Robinson, J.T.: GR+MS+EM-FrM10, 2; GR+MS+EM-FrM3, 1

— S —

Sofue, Y.: GR+MS+EM-FrM8, **1**

— T —

Tetlak, S.: GR+MS+EM-FrM7, 1
Tongay, S.: GR+MS+EM-FrM6, **1**

— W —

Wheeler, V.D.: GR+MS+EM-FrM3, 1

— Y —

Yamashiro, Y.: GR+MS+EM-FrM9, **1**