Friday Morning, November 1, 2013

Graphene and Other 2D Materials Focus Topic
Room: 101 A - Session GR+EM+MS+NS+SP-FrM

2D Materials: Device Physics & Applications
Moderator: L. Cao, North Carolina State University, E. Riedo, Georgia Institute of Technology

8:20am **GR+EM+MS+NS+SP-FrM1 Epitaxial Graphene Electronics**, ***J.A. Robinson***, The Pennsylvania State University **INVITED**

Graphene demonstrates exceptional properties such as high charge carrier mobility and high saturation velocity. Such attributes make graphene a promising candidate for radio frequency (rf) applications. However, one of the key limitations to the realization of graphene's full potential comes from its interaction with dielectric overlayers and metal contacts, which act to limit the excellent charge transport properties of graphene. We have directly demonstrated the importance of buffer elimination at the graphene/SiC(0001) interface where enhanced carrier mobilities of >3000 cm^2/Vs across large scale wafers is possible. Additionally, we have developed a robust method for forming high quality ohmic contacts to graphene, which improves the contact resistance by >1000X compared to untreated metal/graphene interfaces. We have also developed methods for ultra-thin gate oxides, and will discuss integration and the importance on improved interfaces between the graphene and dielectric. Each of these developments have provided a means to achieve graphene transistors with current saturation values >1.5 A/mm, transconductance > 400mS, impressive *extrinsic* current gain response of epitaxial graphene transistors (>30 GHz), and *intrinsic* current gain nearing 150 GHz. Additionally, we analyze the third order intermodulation product, gain compression and high frequency noise performance of graphene transistors for low noise amplifier applications and benchmark the graphene transistors with other RF device technologies. The graphene amplifier (un-matched) exhibits an output third order intercept (OIP3) of 19dBm and input 1dB gain compression ($P_{in,1dB}$) of 5.6dBm. Finally, the performance of a graphene mixer will be discussed and evidence is provided that matched graphene mixers can outperform current state-of-the-art technologies.

9:00am **GR+EM+MS+NS+SP-FrM3 Direct Transfer of Graphene Devices on Arbitrary Substrates**, ***Z. Razavi Hesabi***, *C.A. Joiner, T. Roy, E.M. Vogel*, Georgia Institute of Technology

The wide-ranging high performance electronic properties of graphene and its ability to be roll-to-roll manufactured, provides an interesting platform for developing high performance, multifunctional electronics on arbitrary substrates such as paper or plastic. However, these substrates are not compatible with conventional high-temperature semiconductor processing. In this work, graphene devices are fabricated on as-synthesized graphene on copper foil using conventional semiconductor device processing techniques. The fully fabricated devices are then transferred onto the substrate of interest (glass, paper, or plastic) using a conventional PMMA-based wet transfer method. The effect of devices designs and processing conditions such as metal contact area and type (top contact versus mixed edge/top contact) on graphene device performance is investigated. The obtained results show that for top contacts, the Dirac point cannot be observed, while for mixed edge/top contacts, the Dirac point is observed. The obtained results suggest metal doping and edge contact can significantly shift the Dirac point. Overall, the results demonstrate a novel method for fabricating high performance graphene devices on arbitrary substrates.

Key words: Graphene, Field Effect Transistor (FET), Direct Transfer

9:20am **GR+EM+MS+NS+SP-FrM4 1/f Noise in Epitaxial Graphene Field Effect Transistors using Al_2O_3 and HfO_2 High k -Dielectrics**, *H.K. Chan,* Newcastle Univ., UK, *V.D. Wheeler,* U.S. Naval Research Laboratory (NRL), *V.K. Nagareddy,* Newcastle Univ., UK, *L.O. Nyakiti,* NRL, *A. Nath,* George Mason Univ., *R.L. Myers-Ward, Z. Robinson, N.Y. Garces,* NRL, *M.V. Rao,* George Mason Univ., *J.P. Goss, N.G. Wright,* Newcastle Univ., UK, *C.R. Eddy, Jr.,* NRL, *A.B. Horsfall,* Newcastle Univ., UK, ***D.K. Gaskill***, NRL

It has been shown that graphene has substantially low 1/f noise, a characteristic potentially advantageous for electronic sensor applications. Most reports have been from studies of devices on flakes, which lack the desirable scale-up potential for practical applications. Here, we report the 1/f noise behavior for gated graphene devices formed on SiC substrates using low pressure sublimation (LPS) of Si in an Ar ambient. In general, we found that the 1/f characteristics of LPS graphene to be similar to or superior to all prior studies.

The LPS graphene was synthesized in an Aixtron VP508 reactor on ~2.5 cm^2 nominally on-axis 6H(0001) semi-insulating substrates from the same boule. The process was designed to produce nominally 1 ML of graphene on the terraces of the samples; the samples should be identical as the synthesis process has been demonstrated to be uniform and run-to-run reproducible. Samples were processed using typical photolithographic methods before dielectric deposition; a Ti/Au stack was used for ohmic and gate contacts. High-k dielectric deposition was accomplished via a two-step process that includes functionalization of graphene by Fluorine followed by atomic layer deposition (ALD) of 20 nm thick Al_2O_3 and HfO_2. Previously, we have shown that F-functionalization results in pinhole-free coverage of dielectrics and the films possess Dirac voltage shifts of 0.5V and 1.5V and dielectric constants of 9 and 18, for Al_2O_3 and HfO_2, respectively. The 1/f noise data was acquired using a fast Fourier transform analyzer coupled with low noise amplifier and was averaged over 5 different samples on the same substrate for each oxide case; V_{GS} was controlled forward and reverse in the range -3 to 2V.

The 1/f noise magnitude, S_i/I^2,was found to scale with channel dimension and was comparable or smaller in magnitude to reports by others on graphene flakes thus suggesting that the underlying SiC and interface layer does not add an appreciable number of noise generation sites. Comparing samples with a gate oxide to those processed identically but without oxide shows the noise magnitude was similar implying that the F-functionalization-based ALD process does not degrade the graphene channel by inducing interfacial traps. For the gated samples, the composition of the gate oxide had a minor effect on the channel noise magnitude relative to non-gated samples. For HfO_2 devices having an oxide surface coverage of 20 x 4 m m^2, $S_i/I^2=4x10^{-11}$ Hz^{-1} (at 20 Hz). For gated measurements, the 1/f noise magnitude were not flat but showed a slight (20%) dependence on V_{GS}. Both oxides showed noise hysteresis (~15%) although it was more pronounced for the HfO_2 devices.

9:40am **GR+EM+MS+NS+SP-FrM5 MoS_2 MOSFETs: Dielectrics, Metal Contacts and Scaling**, ***P.D. Ye***, Purdue University **INVITED**

The discovery of graphene has unveiled another material family with layered structures, which includes boron nitride, topological insulators such as Bi_2Te_3 and Bi_2Se_3, and transition metal dichalcogenides like MoS_2, WS_2, and $NbSe_2$. Though graphene, a fascinating two-dimensional (2D) crystal, has shown a superior carrier mobility of up to 200,000 $cm^2/V{\cdot}s$, its zero bandgap property limits its application to logic devices as graphene transistors cannot have high on/off ratios. As opposed to the semi-metal graphene, transition metal dichalcogenides (such as MoS_2), as another type of layered structure material, have shown great potential in device applications due to their satisfied bandgaps, thermal stability, carrier mobility, and compatibility to silicon CMOS process. In order to realize high performance MoS_2 MOSFETs [1], three major issues must be solved: 1) how to deposit a high-quality dielectric on 2D crystal, 2) the fabrication of low-resistivity metal-semiconductor junction to be used as device contacts, and 3) the elimination of short channel effects. [2,3] In this talk, I will review the recent progress in this field about these three device aspects and discuss the fundamental physics, chemistry, and posible solutions on these challenges.

The work is in close collaborations with H. Liu, A.T. Neal, and Y.C. Du. The authors appreciate SRC GRC for the support.

[1] Radisavljevic, B.; Radenovic, A.; Brivio, J.; Giacometti, V.; Kis, A. Single-Layer MoS_2 Transistors, *Nat. Nanotechnol.*2011, 6, 147 – 150.

[2] Liu, H.; Neal, A.T.; Ye, P.D. Channel Length Scaling of MoS_2 MOSFETs, *ACS Nano* 2012, 6, 8563-8569.

[3] Liu, H.; Ye, P.D. MoS2 Dual-Gate MOSFET with Atomic-Layer-Deposited Al_2O_3 as Top-Gate Dielectric, *IEEE Electron Device Lett.* 2012, 33, 546-548.

10:20am **GR+EM+MS+NS+SP-FrM7 Broad Band Dielectric Functions of Graphene and MoS_2**, ***W. Li***, *G. Cheng,* National Institute of Standards and Technology (NIST), *Y. Liang,* Peking Univ., China, *K. Xu,* NIST, *A. Boosalis,* Univ. of Nebraska-Lincoln, *P.D. Ye,* Purdue Univ., *A.R. Hight Walker,* NIST, *X. Liang,* Peking Univ., China, *T. Hofmann,* Univ. of Nebraska-Lincoln, *C.A. Richter, D.J. Gundlach, N.V. Nguyen*, NIST

Graphene and MoS_2 are among the most promising candidates for next generation of electronic and photonic devices. Accurate optical properties provide key information necessary for electronic and photonic device design. Here, we report the results of a broad band optical measurement of the dielectric function by spectroscopic ellipsometry (SE) of graphene and MoS_2 grown by chemical vapor deposition (CVD). With the extended spectral range, we are able to observe new higher energy interband absorptions in MoS_2 and a red shift of graphene excitons.

Monolayer graphene grown on a copper foil was transferred onto a fused silica substrate by solvent method; two and three graphene layers were formed by the sequential transfer of each monolayer. MoS_2 was directly grown on sapphire. Raman spectroscopy was performed on each sample. Both the exciton peak (around 4.8 eV) and another absorption peak (around 6.3 eV) were observed from the absorption spectra of graphene. In the IR range, both refractive index (n) and k increase with longer wavelength which is consistent with the reported results.[(a)] It is notable that n increases whereas k decreases as the number of graphene layers increases. This is most likely due to the relatively weak interaction between transferred graphene monolayers. More importantly, we observe a red shift of the exciton peak for two layer graphene (0.04 eV shift) and three layer graphene (0.07 eV shift) relative to that of monolayer graphene, which we attribute to the interlayer screening effects. The theory predicts[(b)] the transmittance of monolayer graphene to depend solely on the universal fine structure constant $a = e^2/\hbar c$, which is related to the graphene's opacity. We find opacity to linearly increase for each of added layer. For example, at 550 nm the transmittance of one, two, and three layers of graphene are 96.9%, 93.6%, and 90.3%, respectively. Raman studies on MoS_2 confirm the presence of 3 layers, consistent with the three layer model derived from ellipsometry. The MoS_2 dielectric function exhibits the well-known A (1.86 eV) and B (2.02 eV) strong excitons which arise from the direct d-d transitions separated by a spin-orbit splitting. A series of higher energy interband transitions are clearly seen at 2.8, 3.1, 4.7 eV of which the 2.8 eV peak is the strongest absorption peak ever reported for MoS_2.

(a) F. J. Nelson, et al., Appl. Phys. Lett. 97, 253110 (2010)

(b) A. B. Kuzmenko, E. van Heumen, F. Carbone, and D. van der Marel, PRL **100**, 117401 (2008); R. R. Nair, P. Blake, A. N. Grigorenko, K. S. Novoselov, T. J. Booth, T. Stauber, N. M. R. Peres,2 A. K. Geim, *Science***320**, 1308 (2008).

10:40am **GR+EM+MS+NS+SP-FrM8 Measurement of Charge Doping of Graphene in a Metal/Graphene/Dielectric Sandwich Structure by C-1s Core Level X-ray Photoelectron Spectroscopy**, ***A. Dahal***, *M. Batzill, R. Addou, H. Coy-Diaz, J. Lallo*, University of South Florida

The contact resistance between graphene and metals critically affects device operations. In most realistic graphene device structures, graphene is supported on an insulating substrate and metals are deposited on top of graphene to make electrical contacts. Thus we should evaluate the contact resistance of a metal/graphene/dielectric sandwich structure rather than just a metal/graphene interface. A critical component for evaluating the contact resistance is the Fermi-level shift in graphene underneath the metal contact. We show that this Fermi-level shift relative to the graphene's Dirac point, can be measured from C-1s core level x-ray photoelectron spectroscopy (XPS). In XPS of solids the binding energy is referenced to the Fermi-level, consequently measurement of C-1s core level of graphene allows us, in the absence of chemical shifts, to determine the Fermi-level of graphene at metal/graphene interfaces as well as at metal/graphene/dielectric interfaces. We show that the Fermi-level shift for metal/graphene interfaces of the weakly interacting metals such as Pt, Ir, Al, and Cu agrees well with previously reported DFT calculations(ref.1). However, the Fermi-level shift of graphene is strongly altered if graphene is sandwiched between a metal and a dielectric oxide. This behavior can be explained by a modified Schottky contact model. In metal/graphene/oxide sandwich structure, metal is replaced by a graphene/metal heterostructure and thus charges in the Schottky contact will be located on the graphene. A simple capacitor model for graphene/oxide interfaces predicts the difference in charge doping for graphene on a metal compared to graphene sandwiched between a metal and dielectric as $\Delta E_F \approx 0.2\times(\Phi_{metal} - \Phi_{dielectric})$,in good agreement with our measurements.

Key words: Interface, Doping, Fermi-level, Spectroscopy, Schottky contact

Ref(1) G. Giovannetti, P. A. Khomyakov, G. Brocks, V. M. Karpan, J. van den Brink, and P. J. Kelly, Physical Review Letters **101,** 026803 (2008).

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