Tuesday Morning, November 1, 2011

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

Graphene: Optical Properties, Optoelectonics and Photonics
Moderator: P.E. Sheehan, U.S. Naval Research Laboratory

8:00am **GR+EM-TuM1 Graphene Optoelectronics: From Ultrafast Lasers to Flexible Displays**, ***A.C. Ferrari***, University of Cambridge, UK **INVITED**

The richness of optical and electronic properties of graphene attracts enormous interest. So far, the main focus has been on fundamental physics and electronic devices. However, we believe its true potential to be in photonics, plasmonics and optoelectronics, where the combination of its unique optical and electronic properties can be fully exploited, the absence of a bandgap can be beneficial, and the linear dispersion of the Dirac electrons enables ultra-wide-band tenability [1]. The rise of graphene in photonics and optoelectronics is shown by several recent results, ranging from solar cells and light emitting devices, to touch screens, photodetectors and ultrafast lasers. Despite being a single atom thick, graphene can be optically visualized [2]. Its transmittance can be expressed in terms of the fine structure constant [3]. The linear dispersion of the Dirac electrons enables broadband applications. Saturable absorption is observed as a consequence of Pauli blocking [4,5]. Chemical and physical treatments enable luminescence [1,6]. Graphene-polymer composites prepared using wet chemistry [4-6] can be integrated in a fiber laser cavity, to generate ultrafast pulses, down to 100fs with up to 1 W average power, and enable broadband tunability [4,5]. Graphene-based mode-locked laser are a near term application for this extraordinary material, and can provide simple, low-cost, and convenient light sources for metrology, sensing, medicine and micromachining. Graphene is an ideal transparent flexible conductor. A flexible electrically switchable smart window will be reported, with over 230 contrast ratio, as well as an electro-tactile screen for mobile phone applications. The optoelectronic properties of graphene can be enhanced by combination with plasmonic nanostructures [7], for example in plasmonic-enhanced photovoltage generation [8]

1. F. Bonaccorso et al. Nature Photonics 4, 611 (2010)

2. C. Casiraghi et al. Nano Lett. 7, 2711 (2007).

3. R. R. Nair et al. Science 320, 1308 (2008).

4. T. Hasan, et al. Adv. Mat. 21,3874 (2009)

5. Z. Sun et al. ACS Nano 4, 803 (2010); Nano Research 3, 653 (2010)

6. T. Gokus et al. ACS nano 3, 3963 (2009)

7. F. Schedin, *ACS Nano* **4**, 5617 (2010).

8. T.J. Echtermeyer et al, submitted (2011)

9:00am **GR+EM-TuM4 Quantum Mechanics-Based Exploration of Graphene-Like Systems to Model Magnetic Resonators**, *X.W. Sha, E.N. Economou,* ***D.A. Papaconstantopoulos***, George Mason University, *M.R. Pederson, M.J. Mehl*, Naval Research Laboratory, *M. Kafesaki*, University of Crete, Greece

Quasi-circular pieces of graphene as well as nanotubes offer the possibility of acting as magnetic resonators to be used in negative refractive index optical metamaterials. The advantage of these graphene pieces is twofold: (a) they are stable even when their size reaches the tens of nanometers; (b) the induced currents in the presence of an AC magnetic field perpendicular to the graphene plane cancel each other in all the interior hexagons and only an edge circular current remains. This current is expected to be ballistic in nature with almost zero resistance. This analog of the split (in the split ring resonators) is expected to be achieved by the substitutional insertion of foreign atoms (e.g. nitrogen atoms). To explicitly and reliably check these ideas we have used the NRLMOL, a first- principles DFT code, in the presence of an AC magnetic field, to calculate the response of various configurations of quasi-circular pieces of graphene with or without the presence of substitutional foreign atoms. In order to be able to extend our calculations to larger systems, of the order of tens of thousands of atoms, we used the NRL-TB method, in which the TB matrix elements were fitted so as to reproduce the energy levels of our DFT approach. Results for the energy levels, some selected eigenfunctions, and the current distribution for several configurations will be presented and evaluated vis-a-vis the intended use as almost lossless magnetic resonators.

9:20am **GR+EM-TuM5 Infrared Optical Conductance of CVD-grown Graphene**, ***J.W. Weber***, *M.C.M. van de Sanden*, Eindhoven University of Technology, Netherlands

The infrared optical conductance of chemical vapour deposited (CVD) graphene is determined from near normal incidence reflection and transmission Fourier transform infrared measurements in the spectral range of 370-7000 cm^{-1}. The real part of the conductance, up to 2500 cm^{-1} , shows both the effect from doping and finite temperature that was shown for exfoliated graphene.[1,2] The conductance for the range 2500-7000 cm^{-1} is increasing from the value for the universal optical conductance ($\pi e^2/2h$) to 1.5 times this value. This could imply that graphene and bilayer graphene have grown in a 1:1 ratio. The graphene is grown via CVD of methane and hydrogen on Cu-foil and transferred to a glass substrate following the procedure of Li *et al*.[3] A three-phase optical model (air/graphene/glass) is used to simultaneously fit the reflection and transmission data and extract the (Kramers-Kronig consistent) optical conductance. The conductance will be used to compare it with the conductance of CVD-graphene that is exposed to a hydrogen plasma.

[1]Mak *et al*. *Phys. Rev. Lett* **101**, 196405 (2008)

[2]Li *et al*. *Nat. Phys*. **4**, 532 (2008)

[3]Li *et al*. *Science* **324**, 1312 (2009)

9:40am **GR+EM-TuM6 Optical Properties of Graphene on MgO and SiC Polytypes Determined by Spectroscopic Ellipsometry**, ***A. Boosalis***, *T. Hofmann, S. Schoche, P.A. Dowben*, University of Nebraska - Lincoln, *S. Gaddam, C. Vamala, J. Kelber*, University of North Texas, *V. Darakchieva*, Linköping University, Sweden, *D.K. Gaskill*, U.S. Naval Research Laboratory, *M. Schubert*, University of Nebraska - Lincoln

Wafer-scale production of epitaxial graphene has been demonstrated recently. It has been observed, however, that the highest quality graphene is achieved from exfoliation, while epitaxial graphene exhibits less desirable electronic and optical characteristics. Identifying substrate effects on epitaxial graphene is of paramount contemporary interest for future device production.

We have determined the complex dielectric function of graphene deposited on a number of different substrates using multiple growth techniques. The investigations were performed in the spectral range from 1.5 to 9.5 eV using spectroscopic ellipsometry. The samples studied here include graphene grown on (111) MgO using chemical vapor deposition (CVD) and graphene grown on SiC by sublimation of silicon from the substrate at high temperature. Several different SiC polytypes, including 4H, 3C, and 6H SiC were studied. Distinct differences in the complex dielectric function of graphene are observed as the underlying substrate differs in material composition and polytype. In particular in the spectral region of the exciton absorption peak (4 eV) the complex dielectric function is sensitive to both substrate and growth parameters. We compare our results with those of recent publications of graphene grown by CVD on SiO_2.

10:40am **GR+EM-TuM9 Plasmon Resonance in Individual Nanogap Electrodes Studied Using Graphene Nanoconstrictions as Photodetectors**, ***S.-F. Shi***, Cornell University, *X. Xu*, University of Washington, *P.L. McEuen, D.C. Ralph*, Cornell University

A plasmonic nanostructure can act like an optical antenna, concentrating light into a deep sub-wavelength volume and enabling manipulation of light-electron interactions at the nanometer scale. Achieving efficient coupling from such antennas to functional electrical devices has been challenging, because the region of field enhancement is so small. We achieve direct electrical read out of the wavelength and polarization dependence of the plasmon resonance in individual gold nanogap antennas by positioning a graphene nanoconstriction within the gap as a localized photodetector. The polarization sensitivities can be as large as 99%, while the plasmon-induced photocurrent enhancement is 2-100. The plasmon peak frequency, polarization sensitivity, and photocurrent enhancement all vary between devices, indicating the degree to which the plasmon resonance is sensitive to nanometer-scale irregularities.

11:00am **GR+EM-TuM10 Large Area Graphene Growth for Optoelectronic Applications**, ***C. Edwards***, *C.L. Berrie, J. Liu, J. Wu*, University of Kansas

Graphene shows great promise for numerous applications within the field of optoelectronics due to its high charge mobility, high optical transmittance, chemical inertness, and flexibility. We are focused on developing large-area graphene sheets that sustain or enhance these characteristics currently present in small-area growth. Chemical vapor deposition of graphene onto various copper substrates has been investigated to understand the role of the substrate in graphene epitaxy and its deposition mechanism. With this understanding it will be possible to use the substrate structure to control the density of surface defects, which is high in current methods for large area fabrication. Also, the effect of nanopatterning and doping graphene grown by chemical vapor deposition has been investigated, and observed improvements in light transmittance and electrical conductivity suggest the potential to favorably modify graphene optical and electrical properties for these applications.

11:20am **GR+EM-TuM11 Stable Chemical Doping of Graphene: Transport, Raman Spectroscopy, SEM, and Transmittance Studies**, ***K. Berke***, *S. Tongay, M. Lemaitre, Z. Nasrollahi, D.B. Tanner, B.R. Appleton, A.F. Hebard*, University of Florida

Since becoming experimentally available by mechanical exfoliation, graphene has been used in various devices such as field effect transistors (FETs), Schottky based solar cells and sensing applications. Although graphene based devices with modest characteristics have been reported, in some of the device geometries a lower graphene sheet resistance with different Fermi level values is still desired. To achieve these ends, graphene's physical properties have been adjusted by *n*- or *p*- chemical doping using $AuCl_3$, Br_2, N_2, and organic solutions. However, these techniques have several drawbacks which prevent their use in devices, namely: environmental instabilities, aging effects and a reduction in optical transparency. Here, we describe our use of a hydrophobic organic complex dopant with strong electronegativity, tight bonding, environmental stability and high optical transmittance which is spin cast onto CVD-prepared graphene films. We observe a typical 75% reduction in sheet resistance upon chemical modification of the graphene. Resistance vs. temperature / magnetic field and Hall measurements imply that the modified graphene sheets are doped, and time-dependent resistance measurements show excellent stability. Using a Horiba Micro Raman instrument we confirm the doping of graphene sheets from the shifts in G and 2D peak positions and intensity ratios. We show transmittance and SEM characteristics of the graphene sheets before and after doping. The presented results may serve as a guide for modification of graphene's properties as desired for various applications.

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