

Tuesday Morning, October 29, 2013

Graphene and Other 2D Materials Focus Topic
Room: 104 B - Session GR+AS+EM+MI+MN-TuM

Optical, Magnetic, Mechanical and Thermal Properties of 2D Materials

Moderator: A.A. Balandin, University of California, Riverside, D. Gunlycke, Naval Research Laboratory

8:00am **GR+AS+EM+MI+MN-TuM1 Long-range Magnetic Order in a Purely Organic 2D Layer Adsorbed on Epitaxial Graphene**, M. Garnica, D. Stradi, S. Barja, F. Calleja, C. Diaz, M. Alcamí, N. Martín, A.L. Vazquez-de-Parga, F. Martín, R. Miranda, Universidad Autónoma de Madrid, Spain

Collective magnetic properties are usually associated to d or f electrons which carry the individual magnetic moments. Band magnetism in organic materials based on π electrons has remained an experimental challenge, in spite of rigorous predictions of a fully spin polarized ground state in half-filled flat band organic systems. Cryogenic Scanning Tunneling Microscopy (STM) and Spectroscopy in UHV and accurate Density Functional Theory (DFT) simulations show that isolated TCNQ molecules deposited on a monolayer of graphene epitaxially grown on Ru(0001) acquire charge from the substrate and develop a sizeable magnetic moment, which is revealed by a prominent Kondo resonance. The magnetic moment is preserved upon dimer and monolayer formation. The self-assembled 2D monolayer of magnetic molecules develops spatially extended spin-split electronic bands visualized in the real space by STM, where only the majority band is filled, thus becoming a 2D, purely-organic magnet whose predicted spin alignment in the ground state is visualized by spin-polarized STM at 4.6 K [1]. Since the added charge occupies spatially extended intermolecular bands with well-defined spin character, one might speculate that the TCNQ monolayer could act as a spin filter or 2D spin polarizer, adding magnetic functionalities to graphene by altering the spin polarization of a current flowing in graphene.

[1] M. Garnica et al, Nature Physics <http://dx.doi.org/10.1038/NPHYS2610> (2013)

8:20am **GR+AS+EM+MI+MN-TuM2 Graphene Thermal Properties and Applications for Thermal Management of Li-Ion Batteries**, P. Goli, S. Legedza, A.A. Balandin, University of California, Riverside

Graphene's superior intrinsic thermal conductivity, flat geometry, flexibility and demonstrated capability for integration with other materials make graphene very promising for thermal management applications [1-2]. The thermal conductivity of graphene flakes incorporated within different materials can degrade due to coupling to the adjacent layers and phonon scattering on defects and edges [2]. At the same time, the thermal conductivity of graphene and FLG in different composite materials can remain relatively high compared to conventional thin films [3]. A possibility of using a mixture of graphene and FLG as fillers in thermal interface materials (TIM) has also been demonstrated [4-5]. In this talk we report on a possibility of using graphene as a filler material in phase-change materials (PCMs) for thermal management of Lithium-ion batteries. Lithium-ion batteries are superior to other types of batteries owing to their high-energy storage density. However, their applications are limited due to strong self-heating effects coupled with the adverse effect of temperature on the battery life-time. Prior work on thermal issues in Li-ion battery packs has demonstrated that a passive thermal management system based on PCMs is a promising approach. The PCM thermal management uses the latent heat stored in the material as its phase changes over a small temperature range. However, PCMs typically have low thermal conductivity (below 1 W/mK at room temperature). They store heat from the batteries rather than transfer it outside. For this reason, the usefulness of PCM passive thermal management for the high-power Li-ion batteries is limited. We found that incorporation of graphene to the hydrocarbon-based PCM allows one to increase its thermal conductivity by more than two orders of magnitude while preserving its latent heat storage ability. A combination of the sensible and latent heat storage together with the improved heat conduction outside of the battery pack leads to a significant decrease in the temperature rise inside a typical Li-ion battery pack. The described combined heat storage – heat conduction approach can lead to a transformative change in thermal management of Li-ion and other types of batteries [6].

[1] A.A. Balandin, et al., Nano Lett., 8, 902 (2008); [2] A.A. Balandin, Nature Mat., 10, 569 (2011); [3] Z. Yan, G. Liu, J.M. Khan and A.A. Balandin, Nature Comm., 3, 827 (2012); [4] K.M.F. Shahil and A.A.

Balandin, Nano Lett., 12, 861 (2012); [5] V. Goyal and A.A. Balandin, Appl. Phys. Lett., 100, 073113 (2012); [6] For details, see at <http://ndl.ee.ucr.edu> [<http://ndl.ee.ucr.edu/>]

8:40am **GR+AS+EM+MI+MN-TuM3 Graphene Nano-Photonics and Carrier Dynamics**, F. Koppens, P.A. Gonzalez, ICFO - The Institute of Photonic Sciences, Spain **INVITED**

In this talk I will review the new and strongly emerging field of graphene nano-photonics. In particular, I will show how to exploit graphene as a host for guiding, switching and manipulating light and electrons at the nanoscale [1,2]. This is achieved by exploiting surface plasmons: surface waves coupled to the charge carrier excitations of the conducting sheet. Due to the unique characteristics of graphene, light can be squeezed into extremely small volumes and thus facilitate strongly enhanced light-matter interactions.

One particular example of these enhanced light-matter interactions is the non-radiative energy transfer from light emitters to graphene. We experimentally and theoretically quantified this energy transfer process and find that the emitter decay rate follows a universal distance-scaling relation and is enhanced by a factor 90 [3]. Additionally, I will discuss novel types of hybrid graphene photodetectors [4] and new exciting results on carrier dynamics and carrier multiplication in graphene. By studying the ultrafast energy relaxation of photo-excited carriers after excitation with light of varying photon energy, we find that electron-electron scattering (and thus carrier multiplication) dominates the energy relaxation cascade rather than electron-phonon interaction [5]. This singles out graphene as a promising material for highly efficient broadband extraction of light energy into electronic degrees of freedom, enabling a new class of high-efficiency optoelectronic and photovoltaic applications.

References

- [1] J. Chen, M. Badioli, P. Alonso-González, S. Thongrattanasiri, F. Huth, J. Osmond, M. Spasenović, A. Centeno, A. Pesquera, P. Godignon, A. Zurutuza, N. Camara, J. Garcia de Abajo, R. Hillenbrand, F. Koppens, "Optical nano- imaging of gate-tuneable graphene plasmons", Nature (2012)
- [2] F. Koppens, D. Chang, J. García de Abajo, "Graphene Plasmonics: A Platform for Strong Light–Matter Interactions", Nano Letters 11, 3370–3377 (2011).
- [3] L. Gaudreau, K. J. Tielrooij, G. E. D. K. Prawiroatmodjo, J. Osmond, F. J. Garcia de Abajo, and F. H. L. Koppens, "Universal Distance-Scaling of Non-radiative Energy Transfer to Graphene", Nano Letters 2012
- [4] G. Konstantatos, M. Badioli, L. Gaudreau, J. Osmond, M. Bernechea, P. Garcia de Arquer, F. Gatti, F. Koppens, "Hybrid graphene-quantum dot phototransistors with ultrahigh gain", Nature Nanotechnology (2012)
- [5] K.J. Tielrooij, J.C.W. Song, S.A. Jensen, A. Centeno, A. Pesquera, A. Zurutuza Elorza, M. Bonn, L.S. Levitov, and F.H.L. Koppens. Nature Physics (2012)

9:20am **GR+AS+EM+MI+MN-TuM5 Graphene Mechanics and NEMS Applications**, J.C. Hone, Columbia University **INVITED**

This talk will review collaborative efforts in characterizing the mechanical properties of graphene, and its application to nano-electromechanical devices (NEMS). We use nano-indentation of freely suspended membranes to measure mechanical properties. These measurements, when combined with nonlinear anisotropic continuum modeling, reveal that graphene is both ultrastiff (in-plane Young's modulus equivalent to 1 TPa) and the strongest known material (in-plane breaking strength equivalent to 100 GPa). Our recent work demonstrates that CVD-grown graphene, even in the presence of grain boundaries, can retain almost all of this intrinsic strength, opening the door to large-area high-strength films. For NEMS applications, we have developed techniques that allow fast, highly sensitive electronic readout. We are applying graphene NEMS to studies of fundamental physics in the quantum Hall regime and applications in electro-mechanical signal processing. In particular, I will discuss our recent work on graphene voltage controlled oscillators for generation of frequency modulated signals.

10:40am **GR+AS+EM+MI+MN-TuM9 Nano-plasmonic Phenomena in Graphene**, D.N. Basov, University of California San Diego **INVITED**

Infrared nano-spectroscopy and nano-imaging experiments have uncovered rich optical effects associated with the Dirac plasmons of graphene [Nano Lett. 11, 4701 (2011)]. We were able to directly image Dirac plasmons propagating over sub-micron distances [Nature 487, 82 (2012)]. We have succeeded in altering both the amplitude and wavelength of these plasmons by gate voltage in common graphene/SiO₂/Si back-gated structures. Scanning plasmon interferometry has allowed us to visualize grain

boundaries in CVD graphene. These experiments revealed that grain boundaries tend to form electronic barriers that impede both electrical transport and plasmon propagation. Our results attest to the feasibility of using electronic barriers to realize tunable plasmon reflectors: a precondition for implementation of various metamaterials concepts. Finally, we have carried out pump-probe experiments probing ultra-fast dynamics of plasmons in exfoliated graphene with the nano-scale spatial resolution.

11:20am **GR+AS+EM+MI+MN-TuM11 Controlled Growth of Large-Area Mono-, Bi-, and Few-Layer Graphene by Chemical Vapor Deposition on Copper Substrate**, *C.-Y. Park, Y. Kim*, Sungkyunkwan University, Republic of Korea

Direct synthesis of graphene using a chemical vapor deposition (CVD) has been considered a facile way to produce large-area and uniform graphene film, which is an accessible method from an application standpoint. Hence, their fundamental understanding is highly required. Unfortunately, the CVD growth mechanism of graphene on Cu remains elusive and controversial.

Here, we present the effect of graphene growth parameters on the number of graphene layers were systematically studied and growth mechanism on copper substrate was proposed. Parameters that could affect the thickness of graphene growth include the pressure in the system, gas flow rate, growth pressure, growth temperature, and cooling rate. We hypothesize that the partial pressure of both the carbon sources and hydrogen gas in the growth process, which is set by the total pressure and the mole fraction of the feedstock, could be the factor that controls the thickness of the graphene. The graphene on Cu was grown by the diffusion and precipitation mode not by the surface adsorption mode, because similar results were observed in graphene/Ni system. The carbon-diffused Cu layer was also observed after graphene growth under high CH₄ pressure. Our findings may facilitate both the large-area synthesis of well-controlled graphene features and wide range of applications of graphene.

11:40am **GR+AS+EM+MI+MN-TuM12 Charged Vacancy Defects in Graphene: Stability and Charge States**, *Y. Liu, M. Weinert, L. Li*, University of Wisconsin Milwaukee

We perform atomic resolution imaging of vacancy defects in graphene using non-contact atomic force microscopy, and directly determine their charges by local contact potential difference measurement. We observe reconstruction, healing, and merging of vacancy defects. Combined with first-principles calculations, we further show that vacancy defects are typically positively charged, while H adsorbates at these sites can produce negatively charged structures, and their charge states are not necessarily integer-valued. These results provide new insights into the stability of charged vacancy defects in graphene, as well as the functionalization of graphene for chemical sensing and catalysis, and underline the tunability of these functions by controlling the size and doping of vacancy defects.

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