Graphene Topical Conference
Room: C3 - Session GR+MI-WeM

Spins in Graphene: Injection and Manipulation
Moderator: O.M.J. van 't Erve, Naval Research Laboratory

8:20am **GR+MI-WeM2 Graphene Extraordinary Magnetoresistive Devices**, ***S. Pisana***, *P.M. Braganca,* Hitachi GST, *M. Pelliccione,* Stanford University*, M. Nishioka, N. Smith, E.E. Marinero, B.A. Gurney*, Hitachi GST

Extraordinary magnetoresistance (EMR) has recently attracted interest for magnetic field sensing applications in the magnetic storage industry [1]. The effect is particularly attractive given the magnitude of its response, which is comparable to current giant magnetoresistive sensors for mesoscopic device sizes, and its lack of thermal magnetic noise, as the structure does not incorporate ferromagnetic materials. EMR devices consist of hybrid semiconductor-metal structures in which the exclusion of current from a metal shunt in a magnetic field modulates the resistance of the device. This functionality can be advantageously combined with the Hall effect with appropriate variations in the device's lead configuration [2].

The EMR response is proportional to the semiconductor's mobility, among other factors. Furthermore, the successful implementation of this type of device for future read sensors in magnetic storage applications restricts the sensing element's position within a few nanometers from the source of magnetic field.

Graphene, a single atom-thick layer of graphite, is a promising electronic material, given its high mobility, high current carrying capabilities and linearly dispersive electronic bands [3]. These qualities make it a promising candidate for magnetic field sensing in an EMR device, allowing for the conceptually smallest magnetic spacing in a structure that is free from thermal magnetic noise.

In this work, we outline the first implementation of graphene EMR devices. We will discuss their mesoscopic fabrication and demonstrate response that is comparable to current magnetic field sensors. Devices with minimum feature of 150 nm (Figure 1) show signals above 2 mV in magnetic fields of 350 Oe at room temperature. The results are summarized in the context of future magnetic field sensors for terabit density data storage.

[1] Solin, S. A.; Thio, T.; Hines, D. R. & Heremans, J. J.; Science **289**, 1530 (2000)

[2] Boone, T. D.; Smith, N.; Folks, L.; Katine, J. A.; Marinero, E. E. & Gurney, B. A.; IEEE Electron Device Letters **30**, 117 (2009)

[3] Geim, A. K. & Novoselov, K. S.; Nature Materials **6**, 183 (2007)

8:40am **GR+MI-WeM3 Electronic Spin Transport and Spin Precession in Single Graphene Layers at Room Temperature**, *B.J. van Wees,* ***N. Tombros***, University of Groningen, the Netherlands **INVITED**

I will give an overview of electron spin injection, spin transport, spin precession and spin manipulation in graphene. The focus will be on recent experiments on single graphene field effect devices with ferromagnetic contacts. The use of the so-called non-local geometry allows a detailed investigation of various aspects of spin injection and spin transport.

I will first give a basic introduction into the "standard model" for spin transport and show how it can be applied to carbon systems, in particular graphene. The Bloch equations will be explained, which describe the processes of spin diffusion, drift, precession and relaxation. Following that will discuss that:

a) Spins can be transported through a graphene layer with a spin relaxation length of about 1.5 micrometer. By applying a perpendicular magnetic field Hanle spin precession can be studied and information about spin relaxation and the carrier diffusion can be obtained [1].

b) By applying a large DC electric field the transport of spins between injector and detector can be manipulated (sped up or slowed down) using carrier drift [2].

c) The spin relaxation is found to be slightly anisotropic, with spins directed perpendicular to the graphene plane relaxing faster than spins directed in the plane [3].

d) Spins can be injected into graphene with an injection efficiency up to 20 percent. This injection efficiency can be enhanced by a current bias which takes the carriers away from the injecting contacts. In this way injection efficiencies up to 38% have been achieved [4].

e) We have observed a scaling between the spin relaxation times and lengths and the carrier mobility in graphene [5,6]. I will discuss the possibility that in intrinsic graphene (where the carriers are only scattered by electron-phonon interaction) spin relaxation lenghts of 100 micrometer in graphene at room temperature might be possible, and even longer ones at lower temperatures. Related to that I will discuss the potential of graphene for future spintronics applications.

[1] N. Tombros et al., Nature 448, 571 (2007)

[2] N. Tombros et al., Phys. Rev. Lett. 101, 046601 (2008)

[3] C. Jozsa et al., Phys. Rev. Lett. 100, 236603 (2008)

[4] C. Jozsa et al., Phys. Rev. B 79, 081402 R (2009)

[5] M. Popinciuc et al., submitted to Phys. Rev. B.

[6] C. Jozsa et al, in preparation.

9:20am **GR+MI-WeM5 Quantum Hall Effect in Suspended Graphene Devices**, ***S.Y. Jung****, N.N. Klimov,* NIST and University of Maryland, College Park, *J.A. Stroscio, D.B. Newell, N.B. Zhitenev*, National Institute of Standards and Technology

High carrier mobility and long coherence lengths are one of the main attributes which have attracted so much attention to graphene as a new electronic material. Recent studies have shown that the mobility in graphene is extremely sensitive to disorder, particularly coming from substrate interactions [1]. Substrate interactions can be minimized or possibility eliminated by fabricating suspended graphene devices [2]. In this presentation, we present results where we systematically study the quantum Hall effect in suspended graphene devices varying device geometry and disorder. Suspended graphene devices allow for a broad range of particular realizations of the disorder potential. Magnetotransport properties are investigated at various temperatures and with respect to the influence of current annealing. Device geometries with two- and four-probe terminals and different aspect ratios are compared and the effects of disorder potential modifications are discussed.

[1]. J. Martin et al, Nature Phys. **4**, 144 (2008).

[2]. K. I. Bolotin et al, Phys. Rev. Lett. **101**, 096802 (2008).

9:40am **GR+MI-WeM6 Spin Injection and Transport in Single Layer Graphene**, ***W. Han*****, K. Pi, K. McCreary, W. Bao, C.N. Lau, R. Kawakami*, University of California, Riverside

Single-layer graphene (SLG) is an attractive material for spintronics due to its tunable carrier concentration and polarity, weak spin-orbit coupling, its quasi-relativistic band structure with symmetric electron and hole bands. We fabricated the SLG spin valves using transparent Co/SLG contacts and studied the spin dependent properties by non-local magnetoresistance (MR) measurements at room temperature. Hanle effect confirms that the non-local signal originates from spin injection and transport and gives a spin relaxation time of ~84 ps and a spin diffusion length of ~1.5 μm. Spacing dependence of the non-local MR indicates a spin diffusion length of ~1.6 μm and a spin injection/detection efficiency of 0.43. Gate voltage dependence shows that the non-local MR is proportional to the conductivity of the SLG, which is the predicted behavior for transparent ferromagnetic/nonmagnetic contacts. Bias dependence of the non-local MR reveal an electron-hole asymmetry in which the non-local MR is roughly independent of bias for electrons, but varies significantly with bias for holes.

10:40am **GR+MI-WeM9 Spin Polarized Electrons in Graphene Nanoribbons**, ***Y.-W. Son***, Korea Institute for Advanced Study, Korea **INVITED**

In this talk, I will discuss the electronic and magnetic properties of graphene nanoribbons with homogeneous edge structures. Several calculation methods including self-energy corrections and/or strong Coulomb interactions are introduced to study magnetic orderings and their robustness along the zigzag shaped edges on both sides of graphene nanoribbons. I will also discuss special interplays between external electric fields and magnetic orderings in graphene nanoribbons and a possible realization of half-metallic phase in conventional experimental setups with various substrates or molecular adsorptions.

***** Falicov Student Award Finalist

11:40am **GR+MI-WeM12 Observation of Charge Puddles and Edge Effect in a Graphene Device by Scanning Gate Microscope**, ***J.S. Chae***, Seoul National University, Korea, *S.Y. Jung, N.B. Zhitenev, J.A. Stroscio*, National Institute of Standards and Technology, *Y. Kuk*, Seoul National University, Korea

Despite the recent progress in understanding the geometric structure of defects and edge atoms and their role in the transport property in a graphene sheet, there has been no report showing direct correlation between them. That is because the structural studies were performed using microscopic tools such as scanning tunneling microscopy and other electron microscopies, while the transport property measurement was done macroscopically in a two or four terminal device with a back gate. Scanning Gate Microscope (SGM) is a unique microscopic tool with which the local electronic structure and the transport property of a device can be measured simultaneously. A SGM uses a conducting tip to apply an electric field locally and measures the transport current through two or four contacts and utilizes the same tip to measure the geometric structure in Atomic Force Microscopy (AFM) mode. In this experiment, we observed a conductance change originated from the spatial distribution of charge puddles with a length scale of ~ 100nm in a graphene device, very similar to the previously reported results[1)] measured with AFM with a single electron transistor tip. We discovered that the charge puddles can be detected only when the local Fermi level of a gated area by the tip bias is near the Dirac point. We also discovered that there is strong conductance enhancement when the tip is placed along the edges of a graphene device. We think that this edge effect can be explained by the fact that there is a strong charge accumulation at the edges in a charged graphene[2)]

1) J. Martin, N. Akerman, G. Ulbricht, T. Lohmann, J. H. Smet, K. von Klitzing & A. Yacoby, Nature Physics, **4**, 144 (2008)

2) P.G. Silvestrov and K.B. Efetov, Phys. Rev. B **77**, 155436(2008)

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