Magnetic Interfaces and Nanostructures
Room: 202 A - Session MI+EM-TuM

Spintronics and Magnetoelectrics
Moderator: P. Fischer, Lawrence Berkeley National Laboratory, M. Donath, Muenster University, Germany

8:00am **MI+EM-TuM1 Molecular Beam Epitaxy and Spintronics**, ***S. Andrieu***, *F. Bonell, T. Hauet,* Institut Jean Lamour, CNRS-Université de Lorraine, France, *F. Bertran*, Synchrotron SOLEIL, France **INVITED**

The growth and control of thin magnetic films has enabled the emergence of new branches of physics like nanomagnetism and spintronics, which stimulate an intense and successful research activity both in fundamental and applied directions. The reduced size of films and devices yields to the occurrence of new magnetic behaviors not present in bulk materials. Similarly, a new electronics based on the use of the spin of the electron was born in the 80's. The role of the Molecular Beam Epitaxy (MBE) was of prime importance in the development of these activities. The discovery of new phenomena was often highlighted from the synthesis of perfectly controlled systems by MBE (GMR in Fe/Cr(001), Half-metal magnetic effect in $LaSrMnO_3$, electric-field effect on magnetic anisotropy in FePt,…). Since the knowledge on the electronic properties of such thin films is crucial to understand the magnetic and electronic transport properties in these MBE-grown model systems, synchrotron radiation facilities were also used (XMCD, spin- and symmetry-resolved photoemission, diffraction,…). The strong impact of MBE growth and SR characterization in the understanding of fundamental issues in nanomagnetism and spintronics is then illustrated through the example of fully epitaxial MgO-based Magnetic Tunnel Junctions (MTJs). The physics of coherent tunneling will be first introduced using the example of Fe/MgO/Fe(001) MTJs [1]. The effect of dislocations in the MgO barrier on transport properties will be illustrated using the example of FeV_x/MgO MTJs [2]. Unexpected transport properties in $FeCo_x$/MgO will be presented and explained with the help of spin and symmetry resolved photoemission [3]. Finally, very recent results will be presented, like manipulation of the magnetic anisotropy at the Fe/MgO interface using an electric field [4], or insertion of the Half-metallic ferromagnetic $(CoFe)_3Ge$ in MgO-based MTJs.

[1] - C. Tiusan et al, J. Phys.Cond. Mat. 19, 165201, (2007)

[2] - F. Bonell et al, Phys. Rev. B, 82, 092405 (2010)

[3] - F. Bonell et al, Phys. Rev. Lett., 108, 176602 (2012)

[4] – C-H. Lambert et al, Appl. Phys. Lett. 102, 122410 (2013) and A. Rajanikanth et al, (2013), submitted

8:40am **MI+EM-TuM3 Engineering Single Spins in Semiconductors for Sensing and Computation**, ***D. Awschalom***, University of California, Santa Barbara, *W.F. Koehl, A.L. Falk,* University of Chicago, *G. Calusine,* University of California, Santa Barbara, *F.J. Heremans,* University of Chicago, *V.V. Dobrovitski,* Ames Laboratory, Iowa State University, *A. Politi*, University of California, Santa Barbara **INVITED**

Semiconductor defects, while generally considered undesirable in traditional electronic devices, can confine isolated electronic spins and are promising candidates for solid-state quantum bits (qubits) [1]. Alongside research efforts focusing on nitrogen vacancy (NV) centers in diamond, an alternative approach seeks to identify and control new spin systems with an expanded set of technological capabilities, a strategy that could ultimately lead to "designer" spins with tailored properties for future quantum information processing. We discuss recent experimental results identifying such spin systems in the 4H, 6H, and 3C crystal polymorphs of silicon carbide (SiC) [2,3]. Using infrared light at near-telecom wavelengths and gigahertz microwaves, we show that these spin states can be coherently addressed at temperatures ranging from 20 K to room temperature. Long spin coherence times allow us to use double electron-electron resonance to measure magnetic dipole interactions between spin ensembles in inequivalent lattice sites of the same crystal. Since the inequivalent spin states have distinct optical and spin transition energies, these interactions could lead to engineered dipole-coupled networks of separately addressable qubits. Together with the availability of industrial scale crystal growth and advanced microfabrication techniques for SiC, these results make this system a promising platform for photonic, spintronic, and quantum information applications that merge quantum degrees of freedom with classical electronic and optical technologies.

This work is funded by the AFOSR and DARPA.

[1] J. R. Weber, W. F. Koehl, J. B. Varley, A. Janotti, B. B. Buckley, C. G. Van de Walle, and D. D. Awschalom, *Proc. Natl Acad. Sci. USA***107**, 8513 (2010).

[2] W. F. Koehl, B. B. Buckley, F. J. Heremans, G. Calusine, and D. D. Awschalom, *Nature***479**, 84 (2011); A. Dzurak, *Nature* **479**, 47 (2011).

[3] A. L. Falk, B. B. Buckley, G. Calusine, W. F. Koehl, V. V. Dobrovitski, A. Politi, C. A. Zorman, P. X.-L. Feng, and D. D. Awschalom, *Nature Comm.* **4**, 1819 (2013).

9:20am **MI+EM-TuM5 Semiconductor Spintronics -- New Avenues and Perspectives: Graphene as a Spin Tunnel Barrier in MTJs and Silicon**, ***B.T. Jonker***, *E. Cobas, O.M.J. van 't Erve, C.H. Li, A.L. Friedman, J.T. Robinson*, Naval Research Laboratory **INVITED**

Graphene has been widely studied for its high in-plane charge carrier mobility and long spin diffusion lengths. In contrast, the out-of-plane charge and spin transport behavior of this atomically thin material have not been well addressed. Tunnel barriers are the basis for many spintronic devices, and to date have relied upon oxides which often exhibit defects, trap states and interdiffusion which compromise performance and reliability. We show here that while graphene exhibits metallic conductivity in-plane, it serves effectively as an insulator for transport perpendicular to the plane. We fabricate magnetic tunnel junctions, and demonstrate electrical spin injection/detection in silicon using graphene as a tunnel barrier.

The graphene was grown by chemical vapor deposition on copper foil and incorporated as the tunnel barrier by physical transfer and standard lithographic processes to form Co / graphene / NiFe magnetic tunnel junctions (MTJs) 20-40 um in diameter [1]. Non-linear *I-V* curves and weak temperature dependence of the zero-bias resistance provide clear evidence for tunneling. The magnetic field dependence exhibits the classic signature of MTJ behavior, and the structures exhibit tunneling magnetoresistance (TMR) to 425 K, in good agreement with theory [2]. The TMR decreases monotonically with both bias and temperature, typical of MTJ behavior.

Single-layer graphene also successfully circumvents the classic issue of conductivity mismatch between a metal and a semiconductor for electrical spin injection and detection, providing a highly uniform, chemically inert and thermally robust tunnel barrier. Hanle spin precession measurements demonstrate spin injection and provide quantitative values for spin lifetimes. Devices with NiFe / single layer graphene / Si contacts exhibit the classic Lorentzian lineshape due to spin injection and dephasing. We demonstrate electrical generation and detection of spin accumulation in silicon above room temperature, and show that *(a)* the corresponding spin lifetimes correlate with the silicon carrier concentration, and *(b)* the contact resistance–area products are two to three orders of magnitude lower than those achieved with oxide tunnel barriers on silicon substrates with identical doping levels [3]. This reduction of contact resistance enables spin injection and quantitative measurements of spin lifetimes in silicon nanowires, as well.

[1] Cobas, Friedman, van't Erve, Robinson, Jonker, *Nano Letters* **12**, 3000 (2012).

[2] Karpan et al, *Phys. Rev. Lett*. **99**, 176602 (2007); *Phys. Rev*. B **78**, 195419 (2008).

[3] van't Erve, Friedman, Cobas, Li, Robinson, Jonker, *Nature Nanotechnology* **7**, 737(2012).

10:40am **MI+EM-TuM9 Graphene Direct Growth on Magnetic Oxides on Co(0001): Graphene Effects on Oxide Magnetic Behavior**, *F. Paquale, Y. Cao, H. Kasi, S. Gaddam,* University of North Texas, *L. Kong, Y. Wang, C. Binek, P.A. Dowben,* University of Nebraska-Lincoln, ***J. Kelber***, University of North Texas

The direct growth of graphene on thin (< 50 Å) magnetic oxides on cobalt or other ferromagnetic substrates (Gr/oxide/Co) presents interesting opportunities for development of practical magnetic and magnetoelectric graphene devices. We have grown single and few layer graphene (Gr) directly on Co_3O_4(111)/Co(0001) by MBE, and have very recently grown graphene by e-beam-assisted deposition on Cr_2O_3(0001)/Co(0001). XPS data demonstrate the presence of a sp^2-indicative $\pi \rightarrow \pi^*$ shakeup feature but with C(1s) peak binding energies of 284.9 (±0.2) eV for Gr/Co_3O_4(0001) -- significantly larger than the 284.5 eV value common for graphitic systems. This indicates significant graphene-to-oxide charge transfer. LEED images yield the expected C_{6v} symmetry and 2.5(±0.1) Å lattice spacing for graphene, with a 2.8(±0.1) Å O-O distance at the oxide surface. All are consistent with the literature and indicate incommensurate graphene/oxide interfaces. Domain sizes of ~ 1800 Å are estimated from the LEED data for Gr/Co_3O_4(111), comparable to HOPG. 3 monolayer (ML)

$Gr/Co_3O_4(111)/Co(0001)$ exhibits room temperature resistivity 10^2-10^3 times smaller than for graphene transferred to other substrates, and consistent with strong p-type doping, as indicated by XPS. Magneto-optic Kerr effect (MOKE) results demonstrate the presence of antiferromagnetic (AF) ordering for the $Gr/Co_3O_4(111)/Co(0001)$ heterostructures up to at least 420 K, with evidence of exchange interaction effects as well. No antiferromagnetic polarization is observed for Co_3O_4/Co films in the absence of graphene, indicating a role played by graphene in the magnetic ordering of the oxide. These results indicate the potential suitability of such films for non-local spin valves and similar devices operating at realistic device temperatures. This talk will also present results for on-going MOKE and transport measurements on graphene/Cr_2O_3/Co(0001) samples. The ability to apply both magnetic and electric fields to such stacks provides the potential for magnetoelectric spin-transistors and tunneling devices.

Acknowledgement: This work was supported by the Semiconductor Research Corporation under Task ID 2123.001 and by C-SPIN, a STARnet center, a Semiconductor Research Corporation program sponsored by MARCO and DARPA.

11:00am **MI+EM-TuM10 Nanocluster Size Effects in Au-Co Nanocomposite Thin Films: Correlated Non-linear Magneto-Optics and Magneto-Transport Studies**, ***K. Yang***, The College of William and Mary, *V. Kryutyanskiy, I. Kolmychek, T. Murzina,* Moscow State University, Russian Federation, *R.A. Lukaszew*, The College of William and Mary

Magnetic materials in nanometer scale typically exhibit significant different magnetic and magnetic-optical properties compared to bulk materials. Composite thin films with magnetic metal clusters embedded in a non-magnetic metal matrix offer a tailored self-assembled nanoscale platform to investigate magneto-optical and magneto-transport properties and possible correlations between them in constrained geometries. The magnetic clusters size as well as the overall composite thin film thickness can be tailored via adequate deposition conditions to achieve a viable nanocluster binary system. We have previously shown that Au/Co/Au trilayers as well as Au-Co nanocomposite thin films exhibit strong enhancement of the linear magneto-optical properties under surface plasmon polariton excitation. [1] Based on these previous results on linear optics measurements, we investigate now the non-linear optical properties such as second harmonic generation (SHG) as well as the magneto-transport properties in Au-Co nanocomposite thin films. Optical SHG is a sensitive probe of surface and buried interfaces due to inversion symmetry breaking at the interfaces of center-symmetric materials which allows probing structural and morphological properties near interfaces. Here we observe a non-monotonous dependence of the SHG magnetic contrast on the cobalt content in Au-Co films, which reveals a sharp increase close to the transition from a granular-like type structure with Co clusters embedded in gold, to an interconnected composite structure when percolation of the cobalt clusters sets in. We also find a SHG enhancement for Co fractional content of 0.35, within the granular structure regime, that can be associated with localized surface plasmon resonance as well as with local field enhancement in an inhomogeneous composite. Furthermore, the magneto-transport measurement (i.e. the magneto-resistance, MR) properties of the Au-Co composite thin films follow similar trend as a function of Co content as the non-linear SHG magnetic contrast before percolation and dramatically deviate once percolation sets in. Thus, our correlated SHG-MR results in Au-Co nanocomposite thin films with varying Co content will be presented and discussed.

[1]. K. Yang et al. Journal of Applied Physics **107**, 103924 (2010)**;** C. Clavero, K. Yang, J. R. Skuza, and R. A. Lukaszew, Optics Express **18**, 7743 (2010).

11:20am **MI+EM-TuM11 Spin and Heat Transport through Interfaces between Metals and Magnetic Insulators**, ***G.E.W. Bauer***, Tohoku University, Japan **INVITED**

Spin caloritronics is the science and technology of the physical phenomena (and their control) associated with the coupling of charge, spin, and heat currents in nanoscale structures and devices [1]. Bilayers of magnetic insulators and normal metals have attracted interest in this field because they display the spin Seebeck effect, i.e. the generation of a spin motive force by an applied temperature difference over the interface. In this talk I will address the theory and applications of power and voltage generation by thermally excited magnetization dynamics at the interface of a magnetic insulator such as yttrium iron garnet (YIG) and normal metals such as platinum.

[1] G.E.W. Bauer, E. Saitoh & B. J. van Wees, Nature Materials 11, 391–399 (2012)

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