Wednesday Morning, November 11, 2009

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.

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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)

Magnetic Interfaces and Nanostructures
Room: C1 - Session MI+EM-WeA

Magnetism and Spin Injection in Semiconductors
Moderator: Y.D. Park, Seoul National University, South Korea

2:00pm **MI+EM-WeA1 Anomalous Nernst Effect in $Ga_{1-x}Mn_xAs$ Ferromagnetic Semiconductors**, ***J. Shi***, University of California, Riverside **INVITED**

The origin of the anomalous Hall effect (AHE) in ferromagnets has been a subject of long-standing debate. Dilute magnetic semiconductors (DMS) provide an excellent test ground for clarifying the issues. In our study, we engineered a series of GaMnAs thin films with different doping levels and with perpendicular magnetic anisotropy which allows us to investigate both electrical and thermoelectric transport properties at zero magnetic field. Both Seebeck and Nernst coefficients (S_xx and S_xy) were measured simultaneously with the longitudinal and transverse resistivities (rho_xx and rho_xy). In addition to an usually large spontaneous or anomalous Nernst effect (ANE), we also found that both AHE and ANE arise from the same physical origin. When the temperature is varied, although the sign of AHE (rho_xy) remains unchanged, the sign of ANE (S_xy) switches at an intermediate temperature below Tc. Furthermore, we found that the same Mott relation which links the electrical conductivity and thermoelectric coefficients works very well for the anomalous transport. A simple Mott relation analysis rules out the extrinsic skew-scattering mechanism immediately with the sign change in S_xy. A further quantitative analysis of the overall temperature dependence yields exponent n=2 in rho_xy ~ rho_xx^n, indicating that the intrinsic spin-orbit effect is likely responsible for both AHE and ANE.

2:40pm **MI+EM-WeA3 Local Structure of Cr in the Epitaxial Ferromagnetic Semiconductor Cr-doped Ga_2Se_3/Si (001)**, ***E. Yitamben****, *T.C. Lovejoy, A. Pakhomov*, University of Washington, *S. Heald*, Argonne National Laboratory, *F.S. Ohuchi, M.A. Olmstead*, University of Washington

The III-VI compound Ga_2Se_3 is an intrinsic vacancy semiconductor which not only can be grown epitaxially on silicon, but, once doped with a transition metal, presents interesting potential for application in spintronics devices, since we have found it to be ferromagnetic at room temperature. Unlike III-V or II-VI materials, the intrinsic vacancies in Ga_2Se_3 create both multiple sites for dopant incorporation, raising the possibility of separate control of magnetic and carrier doping, and anisotropic band-edge states, which may increase both the Curie temperature and the magnetic anisotropy. This work presents experimental investigations of Cr-doped Ga_2Se_3 epitaxially grown on Si(100):As that probe interactions among structure, carriers and magnetism in this new class of dilute magnetic semiconductors.

Inclusion of a few atomic percent Cr into the Ga_2Se_3 lattice results in laminar semiconducting films that are ferromagnetic at room temperature, with a magnetic moment of 4 μ_B per Cr in 6 nm films, and 40% lower in 20 nm films. X-ray absorption and photoemission measurements reveal Cr in an octahedral environment; X-ray and low energy electron diffraction reveal a cubic structure with lattice constant close to that of the underlying silicon. This is surprising, since both the vacancies and Ga cations occupy tetrahedral sites in pure Ga_2Se_3.

Above ~6%, scanning tunneling microscopy (STM) reveals the formation of islands within trenches whose shape and size depend on the Cr concentration and whether or not a Ga_2Se_3 buffer layer is deposited first. The islanded films also exhibit room temperature ferromagnetism, though with about half the magnetic moment per Cr. Unlike low concentration films, they are metallic rather than semiconducting.

Acknowledgments: This work is funded by the NSF Grant DMR-0605601, NSF NER-0508216

3:00pm **MI+EM-WeA4 Ferromagnetism in Gd- and Si-co-implanted GaN**, *R. Davies, B. Gila,* ***C. Abernathy***, *S.J. Pearton, C. Stanton*, University of Florida

Ion implantation has been studied as a magnetic ion incorporation method in semiconductor materials for spintronic applications due to excellent control over the amount of the implanted ion and the resultant magnetic properties of the implanted material. GaN thin films grown via metal-organic chemical vapor deposition (MOCVD) were co-implanted with Gd^+ ions with an energy of 155 keV and dose of 2.75×10^{10} cm^{-2} and Si^{4+} ions with energies of 5 keV and 40 keV and corresponding doses of 8×10^{11} cm^{-2} and 3.6×10^{12} cm^{-2}. Before annealing, x-ray diffraction measurements revealed that the implanted GaN thin films exhibited no secondary phase formation or clustering effects attributable to Gd. Superconducting quantum interference device (SQUID) magnetometer measurements indicated that a Gd- and Si-co-implanted GaN thin film exhibited about an order of magnitude higher magnetic moment than a Gd-implanted GaN thin film. Both of these thin films displayed ferromagnetic ordering and Curie temperatures above room temperature. The co-implanted GaN thin film also demonstrated a larger magnetic moment than a Gd- and Si-co-doped GaN thin film grown via molecular beam epitaxy (MBE) while possessing a smaller Gd concentration. The orientation of the applied magnetic field with respect to the thin film surface was seen to have an effect on the measured magnetic properties of the thin films. This orientation dependence may help elucidate the relationship between the defects produced by the implantation process and the ferromagnetic ordering exhibited by these materials.

4:00pm **MI+EM-WeA7 Structural and Electronic Properties of EuO and Gd-doped EuO Films Prepared Via Pulsed Laser Deposition**, *X. Wang, K. Fox, W. Wang,* ***J. Tang***, University of Wyoming, *M.J. An, K. Belashchenko, P.A. Dowben*, University of Nebraska-Lincoln

Methods to prepare EuO thin films reported in the literature include reactive thermal evaporation of Eu in the presence of oxygen gas and molecular beam epitaxy (MBE). We have successfully prepared single phase polycrystalline and epitaxially grown EuO and Gd-doped EuO via pulsed laser deposition (PLD) using metal targets. This opens a new route to the preparation of this interesting material with high quality. Samples prepared in vacuum exhibit the typical M(T) curve for a ferromagnet and have a Curie temperature of 70 K. When the samples were grown under ultrahigh purity H_2 flow, they show the "double-dome" feature characteristic of oxygen deficient EuO. Tc as high as 150 K has been observed for EuO. The increased Curie temperature is attributed to the magnetic coupling enhanced by the 4f-5d coupling between the Eu moments and doped electrons. Our results reaffirm that oxygen vacancies alone can substantially increase the Tc. Calculations on the phase diagram (for Gd+EuO), the effects of oxygen vacancies and associated band structures and density of states will be presented.

4:20pm **MI+EM-WeA8 Magnetic Molecules on GaN: A Low Temperature STM Investigation**, ***K. Clark***, *D. Acharya, V. Iancu, E. Lu, A. Smith, S.-W. Hla*, Ohio University

Spin electron interactions involving magnetic molecules and semiconductor surfaces are of great interest for the development of molecular spintronic devices. Due to its wide range of applications, GaN (0001) surface has received a special attention for the development of novel electronic devices. Here, we studied electronic and structural properties of TBrPP-Co molecules deposited on a freshly grown nitrogen polar GaN (0001) surface using a scanning tunneling microscopy and spectroscopy at 4.6 K under an ultra-high-vacuum condition. The TBrPP-Co molecule has a spin-active cobalt atom caged at the center of porphyrin unit and four bromo-phenyl groups are attached to its four corners. On GaN(0001), the molecules bind the surface via two molecular conformations: saddle and planar. In saddle conformation, the central part of the molecule is bent by lifting the two pyrrole units of the porphyrin macrocycle. STM images shows various self-assembled clusters of molecules on GaN(0001) surface. Within the self-assembled molecular clusters, the molecules are aligned either parallel or 90 degree rotated to each other. In the presentation, we will discuss the spin-electron coupling of this molecule-surface system. This work is supported by the Ohio University BNNT, NSF-PIRE: OISE 0730257, NSF-EMT: CCF-0622158, and the United States Department of Energy, DE-FG02-02ER46012 grants.

4:40pm **MI+EM-WeA9 Electrical Injection, Detection and Modulation of Spin Currents in Silicon**, ***O.M.J. van 't Erve***, *C. Awo-Affouda, A.T. Hanbicki, M.A. Holub, C.H. Li, P.E. Thompson, B.T. Jonker*, Naval Research Laboratory **INVITED**

The electron's spin angular momentum is one of several alternative state variables under consideration on the International Technology Roadmap for Semiconductors for processing information in the fundamentally new ways. Significant progress has recently been made on spin injection into the technologically important semiconductor, Si, using vertical device structures. Here we will present the electrical injection, detection and magnetic field modulation of lateral diffusive spin transport through silicon using Fe/Al2O3 surface contacts. The tunnel contacts are used to create and

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analyze the flow of pure spin current in a silicon transport channel. A nonlocal detection technique has been used to exclude spurious contributions from AMR and local Hall effects. The nonlocal signal shows that a spin current can be electrically detected after diffusive transport through the silicon transport channel and the signal depends on the relative orientation of the magnetization of the injecting and detecting contacts. Hanle effect measurements up to 125 K demonstrate that the spin current can be modulated by a perpendicular magnetic field, which causes the electron spin to precess and dephase in the channel during transport. By changing the bias on the injector contact we can either inject or extract spin from the Silicon channel. Here we will show using Hanle and lateral spin-valve measurements that we can change the polarization of the spin accumulation by going from the injection regime to the extraction regime and we will compare the efficiency of spin-injection versus spin extraction.

The realization of efficient electrical injection and detection using tunnel barriers and a simple device geometry compatible with "back-end" Si processing should greatly facilitate development of Si-based spintronics.

This work was supported by ONR and core NRL programs.

5:20pm **MI+EM-WeA11 Order From Chaos: α-Fe(001)/GaAs(001)**, ***J.G. Tobin***, *S.W. Yu*, Lawrence Livermore National Laboratory, *S.A. Morton*, Lawrence Berkeley National Laboratory, *G.D. Waddill*, Missouri University of Science and Technology, *J.D.W. Thompson, J.R. Neal, M. Spangenburg, T.H. Shen*, University of Salford, UK

For many years, the technological possibilities of spintronic or magneto-electronic devices [1], particularly when coupled with potentially pure spin sources such as half-metallic ferro-magnets, [2] have engendered great interest. Despite the limitations encountered in such potential sources [3], there is still ample reason to pursue such concepts. This is because, in part, even with sources that operate below 100% polarization, technologically important devices should emerge. [1] However, the challenges of device integration remain significant even for cases with lowered expectations, because often the physical realities of intermixing, disorder and alloying can creep into the attempts to fabricate structures based upon ideal conceptual designs. Within this context, ferromagnetic-semiconductor interfaces are potentially important for the future applications of spintronic devices. One possibility for a room temperature spin injector is Fe/GaAs. The growth of Fe upon GaAs(001) has been studied with Photoelectron Spectroscopy (PES), including Spin-Resolved PES . Despite evidence of atomic level disorder such as intermixing, [4] an over-layer with the spectroscopic signature of α-Fe(001), with a bcc real space ordering, is obtained. The results will be discussed in light of the possibility of using such films as a spin polarized source in device applications. Lawrence Livermore National Laboratory is operated by Lawrence Livermore National Security, LLC, for the U.S. Department of Energy, National Nuclear Security Administration under Contract DE-AC52-07NA27344. Work that was performed by UMR personnel was supported in part by the Office of Basic Energy Science at the U.S Department of Energy. Work that was performed by LLNL personnel was supported in part by the Office of Basic Energy Science at the U.S Department of Energy and Campaign 2 of WCI at LLNL. We would also like to thank J.A.D. Matthew, D. Greig, A.E.R. Malins, E.A. Seddon, and M. Hopkinson for their help with this project.

References

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3. P. Dowben, J. Phys. Condensed Matter 19, 310301 (2007).
4. J.D.W. Thompson, J.R. Neal, T.H. Shen, S.A. Morton, J.G. Tobin, G.D. Waddill, J.A.D. Matthew, D. Greig, and M. Hopkinson, J. Appl. Phys. 104, 024516 (2008) and references therein.

5:40pm **MI+EM-WeA12 Enhancement of Spin Injection Efficiency by Interface Modification for Fe and $Fe_{31}Co_{69}$ Thin Films on GaAs(001)**, ***S.F. Alvarado***, *G. Salis, A. Fuhrer, L. Gros, R.R. Schlittler*, IBM Zurich Research Laboratory, Switzerland

We report on a detailed study of the influence of ferromagnet/semiconductor interface modifications on the electrical spin injection efficiency of Fe and $Fe_{31}Co_{69}$ thin film electrodes into the GaAs(001) surface. These modifications are induced by: a) Varying the As/Ga surface concentration of GaAs(001); and b) Post-growth annealing of the ferromagnetic thin films. Electrical spin injection experiments are carried out in a non-local device geometry at temperatures between 2.5 and 300 K. Devices were fabricated by means of either optical, e-beam, or nanostencil lithography. Non-local spin signals in the range of 2V/A at a temperature of 5K have been detected between two strip electrodes, one 2 and the other 6 μm in width, 60 μm long, separated 3 μm from each other. The spin-polarization characteristics of the devices are observed to strongly depend on substrate surface preparation and annealing treatment of the metal/semiconductor devices. The latter has a very strong influence on the magnitude of the non-local spin polarization signal, which we observe to increase by about two orders of magnitude after annealing steps from 120 °C up to 290 °C.

Magnetic Interfaces and Nanostructures
Room: C1 - Session MI-ThM

Magnetization Dynamics, Imaging and Spectroscopy
Moderator: A.T. Hanbicki, Naval Research Laboratory

8:00am **MI-ThM1 Correlated Magnetic Domain Structure and Magnetic Anisotropy Studies on Epitaxial Au / FePd(001) / MgO(001) Thin Films**, ***J.R. Skuza****, *C. Clavero, K. Yang,* College of William & Mary*, B. Wincheski,* NASA Langley Research Center*, R.A. Lukaszew*, College of William & Mary

The FePd alloy system can exhibit the $L1_0$ chemically ordered phase when the Fe:Pd stoichiometry of the alloy is near 1:1.[1] The crystallographic structure of the $L1_0$ ordered alloy is characterized by alternating Fe and Pd atomic layers along a cubic stacking direction, which as a consequence suffers a tetragonal distortion. This tetragonal distortion induces a strong perpendicular magnetic anisotropy (PMA) when the layering is parallel to the film plane and the material is in thin film form. The origin of the strong PMA is the large spin-orbit coupling of the paramagnetic Pd atoms and a strong hybridization of their *4d* bands with the highly polarized Fe *3d* bands.[2] Although the mechanism of PMA is well known, controlling it in thin film form is non-trivial and warrants further study to be useful in applications such as magneto-recording media.

We will report on our correlated studies of the magnetic domain structure with the PMA in epitaxial Au / FePd(001) / MgO(001) thin films. Epitaxial FePd thin films were grown using magnetron sputtering in an ultra-high vacuum deposition system at elevated temperatures (400 – 600 °C) and on MgO(001) substrates to achieve highly ordered films with strong PMA. The films were subsequently capped with Au at room temperature (RT) to prevent oxidation, and alteration of the magnetic anisotropy.[3] Reflection high energy electron diffraction was used *in situ* to monitor the epitaxial growth and x-ray diffraction techniques were used *ex situ* to monitor the chemical ordering of the films. Magnetic anisotropy values were obtained from hysteresis loops measured at RT using a Superconducting Quantum Interference Device magnetometer and also by ferromagnetic resonance scans. The magnetic domain structure was investigated using a Nanotec scanning probe microscope with a magnetically coated tip in non-contact mode. These studies have improved our understanding of these strong PMA materials, enabling correlations between the observed domain structure and the magnetic anisotropy, along with comparison to models of domain structure.[4]

[1] T. B. Massalski *et al*. (eds.), Binary Alloy Phase Diagrams, (ASM International, 1990), p. 1751.

[2] A. Cebollada *et al.*, Magnetic Nanostructures, edited by H. S. Nalwa (American Scientific Publishers, 2002), pp. 94-100.

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[4] A. Hubert and R. Schafer, Magnetic Domains The Analysis of Magnetic Microstructures (Springer, 2000), pp. 107-354.

This work was supported by the Virginia Space Grant Consortium, National Science Foundation (DMR Grant #0355171), the American Chemical Society (PRF Grant #41319-AC), and the Research Corporation Cottrell Scholar Award.

8:20am **MI-ThM2 Dependence of the Domain Wall Pinning Strengths to Lateral Constriction Size and Electrical Bias in GaMnAs**, ***S.U. Cho****, H.K. Choi, Yang, Park,* Seoul National University, Korea*, F. DaSilva, T. Osminer, D.P. Pappas*, National Institute of Standards and Technology

Dynamics of domain wall (DW) motion and spin-polarized transport across DWs have received much attention due to their potential applications in large-scale memory storage and logic devices. Particularly for GaMnAs, spin-polarized current induced magnetization switching has been demonstrated [1]. Lateral nanoconstrictions (NC), from which DWs can form and be pinned, in GaMnAs have been utilized to demonstrate nonvolatile memory elements [2] as well as structures showing large magneto-resistances (MRs) [3]. Here, we investigate the size dependence of constrictions in GaMnAs epifilms, particularly the dependence of DW pinning strength as function of lateral constriction size, as well as electrical bias across the constriction. A method to realize nanoconstrictions without plasma-assisted methods and nonlinear IV transport across NC junctions have been reported previously [4]. For this study, we present magnetotransport measurements on identically sized constrictions in series (up to five NC in series) equally spaced apart (~ 2 microns). For large constrictions, the overall resistance (<25 kΩ at room temperature) as function of applied field shows a background negative MR response which can be attributed to anisotropic magnetoresistance with distinct jump-down behavior. The number of distinct jump-down behavior corresponds to number of NC plus one with little dependence of jump field to bias current. Thus, for large constrictions, the geometrical lateral constrictions act 'to seed' DWs. For smaller constrictions (overall resistance > 25 kΩ at room temperature), the MR response is more complex as DW are formed and pinned at the lateral constrictions. MR responses show jump-up behavior along with a complex dependence on jump field to bias current. Furthermore, we will discuss the complex switching behavior observed in small constrictions in series in terms of effects attributed to DW motion and spin-polarized transport across DWs.

[1] M. Yamanouchi *et al.*, Nature **428**, 539 (2004).

[2] K. Rappert *et al.*, Nat. Phys. **3**, 573 (2007).

[3] C. Rüster *et al*., Phys. Rev. Lett. **91**, 216602 (2003); A.D. Giddings *et al*., Phys. Rev. Lett. **94**, 127202 (2005).

[4] S.U. Cho *et al*. Appl. Phys. Lett. **91**, 122514 (2007).

8:40am **MI-ThM3 Racetrack Memory: A Current Controlled Domain Wall Shift Register**, ***S.S.P. Parkin***, IBM Almaden Research Center **INVITED**

Racetrack Memory[1] promises a novel storage-class memory with the low cost per bit of magnetic disk drives but the high performance and reliability of conventional solid state memories. Unlike conventional memories, the fundamental concept of Racetrack Memory is to store multiple data bits, perhaps as many as 10 to 100, per access point, rather than the typical single bit per transistor. In Racetrack Memory the data is stored in the form of a series of magnetic domain walls along magnetic nanowires which are oriented either parallel or perpendicular to the surface of a silicon wafer. These distinct structures form "horizontal" and "vertical" Racetrack Memories. Conventional CMOS devices and circuits are used to provide for the creation and manipulation of the domain walls in the magnetic nanowires or "racetracks". The domain walls are shifted back and forth along the nanowires using nano-second long current pulses via the transfer of spin angular momentum from the spin polarized current. Note that the shifting of neighboring domain walls in the same direction along a nanowire is not possible using conventional means of manipulating domain walls with localized magnetic fields.

In this talk we discuss progress towards building a Racetrack Memory and the fundamental physics underlying it. In particular, we discuss the current and field controlled dynamical motion of magnetic domain walls in magnetic nanowires formed from permalloy and related materials.

[1] S.S.P. Parkin, M. Hayashi and L. Thomas, Science **320**, 190 (2008); S.S.P. Parkin, Scientific American (June, 2009).

9:20am **MI-ThM5 Localized Magnetic and Electric Field Response in Mesoscopic InAs Quantum Well Hall Crosses**, ***M. Nishioka****, L. Folks, J. Katine, E.E. Marinero, B.A. Gurney*, Hitachi GST

Transport properties of mesoscopic Hall crosses in localized magnetic and electric fields have received considerable attention because of their potential application to detection of localized magnetic fields with nanometer resolution. We recently made the first measurement of the response of the Hall voltage to the localized magnetic and electric fields in Hall crosses down to 50 nm x 50 nm cross-sections [1]. Hall crosses, based on InAs quantum well heterostructures, were scanned with a magnetically-coated probe which was also electrically gated to generate both localized electric and magnetic fields. We found that the Hall crosses were sensitive to magnetic fields at the center of the cross. Also, the sensitivity to the localized magnetic field was found to be much larger than that to the localized electric field.

In this work, we report the response to localized magnetic and electric fields of similar crosses configured electrically in "the bend resistance (BR) geometry", where current is passed between adjacent arms of the cross and a voltage is measured between the remaining arms. To our knowledge the response of such heterostructures in the BR configuration to localized magnetic and electric fields has not been previously reported. Figure 1 shows the BR response when the gate voltage applied to the probe and the current applied to the Hall cross are 1 V and -600 μA, respectively. The magnetic field created by the magnetic tip at the InAs quantum well is ~ 600 Oe. The prominent feature in this image is that the BR is sensitive to the localized fields both at the center and the two corners. This is quite different from the response of the Hall resistance [1] where magnetic

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sensitivity was predominant at the cross center. By using both non-magnetic and magnetic probes, we have found that the response to localized electric fields is comparable to localized magnetic fields. Thus, the mapping in Fig. 1 shows significant contributions from both fields. It may therefore be possible to combine the electric field sensitivity of BR measurements with conventional Hall measurements to obtain localized electric and magnetic field information on the nanometer size scale from the same device.

[1] L. Folks *et. al.*, "Near-surface nanoscale InAs Hall cross sensitivity to localized magnetic and electric fields", accepted by Journal of Physics: Condensed Matter.

9:40am **MI-ThM6 Isolation of Exchange- and Spin-orbit- Driven Effects via Manipulation of the Axis of Quantization**, *T. Komesu*, ***G.D. Waddill***, Missouri University of Science and Technology, *S.W. Yu, M.T. Butterfield, J.G. Tobin*, Lawrence Livermore National Laboratory

Double Polarization Photoelectron Spectroscopy (DPPS), using circularly polarized xrays and true spin detection, has been performed using the 2p core levels of ultra-thin films of Fe and Co. This includes both the separation into magnetization- and spin- specific spectra and an Instrumental Asymmetry analysis. By simply by choosing different axes of quantization it is possible to selectively manipulate the manifestation of exchange and spin-orbit effects. Furthermore, the underlying simplicity of the results can be confirmed by comparison to a simple yet powerful single-electron picture.

The interplay of spin-orbit and exchange effects is of crucial importance to the understanding of complex electronic structure. For example, in the highly relativistic 5f systems, this interplay may be the key to understanding electron correlation. [1] One way to address this crucial issue is via photon-helicity- specific and spin-polarized photoemission from core levels, which is strongly dependent upon each of the two effects. [2] In fact, it is possible to observe strongly spin polarized photoemission from completely "non-magnetic" systems. [3] Here, using circularly polarized x-rays and true spin detection, it will be demonstrated how each of the effects, exchange and spin-orbit, can be isolated and quantified, simply by choosing different axes of quantization within the same overall experimental geometry. Moreover, the underlying simplicity of the results will be illustrated by the utilization of separate magnetization- and spin-specific spectra, as well as a simple but powerful single-electron model.

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10:40am **MI-ThM9 Magnetic Soft X-ray Microscopy: Challenges and Opportunities to Image Fast Spin Dynamics on the Nanoscale**, ***P.J. Fischer***, Lawrence Berkeley National Laboratory **INVITED**

The manipulation of spins on the nanoscale is of both fundamental and technological interest. In spin based electronics the observation that spin currents can exert a torque onto local spin configurations which can e.g. push a domain wall has stimulated significant research activities to provide a fundamental understanding of the physical processes involved.

Magnetic soft X-ray microscopy is a powerful analytical technique since it combines X-ray magnetic circular dichroism (X-MCD) as element specific magnetic contrast mechanism with high spatial and temporal resolution. Fresnel zone plates used as X-ray optical elements provide a spatial resolution down to currently <15nm [1] thus approaching fundamental magnetic length scales such as the grain size [2] and magnetic exchange lengths. Images can be recorded in external magnetic fields giving access to study magnetization reversal phenomena on the nanoscale and its stochastic character [3] with elemental sensitivity [4]. Utilizing the inherent time structure of current synchrotron sources fast magnetization dynamics with 70ps time resolution, limited by the lengths of the electron bunches, can be performed with a stroboscopic pump-probe scheme.

I will review recent achievements with focus on current induced wall [5] and vortex dynamics in ferromagnetic elements [6].

Future magnetic microscopies are faced with the challenge to provide both spatial resolution in the nanometer regime, a time resolution on a ps to fs scale and elemental specificity to be able to study novel multicomponent and multifunctional magnetic nanostructures and their ultrafast spin dynamics. The unique features of soft X-ray microscopy and the current developments with regard to improved X-ray optics and high brilliant fsec X-ray sources seems to make this technique a strong candidate to meet this challenge.

Collaboration with M.-Y. Im, B.L. Mesler, W.Chao (CXRO), G. Meier, L. Bocklage, M. Bolte, R.Eiselt, B. Krueger, D. Pfannkuche, U. Merkt (U Hamburg), S. Kasai, K. Yamada, K. Kobayashi, T. Ono (U Kyoto), Y. Nakatani (U Chofu), H. Kohno (U Osaka), A. Thiaville (U Paris-Sud), D.H. Kim (Chungbuk U) and S.-C. Shin (KAIST) is greatly appreciated. Supported by the Director, Office of Science, Office of Basic Energy Sciences, Materials Sciences and Engineering Division, of the U.S. Department of Energy.

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Magnetic Interfaces and Nanostructures
Room: C1 - Session MI+TF-ThA

Magnetic Thin Films: Multilayers and Nanostructures
Moderator: D.P. Pappas, National Institute of Technology

2:00pm **MI+TF-ThA1 Magnetic Recording Sensor Materials and Technology Above 1 Tb/in^2**, ***J.R. Childress***, Hitachi Global Storage Technologies **INVITED**

Magnetic recording is constantly evolving to reach specific technology targets. Today's hard disk drives can store information at >300 Gbit/in^2, and represent a striking example of nano-technology integrated into everyday life: data bits < 100nm x 20nm, read sensors with dimensions < 80nm, and read/write heads flying < 10nm above the disk. The specific challenge for the read sensor is to maintain adequate signal-to-noise ratio as its dimensions are reduced. For example, the development of recording head sensors for 1 Tb/in^2 and above requires sensors dimensions < 30nm. In this regime, all-metal current-perpendicular-to-the-plane (CPP) giant magnetoresistive (GMR) sensors are an attractive alternative to CPP tunnel-magnetoresistance (TMR) sensors. With typical resistance-area products in the range 0.03-0.10 Ω-μm^2, CPP-GMR sensors have the potential to deliver low sensor impedance at the smallest conceivable dimensions, and therefore lower noise and higher bandwidth performance. Among the challenges that CPP-GMR sensors face are low signal levels due to their low resistance, typically low DR/R when using thin magnetic layers, as well as current-induced noise and instability due to the spin-torque effect. I will review several paths that we have recently explored to increase signal and reduce spin-torque effects in CPP-GMR sensors. For increased signal, a key may be the synthesis and integration of new ferromagnetic thin-films alloys with high spin-polarization at the Fermi level (and therefore resulting in high magnetoresistance spin-valves), such as the predicted half-metallic Heusler alloys. For lower spin-torque effects we have demonstrated the effectiveness of dual spin-valves sensors, rare-earth cap layers for increased Gilbert damping, and synthetic-ferrimagnet free layers. I will present some of the physical concepts behind these approaches, and discuss recent data in the context of the specific technological requirements for magnetic recording around 1 Tb/in^2.

2:40pm **MI+TF-ThA3 Synthesis of Highly Magnetostrictive Single Crystal $Fe_{1-x}Ga_x$ Thin Films**, ***A. McClure***, *H Li,* Montana State University, *J.X. Cao, R.Q. Wu,* University of California, Irvine, *E. Arenholz,* Advanced Light Source, *Y.U. Idzerda*, Montana State University

The $Fe_{1-x}Ga_x$ alloy system is a highly anisotropic magnetostrictive material at the appropriate alloy concentration (termed Galfenol at x ~ 0.2) [1]. In thin film form, the atomic pinning of such a material to a substrate can strongly modify the magnetic anisotropy and therefore the magnetization dynamics in a non-isotropic manner, as is demonstrated by a strong angular dependence of the ferromagnetic resonance (FMR) linewidth.

Single crystal $Fe_{1-x}Ga_x$ thin films of various Ga concentrations were prepared on GaAs(001) and MgO(001) substrates by molecular beam epitaxy (MBE), with and without ZnSe buffer layers, respectively. For both substrates, reflection high energy electron diffraction (RHEED) measurements, performed *in-situ* during the growth, show single crystal epitaxial growth of the bcc structure for alloy compositions up to x = 0.7, well beyond the bulk stability region. Vibrating sample magnetometry (VSM) measurements show a reduction in the saturation magnetization with the incorporation of Ga, as well as a migration of the magnetic easy and hard axes that varies slightly between the two substrates. This slight variation is most likely due to the additional uniaxial magnetic anisotropy present in the films grown on the GaAs substrate due to the directional bonding from the zinc-blende surface. X-ray magnetic circular dichroism (XMCD) performed at the Fe $L_{2,3}$-edges reveals a very gradual decrease (10%) in the elemental Fe moment as the Ga concentration approaches 20% followed by a precipitous drop in moment for higher concentrations, while X-ray absorption spectroscopy (XAS) and XMCD measurements performed on the Ga $L_{2,3}$-edges show an evolution in the local Ga electronic structure (a narrowing of 1.6 eV in the L_3 peak position) and establishes an induced moment in the gallium of 0.1 m_B anti-aligned to the Fe moment, in remarkably strong agreement with *ab-initio* density functional (GGA) calculations.

[1] A. E. Clark, J. B. Restorff, M. Wun-Fogle, T. A. Lograsso, and D. L. Schlagel, IEEE Trans. Magn. **36**, 3238 (2000).

3:00pm **MI+TF-ThA4 Anisotropic Transport in Manganite Films Driven by Selective Tailoring of Emergent Electronic Phase Separation**, ***T.Z. Ward***, *J.D. Budai, Z. Gai, J.Z. Tischler, L. Yin, J. Shen*, Oak Ridge National Laboratory

Complex oxides show a wide range of unique behaviors due to their often inseparable energy overlaps of spin-charge-lattice-orbital interactions. These interactions form the basis for emergent electronic phase separation in many complex materials which have been linked to exotic behaviors such as colossal magnetoresistance, the metal-insulator transition, and high T_C superconductivity. By selectively tuning the energetic landscape that shapes the emergent formation of electronic phase separation, we have uncovered never before seen anisotropic transport properties that promise new tunable device applications while answering fundamental questions on the role of electronic phase separation in manganites. Using $La_{5/8-x}Pr_xCa_{3/8}MnO_3$ (x = 0.3) (LPCMO) as a model system, we have found that we can selectively induce anisotropic electronic domain formation along one axis of a pseudocubic perovskite single crystal thin film manganite by epitaxially locking it to an orthorhombic substrate. Simultaneous temperature-dependent resistivity measurements along the two perpendicular in-plane axes show significant differences in the metal-insulator transition temperatures and extraordinarily high anisotropic resistivity on macroscales of up to 20000%. These findings show that emergent electronic phase domain formation can be selectively tuned over long distances which opens the door to new device engineering and a fuller understanding of the balanced energetics that drive emergent behaviors in complex materials.

3:40pm **MI+TF-ThA6 Spin-Torque Behavior of Perpendicular Anisotropy Nanopillar Devices**, ***E.E. Fullerton***, *I. Tudosa,* University of California, San Diego, *J. Cucchiara, S. Mangin,* U. Nancy, France, *Y. Henry,* IPCMS, France, *J. Katine,* Hitachi GST, *D. Ravelosona*, IEF, France **INVITED**

Spin torque reversal of nano-elements with perpendicular magnetic anisotropy have considerable interest for both the fundamental study of spin torque reversal and for possible spin-torque based devices. This ability to locally control magnetization opens the door to a range of applications such as high-density magnetic random access memories, tunable high frequency oscillators and possibly programmable logic devices. In perpendicular anisotropy systems the demagnetization field is commensurate with the anisotropy axis and can be described as an effective uniaxial anisotropy. Both the critical current for spin-torque reversal and the thermal stability are then proportional to the effective anisotropy [1-3] as shown experimentally for [Co/Pt]/[Co/Ni]/Cu/[Co/Ni] nano-pillar samples[2, 3]. In this presentation we describe recent experimental and theoretical studies of the influence of spin currents on the field and angular dependence of the free layer switching fields. The angular dependence of the switching field in the absence of current is well described by the Stoner-Wohlfarth asteroid for a uniaxial system. With the addition of current we find that spin-torque reversal is most efficient when the applied field is parallel to the anisotropy axis. Surprisingly, for fields applied at an angle to the anisotropy axis the switching fields are current independent for currents lower than a critical value and the critical current increases with increasing field angle. We will discuss the origin of this phenomena and results for coupled reversal of the free and reference layer.

[1]. J. A. Katine and E. E. Fullerton, J. Magn. Magn. Mater. **320**, 1217 (2008).

[2] S. Mangin et al., Nat. Mater. **5,** 210 (2006).

[3] S. Mangin et al., Appl. Phys. Lett. **94,** 012502 (2009).

4:20pm **MI+TF-ThA8 Spin Transfer Switching in Magnetic Tunnel Junctions with Co-Based Perpendicular Magnetic Anisotropy Multilayers**, ***Z.R. Tadisina***, *A. Natarajarathinam, S. Gupta, T. Mewes, P. LeClair,* University of Alabama, *E. Chen, S. Wang,* Grandis, Inc., *W.F. Egelhoff*, NIST

Spin transfer switching (STS) has been studied for CoFeB/MgO/CoFeB magnetic tunnel junctions (MTJ) with perpendicular magnetic anisotropy (PMA) free and reference layers. The PMA multilayer material systems were studied as a function of bilayer thickness, bilayer ratio, and number of bilayers for Co/M multilayers, where M was Ni, Pd or Pt. After initial matrix experiments carried out to determine the experimental parameter space, a statistical Design of Experiments (DOE) was conducted to optimize the film structure that would maintain stable perpendicular anisotropy for a reasonable thickness of CoFeB, as well as minimize the damping parameter, α. For Co/Ni multilayers, the damping parameter varied from 0.016 to 0.023 as a function of the number of multilayers. As predicted and experimentally confirmed by others[1,2], we observed a critical thickness of Co above which

the PMA disappears and in-plane anisotropy is observed. The magnetic behavior of these PMA systems was studied by vector magnetometry and alternating gradient magnetometry. X-ray diffraction, transmission electron microscopy (TEM) and local electrode atom probe (LEAP) studies were carried out to investigate the structure of the multilayers, interface smoothness, and growth of (111) texture as a function of deposition conditions and post-deposition annealing. Stress and magnetic force microscopy (MFM) studies confirmed the presence of stripe domains in the PMA stacks. The resistance-area (RA) product and tunneling magnetoresistance (TMR) of the unpatterned MTJ stacks were tested by current-in-plane tunneling (CIPT) measurements to optimize the MgO barrier and PMA stacks prior to actual device fabrication. The transport properties of the patterned MTJ stacks were tested in a PPMS system for both field and current switching from 10K to 400 K to test the thermal stability of these devices.

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2. M. Tekielak, P. Mazalski, A. Maziewski, R. Schäfer, J. McCord, B. Szyman´ski, M. Urbaniak, and F. Stobiecki, "Creation of Out-of-Plane Magnetization Ordering by Increasing theRepetitions Number N in (Co/Au)N Multilayers," IEEE Trans. Magn. vol. 44, pp. 2850-2853, November 2008.

4:40pm **MI+TF-ThA9 Experimental Evidence for an Angular Dependent Transition of Magnetization Modes in Magnetic Nanotubes**, ***O. Albrecht***, *R. Zierold*, University of Hamburg, Germany, *C. Patzig*, Leibniz-Institute of Surface Modification, Germany, *S. Allende*, FCFM Universidad de Chile, *D. Görlitz*, University of Hamburg, Germany, *B. Rauschenbach*, Leibniz-Institute of Surface Modification, Germany, *K. Nielsch*, University of Hamburg, Germany

Highly anisotropic magnetic nanostructures maybe used to overcome the superparamagnetic limit found in magnetic nanoparticles. A well known approach which yields highly anisotropic structures is the creation of magnetic nanotubes. An established route for the fabrication of tubular structures is the use of porous alumina membranes as templates for subsequent covering with a magnetic layer by atomic layer deposition (ALD).

By using glancing angle deposition (GLAD), we present an new approach for a template synthesis to realize magnetic nanostructures.

The combination of GLAD and ALD techniques has the ability to build more complex magnetic nanostructures such as zigzag structures consisting of segmented tubes with adjustable angle between them.

We investigate the angular dependent magnetization determined by SQUID magnetometry at room temperature for all three directions in space.

The main result is the experimental evidence for theoretically predicted transition between two magnetization reversal modes (Vortex to Transverse).

5:00pm **MI+TF-ThA10 Experimental Observation of Ligand Induced Paramagnetism in CdSe Nanocrystals**, ***J.R.I. Lee***, Lawrence Livermore National Laboratory, *R.W. Meulenberg*, University of Maine, *S.K. McCall*, Lawrence Livermore National Laboratory, *K.M. Hanif*, Naval Research Laboratory, *J.C. Lang*, *D. Haskel*, Argonne National Laboratory, *L.J. Terminello*, *T. van Buuren*, Lawrence Livermore National Laboratory

The observation of magnetism has recently been reported for numerous nanoscale materials that do not demonstrate comparable behavior in bulk form. This is intriguing because coupling the magnetic properties of the nanocrystalline materials with their size-dependent optical and electronic behavior presents the potential for application in a variety of technologies. Identifying the origin of the magnetic properties is, therefore, of paramount importance. To date, several conflicting mechanisms have been proposed in studies of a number of nanoscale systems and, significantly, the cause of the magnetism remains a matter of some controversy in the literature. For example, the ferromagnetic behavior observed for Au nanocrystals (NCs) has been attributed to interactions with the organic surface passivant in one study and an intrinsic property of the nanoscale metal in another. Comparable sources have been also been proposed for the magnetic properties of CdSe NCs, along with an alternative possibility that defect sites are responsible. We report a systematic investigation of the effects of the surface passivant on CdSe NCs using a combination of x-ray magnetic circular dichroism (XMCD) spectroscopy, superconducting quantum interference device (SQUID) magnetometry and x-ray absorption spectroscopy (XAS). The suite of experiments demonstrates that, contrary to the findings of prior studies, our NCs are not ferromagnetic and instead exhibit paramagnetic behavior. In addition, the magnetic susceptibility is dependent on interactions with the organic molecule used to passivate the surface of the CdSe NCs. More specifically, the paramagnetic properties depend upon electron transfer at the molecular level via π-back donation between surface Cd atoms and the organic ligands.

Project 07-LW-041 was funded by the LDRD Program at LLNL. This work was partially supported by the OBES, DMR, under the auspices of the U.S. DOE by LLNL under Contract DE-AC52-07NA27344. Use of the ALS and APS was supported by the U.S. DOE, Office of Science, OBES, under Contracts DE-AC02-05CH11231 and DE-AC02-06CH11357, respectively.

5:20pm **MI+TF-ThA11 Artificial Nanomagnets With Lateral Confinement**, *L. Yin*, ***Z. Gai***, *J. Shen*, *D. Xiao*, *Z.Y. Zhang*, Oak Ridge National Laboratory, *N. Widjaja*, The University of Tennessee, Knoxville, *E.W. Plummer*, Louisiana State University

We introduce a novel way—curved Cu(111) substrate—to smoothly modify the surface states by introducing a miscut angle and study the impact of modifying vicinal surface states on the ferromagnetic behavior of Fe nanodots. Fe nanodots are grown on a Cu(111)-curved substrate where the miscut angle changes from 0° (very large terrace width) to 8° (15-Å terrace width). With this curved substrate, the same growth parameter can be ensured in the whole miscut angle studied. When the Fe nanodot assemblies have an in-plane easy axis, two distinct regimes and a critical terrace width, separating these two regimes, can be identified. However, when the Fe nanodot assemblies have a perpendicular easy axis, we only observe one regime marked by a slight decrease in the critical temperature (T_c). There are three contributing factors: the vicinal surface state, the competition between the Fe nanodots diameter and the terrace width, and the in-plane uniaxial magnetic anisotropy. The couplings between these three factors lead to the interesting behavior observed in the Fe/vicinal Cu(111) nanodot assemblies. The vicinal surface strongly affects the coupling between Fe nanodots.

*Supported in part by Office of Basic Energy Sciences, U. S. DOE.

Magnetic Interfaces and Nanostructures
Room: Hall 3 - Session MI-ThP

Magnetic Interfaces and Nanostructures Poster Session

MI-ThP1 Characterization of Aluminum Oxide Tunnel Barrier for use in a Non-Local Spin Detection Device, ***J.R. Abel***, *J.J. Garramone, E. Bersch, A.C Diebold, V.P. LaBella*, University at Albany

Aluminum oxide can be utilized as an interface layer between ferromagnetic metals and silicon to achieve spin injection into silicon. Utilizing the spin of the electron as well as its charge has the potential to be utilized for logic devices in the post CMOS era. The goal of our research is to inject and readout spins using a non-local measurement device that utilizes 1-2 nm aluminum oxide interface layers as tunnel barriers.

The first step of fabricating a non-local measurement device out of silicon is the growth of an aluminum oxide tunnel barrier[1]. Si (001) wafers were dipped in 49% HF solution for approximately 2 min to remove the native oxide layer. The wafers were then immediately loaded into an ultrahigh vacuum MBE machine, degassed at 400 C and cooled to room temperature. After cooling, a desired thickness of aluminum was deposited from a Knudsen cell. The sample was then transferred back into the load lock and exposed to approximately 130 mTorr of pure O_2 for 20 min. The process was repeated to create samples with a thickness of 1 nm, 2 nm, and 3 nm of aluminum oxide. Each thickness was grown in 0.5 nm and 1 nm steps. In addition, a 2 nm sample was grown, in one 2 nm step.

X-ray photoelectron spectroscopy was performed to characterize the film stoichiometry. It was observed that all the aluminum was bonded to the oxygen for the films grown in 0.5 nm and 1 nm steps. Whereas the 2 nm sample grown in one 2 nm step not all the aluminum bonded to oxygen, leaving a partially un-oxidized aluminum film. In addition XPS was used to measure the band gap of the fully oxidized films to be 6.61 eV in good agreement with films of similar thickness[2]. We will also report on current voltage measurements of these films after they have been capped with metal and application of "Rowell criteria" to demonstrate tunneling as the dominant transport mechanism.

References:

[1] O. van't Erve, A. Hanbicki, M. Holub, C. Li, C. Awo-Affouda, P. Thompson and B. Jonker, Appl. Phys. Lett. **91**, 212109 (2007).

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MI-ThP2 Highly Selective Etching of Magnetic Layer using Organic Gases in an Inductively Coupled Plasma Etching System, ***S.K. Kang***, *M.H. Jeon, J.Y. Park,* SKKU Advanced Institute of NanoTechnology (SAINT), S. Korea, *B.J. Park, TH. Min, G.Y. Yeom*, Sungkyunkwan University, S. Korea

Magnetic random access memory (MRAM) has made a prominent progress in memory performance and has brought a bright prospect for the next generation nonvolatile memory technologies due to its excellent advantages. Dry etching process of magnetic thin films is one of the important issues for the magnetic devices such as magnetic tunneling junctions (MTJs) based MRAM. MTJs which are the basic elements of MRAM can be used as bits for information storage. CoFeB is a well-known soft ferromagnetic material, of particular interest for magnetic tunnel junctions (MTJs) and other devices based on tunneling magneto-resistance (TMR), such as spin-transfer-torque MRAM. One particular example is the CoFeB–MgO–CoFeB system, which has already been integrated in MRAM. In all of these applications, knowledge of and control over the etching properties of CoFeB is crucial. Recently, transferring the pattern by using an Ar^+ ion milling is a commonly used, although the redeposition of back-sputtered etch products on the sidewalls and the low etch rate of this method are main disadvantages. So the other method which has reported about much higher etch rates of >50 Å/s for magnetic multilayer structures using Cl_2/Ar plasmas is proposed. However, the chlorinated etch residues on the sidewalls of the etched features tend to severely corrode the magnetic material. Besides avoiding corrosion, during etching facets form at the sidewalls of the mask due to physical sputtering of the mask material.

Therefore, in this work, magnetic material such as CoFeB was etched in an ICP using the gases which can be expected to form volatile metallo-organic compounds. As the gases, carbon monoxide (CO) and ammonia (NH_3) were used as etching gases to form carbonyl volatiles, and the etched features of CoFeB thin films under by Ta masking material were observed with electron microscopy to confirm etched resolution. And the etch conditions such as bias power, gas combination flow, process pressure, and source power were varied to find out and control the properties of magnetic layer during the process.

MI-ThP3 Instrumentation for the Investigation of Switching Field Distribution on Permalloy ($Ni_{81}Fe_{19}$) Nanoscale Structures, ***J. Bates***, *C.V. Cojocaru, Y. Miyahara, P. Grutter*, McGill University, Canada

There is an ongoing interest in understanding the switching field distribution (SFD) of nanoscale patterned magnetic elements, which show great potential for novel applications such as magnetic quantum cellular automata [1] or magnetic random access memory [2] architectures. To make these architectures technologically viable, it is essential for patterned magnetic elements, to have a reproducible and controllable magnetic switching mechanism, thus a narrow SFD. Factors that affect the SFD are not known *a priori* and might be of various natures: thermal effects, shape, imperfections in fabrication, microstructure, edge roughness, seed-layer, anisotropy variations and magnetostatic interactions with neighbors etc.

To address these issues we used a combination of atomic/magnetic force microscopy (AFM/MFM) [3] and transmission electron microscopy (TEM) on indexed arrays of permalloy nanoscale structures, sputter-deposited via stenciling on ultra thin silicon nitride membranes. The stencil-masks used during the deposition process features ordered arrays of nano-apertures, prepared by focused ion beam milling. The stenciling process is parallel, resistless, and allows for the direct organization of structures having different aspect ratios (length/width) into any desired architecture.

Permalloy structures were characterized initially by AFM to assess their topography. Then MFM was used in constant height mode in order to obtain magnetic state (domains) and SFD of the structures. Magnetization reversal was studied by applying an *in situ* magnetic field parallel to the sample surface with a pair of rotating NdFeB permanent magnets. Structures with in plane aspect ratios below 4:1(400nm:100nm) revealed a multidomain state thus complex switching behavior, while structures with an aspect ratio above showed a bipolar state and switched coherently. Structures that switched at lower fields were identified as "early" switchers and structures that switched at larger fields were identified as "late" switchers. TEM images of the "early" and "late" switchers have been compared to normal switchers to look for structural variations, which may induce differences in behavior and broaden the SFD.

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MI-ThP4 Core and Valence Band Photoemission of M[TCNE] Organic-based Magnets, *M.S. Driver, S.Z. Janjua,* University of Missouri - Kansas City, *K.I. Pokhodnya,* North Dakota State University, ***A.N. Caruso***, University of Missouri - Kansas City

A family of organic-based magnets of $M^{II}[TCNE]_x \bullet zS$ (M = V, Mn, Fe, Co, Ni; TCNE = tetracyanoethylene; S = CH_2Cl_2) composition exhibit ordering temperatures ranging from 44 (M = Co, Ni) to ~400 K for M = V. The exchange mechanism in this class of magnets is not well understood and changes dramatically with transition metal type. Core and valence band photoemission have been completed, above and below the transition temperature for the above systems and will be presented. The binding energies of the metal and organic core levels, relative to M^{II} and $[TCNE]^{\bullet-}$ will be presented within the context of exchange strength, transition temperature and metal-to-ligand symmetry overlap. The goal of our groups is to provide, through multiple spectroscopies (some pressure dependent), a picture for the binding energy and spin polarization of the occupied/unoccupied electronic structure as well as the exchange mechanism and bonding as the transition metal type is varied in roughly the same physical structure.

MI-ThP5 Electrical Spin injection from Fe into ZnSe, ***A.T. Hanbicki***, *G. Kioseoglou, M.A. Holub, O.M.J. van 't Erve, B.T. Jonker*, Naval Research Laboratory

The wide bandgap semiconductor ZnSe is an opto-electronic material with a comparable spin lifetime and small lattice mismatch to GaAs. Novel spintronic devices that incorporate ZnSe/GaAs heterostructures will require the facile transport of spin information across several heterointerfaces including spin injection into the ZnSe. We have electrically injected spin-polarized electrons from a ferromagnetic Fe contact into a ZnSe epilayer grown on a GaAs heterostructure. The injected carriers proceed through 300 nm of ZnSe and recombine in the GaAs emitting light characteristic of the bulk GaAs exciton. We measure spin polarizations in excess of 40% in the GaAs based on analysis of the circular polarization of the electroluminescence. We report results as a function of applied magnetic

field, device current and temperature. The spin injection process and transport through the ZnSe layer sustains significant spin populations in this heterostructure.

This work was supported by core programs at NRL.

Magnetic Interfaces and Nanostructures
Room: C1 - Session MI-FrM

Molecular/Organic Based Magnetism
Moderator: A.N. Caruso, University of Missouri-Kansas City

8:20am **MI-FrM1 Molecular/Organic based Magnetism: New Chemistry, Physics, and Technologies**, ***A.J. Epstein***, The Ohio State University **INVITED**

In recent years a broad range of magnetic and magnetotransport phenomena have been reported for organic semiconductors. Unpaired spins in the p orbitals of organic systems have been shown to yield new physics and be the basis of potential new technologies of broad interest. Organic-based magnets with magnetic ordering temperatures from a few K [1] to > 400 K [2] have been successfully synthesized. In addition, new magnetic phenomena have been discovered including fractal magnetism, photonically controlled magnetism, nanoscale magnetic bubbles, and fully spin polarized magnetic semiconductors[3]. Further, magnetotransport (MR) in magnetic and nonmagnetic organic semiconductors has revealed a host of heretofore unknown spin-dependent phenomena, including 20% change in resistance at room temperature for application of as little as 100 Oe to nonmagnetic organic semiconductors. The room temperature magnetic semiconductors $V[TCNE]_{x\sim2}$, (TCNE ≡ tetracyanoethylene) [2,3] has many new properties such as fully spin polarized energy bands and magnetism from 0 to 400 K and photonic response. The analogue $Fe[TCNE]_x$ forms monolayer thick spin layers that produce 'spin bubbles' upon application of a critical field.

These advances in science have prompted interest in the possibility of technologies based on these new materials. These new potential technologies will be discussed with emphasis on organic-based spintronics including tunneling magnetoresistance (TMR) and giant magnetoresistance (GMR) devices and also use of these materials as sensors in the emerging THz range.

This work was supported in part by NSF, DOE, AFOSR, and OSU Inst. for Mater. Res.

[1] S. Chittipeddi, K. Cromack, J.S. Miller, and A.J. Epstein, "Ferromagnetism in Molecular DecamethylferroceniumTetracyanoethenide (DMeFc)(TCNE)", Phys. Rev. Lett. 58, 2695 (1987).

[2] J.M. Manriquez, G.T. Yee, R.S. McLean, A.J. Epstein, and J.S. Miller,"A Room Temperature Molecular/Organic-Based Magnet", Science 252, 1415 (1991).

[3] A.J. Epstein, "Organic-based Magnets: Opportunities in Photoinduced Magnetism, Spintronics, Fractal Magnetism, and Beyond", Mater. Res. Soc. Bull. 28, 492-499 (2003).

[4 V.N. Prigodin, J.D. Bergeson, D.M. Lincoln, and A.J. Epstein, "Anomalous Room Temperature Magnetoresistance in Organic Semiconductors", Synth. Met. 156, 757 (2006).

[5] T. Francis, O¨. Mermer, G. Veeraraghavan, and M. Wohlgenannt, "Large Magnetoresistance at RoomTemp. in Semiconducting Polymer Sandwich Devices",New J. Phys. **6**, 185 (2004).

9:00am **MI-FrM3 Tuning Molecule-Mediated Spin Coupling in Bottom-Up Fabricated Vanadium-TCNE Nanostructures**, *D. Wegner, R. Yamachika,* ***X. Zhang,*** *Y. Wang,* University of California, Berkeley and Lawrence Berkeley National Laboratory, *T. Baruah,* University of Texas, El Paso, *M.R. Pederson,* Naval Research Laboratory, *B.M. Bartlett, J.R. Long,* University of California, Berkeley, *M.F. Crommie*, University of California, Berkeley and Lawrence Berkeley National Laboratory

We have fabricated hybrid organic/inorganic magnetic molecules based on vanadium atoms and tetracyanoethylene (TCNE) ligands in an atom-by-atom fashion using a cryogenic scanning tunneling microscope. Using tunneling spectroscopy we observe spin-polarized molecular orbitals as well as a structure-dependent Kondo resonance. For complexes having two V atoms, the Kondo behavior can be switched on and off by a minute structural change that leaves the spin-containing orbital essentially unchanged. This can be explained by a tunable, structure-dependent change in the vanadium spin-spin coupling strength through the TCNE molecule, as confirmed by density functional calculations. The present findings offer a new route for designing molecular spin nanostructures with atomic-scale precision.

9:20am **MI-FrM4 Resolving the Interface Magnetism of a Molecule-Based Spin Filter**, *J. Brede, S. Kuck,* ***G. Hoffmann***, University of Hamburg, Germany, *P. Lazic, S. Blügel,* FZ Jülich, Germany, *R. Wiesendanger,* University of Hamburg, Germany, *N. Atodiresei*, FZ Jülich, Germany

The use of magnetic molecules opens a gateway to a flexible design of spintronic devices to store, manipulate, and read spin information at nanoscale level. Crucial is the precise knowledge of molecular properties at the interface towards an electrode. Progress into this field relies on resolving and understanding the physics at the relevant interface, the role of individual molecular constituents, and the impact of the atomic environment nearby on molecular properties. Here, we apply spin-polarized scanning tunneling microscopy to resolve the physics of such an interface formed of a magnetic metal-organic molecule adsorbed on a magnetic substrate to observe on an atomic scale the operation of single-molecule spin filter. The experimental data reveal a significant and strongly site dependent localization of spin split states at the interface. To understand the resulting spin-polarization, density functional theory calculations are performed with an extension to describe correlation effects present due to the close proximity of a molecule and a metallic substrate. The results of the joint work are presented and the physical processes at the molecule-electrode interface are discussed.

Acknowledgements: This work was supported by the DFG within the GrK 611 and the SFB 668-A5 and by the European Union in the project "SPiDMe".

9:40am **MI-FrM5 The Densest Iron Coordination Network Based on Carboxylate Ligands**, ***D. Ecija,*** *C. Urban, M. Trelka,* Universidad Autonoma de Madrid, Spain, *C. Marti-Gastaldo, E. Coronado,* ICMOL & Universidad de Valencia, Spain, *J.M. Gallego,* ICMM-CSIC, Spain, *R. Otero, R. Miranda*, UAM & IMDEA-Nano, Spain

Over the last decade there has been a tremendous effort in order to create new kinds of supramolecular organic nanostructures on surfaces, with the prospect of possible catalytic, electronic, optical or magnetic applications. In particular, a lot of attention has been paid to metalorganic coordination networks (MOCNs), with the idea of creating functional metallo-supramolecular arrays on surfaces which combine the properties of their constituent metal ions and ligands.

Following this approach, the chemisorption of small molecules with ending carboxylic acids on metal surfaces has been extensively studied and deprotonation of the acid groups to produce carboxylate groups described [1]. These deprotonated groups can interact strongly with both metal surfaces and metal adatoms (either intentionally deposited or already existing as a 2D background gas that results from the emission of atoms from low coordination sites such as steps and kinks). This metal-to-carboxylate interaction, when properly addressed, leads to the formation of regular patterns of MOCNs. We have deposited oxalic acid, i.e. the smallest possible molecule with two carboxylic groups ($C_2O_4H_2$), on non magnetic Cu(100) surfaces, both clean and with a small pre-deposited amount of Fe. Scanning Tunnelling Microscopy (STM) shows that moderate annealing of these systems lead to the formation of two different, new MOCNs: a rectangular copper-oxalate network, and a honeycomb iron-oxalate network, where the regularly spaced Fe spins have the smallest distance (5.2 Å) reported up to date, making the Fe-oxalate MOCN a promising system for an in-depth study of their magnetic properties.

[1] S. Stepanov, N. Lin, J. V. Barth, J. Phys.: Condens. Matter 20 (2008) 184002.

10:00am **MI-FrM6 Spatially Extended Kondo Resonance in Magnetic Molecules**, *U.G.E. Perera,* Ohio University, *H.J. Kulik,* Massachusetts Institute of Technology, *V. Iancu,* Ohio University, *L.G.G.V. Dias da Silva,* Oak Ridge National Laboratory and University of Tennessee, ***S.E. Ulloa,*** Ohio University, *N. Marzari,* Massachusetts Institute of Technology, *S.-W. Hla*, Ohio University

Molecules containing transition-metal complexes have great potentials in the emergent fields of spintronics and molecular electronics. Especially, controlling their spin states and spin polarization is a key challenge for future applications. Here, we report an extensive and unusual redistribution of spin density for self-assembled TBrPP-Co [5, 10, 15, 20 –Tetrakis -(4-bromophenyl)-porphyrin-cobalt] molecules adsorbed on a Cu(111) surface as a model system to investigate spin polarization, the effect of molecular orbital in Kondo resonances. The TBrPP-Co molecule has a spin-active cobalt atom caged at the center of porphyrin unit and four bromo-phenyl groups are attached to its four corners. STM imaging shows the molecules with four pronounced lobes. These molecules readily self-assemble and

form ordered, ribbon-like monolayer islands on Cu(111), with a preferential growth direction ~7º deviated from the [110] surface directions. We probe the spatially extended Kondo resonance of the molecules by monitoring the effective Kondo temperature with differential conductance (dI/dV) tunneling spectroscopy, finding it much larger on the macro-cycle itself than on the central cobalt atom. The origin of this effect is explained by means of first-principles and numerical renormalization group calculations, highlighting how it is possible to engineer spin polarization and electronic transport by means of adsorption chemistry. This work is supported by the US Department of Energy Basic Energy Sciences grant no. DE-FG02-02ER46012.

10:20am **MI-FrM7 Pressure Dependent Magnetic and Optical Properties of M [TCNE] $(MeCN)_2X$ (M= V, Fe, Mn, Co, Ni; TCNE = tetracyanoethylene) Organic-Based Magnets**, ***K.I. Pokhodnya****, C. Olson,* North Dakota State University*, A. Midgley, M.B. Kruger, A.N. Caruso*, University of Missouri - Kansas City

M-TCNE molecule-based ferrimagnets demonstrate high magnetic ordering temperatures up to 400 K (M = V) due to strong AFM exchange between *d*-electrons of the metal and the anion-radical spin of the TCNE ligand. Magnetic and optical properties of the family of molecule-based 2D magnets $[M(TCNE)(NCMe)_2]$ X (M=Fe, Mn, Ni; X=BPh_4, $FeCl_4$, SbF_6) will be discussed. Classical bonding-sensitive IR spectroscopy has difficulties distinguishing between the bonding and backbonding interactions (possibly mediating the strong superexchange), since their effects on CN bond stretching mode frequencies may cancel each other. In contrast, Raman active n(C=C) modes solely depend on charge transfer to/from the p* antibonding orbital, and thus are only backbonding sensitive. The observed strengthening of the n(C=C) and n(NºC) Raman modes for the compounds with higher T_c suggests the depopulation of the p* orbital and enhanced ligand to metal charge transfer resulting in a hybrid M3*d*-CN ground state with substantial admixture of ligand electron. The observed pressure-induced strengthening of the n(C=C) and n(NºC) Raman modes is in accord with proposed backbonding model. The correlation between the frequency shift (degree of backbonding) and magnitude of T_c from M(T) is established.

10:40am **MI-FrM8 UV/Vis Magnetic Circular Dichrosim of Fe[TCNE]**, ***S.Z. Janjua****, A.N. Caruso*, University of Missouri - Kansas City

The unoccupied electronic structure of the $Fe^{II}[TCNE]_x$•zS (TCNE = tetracyanoethylene; S = CH_2Cl_2) organic-based magnet has been studied using x-ray magnetic circular dichroism (XMCD) and standard x-ray absorption, but no clear picture of the binding energies nor their spin polarization has been determined. UV/Vis MCD studies have been completed, and will be presented within the ligand to metal charge transfer transition model, as a complimentary and possibly more sensitive means by which the unoccupied electronic structure may be determined. Further, the UV/Vis MCD were conducted to investigate the charge and intervalance transfer from ligand to metal orbital's.

11:00am **MI-FrM9 Perspectives in Multi-Functional Single-Molecule Magnets and Single-Chain Magnets**, ***M. Yamashita***, Tohoku University, Japan **INVITED**

Recently, the quantum molecular nano-magnets have been attracting much attention from the viewpoints of the basic sciences as well as the applied sciences such as memory storages, quantum computers, etc. So far more than 300 single-molecule quantum magnets have been reported, while about 20 types of single-chain quantum magnets have been reported. They have several interesting themes to be resolved as follows: (1) High blocking temperature, (2) Quantum GMR, (3) Memory storage into one quantum molecule magnet, (4) Quantum computer, (5) Quantum FET, (6) Glauber dynamics, (7) Multi-functionalities, (8) Kondo effect, etc.

As for (1), since the potential barrier of the double wells is defined as DS^2 and $(8J+D)S^2$ for the single-molecule magnets and single-chain magnets, respectively, we must increase the *D*, *S*, and *J* parameters to raise the blocking temperatures of these compounds. However, the control of the parameter *D* is very difficult. Then, we propose the conducting quantum molecular magnets. By the interaction between conducting electrons and localized quantum molecule magnets, the coherence among the quantum molecule magnets is strengthened and then the spin flips are made difficult, resulting in raising the blocking temperature. According to such a strategy, we have synthesized three types of conducting single-molecule magnets such as $[Mn_4(hmp)_6(MeCN)_2][Pt(mnt)_2]_6$, $[Mn_2(5\text{-}MeOsaltmen)_2(MeCN)_2][Ni(dmit)]_7(MeCN)$, and $[Mn_2(5\text{-}Rsaltmen)_2][Ni(dmit)_2]_2$. As for (2), since in the quantum molecular magnets, we can create artificially the large spin numbers such as *S* =10, 20, 30, etc, we can anticipate new quantum GMR phenomena by interacting between large *S* and conducting electrons. According to such a strategy, we try to synthesize a metallic single-molecule magnet. Otherwise, we have a plan to occur a photo-induced phase transition from semiconductor to metallic state in conducting single-molecule magnet. As for (3), we have accessed to one single-molecule magnet of Pc_2Tb by STM. We have a plane to input one memory into one single-molecule magnet and output it from one single-molecule magnet by using spin-polarized STM. We have observed Kondo Effect at 4.8 K in this compound by STS for the first time. As for (7), we have synthesized the single-molecule magnet with photo-induced switching and the single-chain magnet with absorption and desorption of crystal solvents reversibly like a spo

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