Wednesday Afternoon, October 31, 2012

Magnetic Interfaces and Nanostructures
Room: 6 - Session MI+OX-WeA

Spintronics, Magnetoelectrics, Multiferroics
Moderator: G.J. Mankey, University of Alabama

2:00pm **MI+OX-WeA1 Imaging of Temperature-Driven Nucleation of Ferromagnetic Domains in FeRh Thin Films**, ***C. Baldasseroni***, *C. Bordel*, Univ. of California Berkeley, *A.X. Gray*, SLAC National Accelerator Lab, *A.M. Kaiser*, Peter-Grünberg-Institut, Germany, *F. Kronast*, Helmholtz-Zentrum Berlin für Materialien und Energie, Germany, *J. Herrero-Albillos*, Centro Univ. de la Defensa, Spain, *C.M. Schneider*, Peter-Grünberg-Institut, Germany, *C.S. Fadley*, Lawrence Berkeley National Lab, *F. Hellman*, Univ. of California Berkeley

Equiatomic FeRh is a unique material that undergoes a first order antiferromagnetic (AF) to ferromagnetic (FM) transition just above room temperature (near 350 K). This phase transition can be driven by temperature or magnetic field and is coupled to a lattice expansion. Current investigations of this unique transition range from the fundamental understanding of the origin and nature of the transition to applications associated with the transition such as a giant magnetocaloric effect.

FeRh has been studied in the bulk for over 50 years and most recently in thin film form, where the transition temperature has been shown to be sensitive to changes in composition and substrate-induced strain as well as structural and chemical order. FeRh thin films are also a promising candidate for heat-assisted magnetic recording in an exchange-spring system with a hard magnetic layer (for example FePt). Understanding the magnetic domain structure of FeRh and the mechanisms of the transition at the microscopic level involving nucleation and growth of magnetic domains as a function of temperature is vital for its further application to magnetic storage technology. Although many experimental studies of the transition have been recently performed on FeRh thin films, most of them focus on macroscopic measurements. Only a few studies have attempted at imaging domains through the transition but these have been limited to magnetic force microscopy (MFM) on bulk samples and were limited by lack of temperature control which prevented a study of the nucleation and growth across the full transition.

We used x-ray magnetic circular dichroism and photoemission electron microscopy to study the evolution of ferromagnetic domains across the temperature-driven AF to FM phase transition in uncapped and capped epitaxial FeRh thin films. The coexistence of the AF and FM phases was evidenced across the broad transition and the different stages of nucleation, growth and coalescence were observed. We also found that the FM phase nucleates into single domain islands and the width of the transition of the individual nuclei is sharper than that of the macroscopic transition.

2:20pm **MI+OX-WeA2 Magnetic Properties of Cobalt and Permalloy Thin Films Grown on Self-Assembled Monolayers by Physical Vapor Deposition**, ***G.J. Szulczewski***, *S. Schafer, B. Khodadadi, T. Mewes, J. Kreil, E. Ellingsworth, K. Anderson*, The University of Alabama

In this talk we will present results from a study to understand how terminal functional groups in self-assembled monolayers (SAMs) influence the growth and subsequent magnetic properties of Co and NiFe (permalloy) thin films. Self-assembled monolayers were made from both aryl and alkyl carboxylic acids adsorbed onto oxidized aluminum surfaces. The SAMs were characterized by contact angle measurements and x-ray photoelectron spectroscopy. The magnetic properties of the thin films were characterized by ferromagnetic resonance spectroscopy. In general we find that reactive functional groups, for example thiols, cause the metals to grow as continuous films. In contrast, deposition of the metals onto non-reactive functional groups, for example methyl, leads to penetration of metal atoms through the SAM and cluster formation. The permalloy films are superparamagnetic below ~ 4 nm, while Co films are ferromagnetic at room temperature. The coercivity of the films is also found to vary with functional group. In the case of halide substituents, for example, flouro, chloro, bromo, and iodo on the aryl carboxylic SAMs, there is also a correlation between the magnetic properties of cobalt thin films and the strength of the carbon-halogen bond energy. Cobalt deposited onto SAMs with terminal C-F bonds tends to be non-reactive, while reactive toward C-I bonds. Not only do these reactivity patterns influence the magnetic properties of the thin film, but also they result in a measurable change in the resistance of tunnel junctions bearing these SAMs.

2:40pm **MI+OX-WeA3 Synthesis and Fundamental Properties of Fe16N2 Films - New Excitements of Fe16N2 Research and a 40-year Mystery**, ***J.-P. Wang***, University of Minnesota **INVITED**

Pursuing magnetic materials with giant saturation magnetization (Ms) has huge impacts both scientifically and technologically. However, this effort has been fundamentally shadowed for decades by the classical itinerant magnetism theory. So far, the highest 4piMs value that can be predicted by first principles calculation is 2.45 T for Fe65Co35 alloy.

In 1972, Kim and Takahashi firstly reported a material with a giant saturation magnetization (4piMs ~ 2.9 T), Fe16N2, that surpasses Fe65Co35 alloy. Thereafter, various groups in the world have investigated the formation of Fe16N2 samples including films and particles by a variety of means. Unfortunately, experimentally reported 4piMs values are largely inconsistent ranging from 2.2 T up to 2.9 T. Investigators, including theoreticians, weighted in on one side of this question or the other. In particular, at the annual conference on Magnetism and Magnetic Materials in 1996, a symposium was held on the topic Fe16N2. Key research teams on this topic presented apparently conflicting views on the synthesis and understanding of this material. No decisive conclusion was drawn on whether Fe16N2 has giant saturation magnetization at the moment. Since then, this research topic has been dropped by most of magnetic researchers since year 2000.

In 2010, Wang's group has reported the theory and fundamental experimental evidence of the origin of giant saturation magnetization and produced the Fe16N2 thin films with both giant Ms and high anisotropy. In this talk, Dr. Wang will review the history and analyze the previous inconsistencies and obstacles of the Fe16N2 topic in the past 40 years. Then he will present recent progress from his group and his collaborators on this topic. From X-ray magnetic circular Dichorism (XMCD) experiment, polarization-dependent x-ray absorption near edge spectroscopy (EXANE), polarized neutron reflectivity (PNR) and first-principle calculation, it has been both experimentally and theoretically justified that the origin of giant saturation magnetization and large magnetocrystalline anisotropy is correlated with the formation of highly localized 3d electron states in this Fe-N system. Thirdly, high magnetic anisotropy and high spin polarization ratio of Fe16N2 will be reported and discussed, which may lead to many new applications, such as in spintronic device and rare-earth free magnet. Finally remaining fundamental questions and possible approaches to address them will be reviewed and discussed.

This talk is a joint effort with five research teams at ORNL, Argonne National Lab, Brookheaven National Lab and one lab from Netherland.

4:00pm **MI+OX-WeA7 Spin Transfer Torque MRAM - Modeling, Experiments and Future Prospects**, ***D. Apalkov***, *A. Khvalkovskiy, V. Nikitin, S. Watts, A. Driskill-Smith, D. Lottis, R. Chepulskyy, V. Voznyuk, X. Tang, K. Moon, E. Chen, C.M. Park, M. Krounbi*, Grandis, Inc. **INVITED**

Spin transfer torque magnetic random access memory (STT-MRAM) is a new and promising memory technology that features fast read and write times, small cell sizes of < 6F2, nonvolatility, radiation hardness and low power consumption.

In this work, we will go over the fundamental physics of magnetoresistance and spin transfer torque effects – key scientific phenomena required for STT-MRAM memory operation. The precursor technology – conventional MRAM – is now successfully used in commercial applications; however it cannot be scaled down to compete with DRAM or Flash technologies. We will go over the *Write-Store-Read* (WSR) trilemma, which is the challenge to achieve fast and reliable writing, reading and storing information at the same time in STT-MRAM. For a successful product, the desired probability of a switching error at the current deliverable by the transistor should be less than 10-3 for storage-class memory and 10-9-10-18 for working-class memory. Depending on the switching time, two regimes of switching, thermal and precessional, can be identified, and the switching error can dramatically depend not only on the switching regime but also on the switching time within the regime. For the reading process, one critical parameter is read disturb – probability of inadvertent switching of the element during reading operation. For memory applications, this probability has to be smaller than ~10-20 (with some dependence on particular design and array size). For storing the recorded information, the thermal stability parameter, defined as the ratio of energy barrier to kBT is important and typically has to be larger than 60-80 depending on specific application.

STT-MRAM can be implemented in two major realizations: in-plane and perpendicular. For each of them, single and dual MgO designs can be

implemented, with the dual MgO design having up to 50% reduction of the switching current and providing much better switching symmetry than a single one. Special attention will be paid to our recent developments to of in-plane Dual MTJ design. By building special structure with modified reference layers, we were able to extract contributions from each barrier. Even though STT switching current is reduced in Dual design, the quality of the two barriers in currently built structures is deteriorated as compared to single MTJ. Respectively further improvement from Dual designs is expected if the quality of the two barriers is improved.

4:40pm **MI+OX-WeA9 Epitaxial Growth of Multiferroic Heterostructures of Magnetic and Ferroelectric Oxides using the Dual-laser Ablation Technique**, ***D. Mukherjee***, *M. Hordagoda, R.H. Hyde, N. Bingham, H. Srikanth, P. Mukherjee, S. Witanachchi*, University of South Florida

Epitaxial multiferroic $PbZr_{0.52}Ti_{0.48}O_3$ (PZT)/ $CoFe_2O_4$ (CFO)/ $La_{0.7}Sr_{0.3}MnO_3$ (LSMO) composite thin films were fabricated on single-crystal $SrTiO_3$ substrates using the dual-laser ablation process. In this process, the target was initially heated by a pulsed CO_2 laser to produce a transient molten layer, from which a spatially-overlapped and slightly time-delayed pulsed KrF laser initiated the ablation. This not only resulted in a drastic reduction of particulates in the deposited films but also overcame the problem of non-congruent ablation of PZT, due to the high volatility of Pb, leading to stoichiometric PZT film deposition [1]. Moreover, the optimum coupling of the laser energies led to higher ionization of the ablated species particularly atomic oxygen (O) as seen in the optical emission spectra of the plumes. The higher excitation of O led to enhanced gas phase reaction and consequently reduced the oxygen vacancy-related point defects inherent in oxide films. X-ray diffraction (XRD) studies revealed the single crystalline nature and the cube-on-cube epitaxial relationship in the PZT/CFO/LSMO films. Atomic force microscopy revealed surface roughness values as low as 1.6 nm for the top PZT layers. Cross-sectional high resolution transmission electron microscope (HRTEM) images not only evidenced the epitaxial growth but also atomically sharp and flat interfaces with no structural defects (Suppl. PDF). The lattice parameters calculated from the HRTEM images matched well with the values obtained from XRD. Selected area electron diffraction (SAED) patterns showed linear square arrays confirming the single crystalline nature of the interfaces. Magnetization measurements exhibited perpendicular magnetic anisotropy with the easy axis along the film plane for the PZT/CFO/LSMO films, similar to PZT/LSMO bilayer thin films. PZT/CFO/LSMO films showed enhanced in-plane saturation magnetization (M_s) values of 360 emu/cm^3 as compared to 280 emu/cm^3 for PZT/LSMO and larger coercive field of 2.5 kOe as compared to 0.1 kOe for PZT/LSMO thin films. For ferroelectric measurements, top LSMO dot electrodes with 100 μm diameter were deposited using laser ablation to make LSMO/PZT/CFO/LSMO capacitors. Polarization measurements showed well saturated and square hysteresis loops at low nominal switching voltages of 5 V and with higher remnant polarization (P_r) values of 120 μC/cm^2 as compared to 90 μC/cm^2 for PZT/LSMO thin films.

[1]. D. Mukherjee et al, "Role of dual-laser ablation in controlling the Pb depletion in epitaxial growth of $Pb(Zr_{0.52}Ti_{0.48})O_3$ thin films with enhanced surface quality and ferroelectric properties", Journal of Applied Physics 111, 064102 (2012).

5:00pm **MI+OX-WeA10 The Highly Polarized Surface of Magnetoelectric Antiferromagnet**, ***N. Wu***, *X. He, J. Santana, J. Wang*, University of Nebraska-Lincoln, *E. Vescovo*, Brookhaven National Laboratory, *C. Binek, P.A. Dowben*, University of Nebraska-Lincoln

Manipulation of magnetically ordered states by electrical means is among the most promising approaches towards novel spintronic devices. Electric control of the exchange bias can be realized when the passive antiferromagnetic pinning layer is replaced by a magneto-electric antiferromagnet, like the prototypical magneto-electric Cr_2O_3(0001). Chromia works well in this case so long as there is also a finite remanent spin polarization at the surface or boundary, which can be achieved by cooling the thin film in the presence of both magnetic and electrics fields. We have demonstrated that a very unusual high polarization can exist at the surface of the Cr_2O_3 (0001) from spin-polarized photoemission [1] and is robust against surface roughness. Both magnetic single domain and multi-domains were imaged by magnetic force microscopy and X-ray magnetic circular dichroism – photoemission electron microscopy (XMCD-PEEM) [2] as achieved by field cooling in the presence of electrics fields. The similar boundary magnetization has also been observed on the (110) surface of Fe_2TeO_6 by the XMCD-PEEM, which suggests this possible interface spin polarization to be a more universal phenomenon for magnetoelectric antiferromagnets.

References:

[1] Xi He, Yi Wang, Ning Wu, Anthony N. Caruso, Elio Vescovo, Kirill D. Belashchenko, Peter A. Dowben and Christian Binek, Nature Materials 9, 579 (2010).

[2] Ning Wu, Xi He, Aleksander L. Wysocki, Uday Lanke, Takashi Komesu, Kirill D. Belashchenko, Christian Binek, and Peter A. Dowben, Physical Review Letters 106, 087202 (2011).

5:20pm **MI+OX-WeA11 Sub-monolayer Spin Rotation of Photoelectrons from FePc on Fe(110)**, ***J.E. Rowe***, *D.B. Dougherty, A.A. Sandin*, North Carolina State University, *E. Vescovo*, Brookhaven National Laboratory

Spin-resolved photoemission at the National Synchrotron Light Source, Brookhaven National Laboratory has been used to study the occupied electronic states of sub-monolayers to multi-layers of iron phthalocyanine (FePc) adsorbed on ~10-20 monolayer epitaxial films on Fe(110) on W(110). We find that the spin-resolved photoemission changes rapidly as a function of coverage and the initial (majority spin axis along [110] rotates by ~ 30 degrees for sub-monolayer coverage and then becomes unpolarized at ~1 monolayer (ML). The coverage is determined by work function measurements which show that the initial work function of clean Fe(110) of 5.0 eV decreases monotonically to a value of ~3.8 eV at a coverage that we assign as ~1 monolayer of FePc. These values were determined from the measurements of the photoelectron spectrum using the low-energy vacuum-level cutoff of a biased sample. We used low intensity light at 41.4 eV photon energy to provide accurate intensity data and a well-defined vacuum-level threshold.

Our spin-resolved data for clean Fe(110) show highly spin-polarized photoelectrons from the Fermi energy to values about 3.5 eV below the Fermi energy for an applied B-field along [110] both for majority-spin and minority-spin electrons. The polarization is about 60% at -3.2 eV below E-Fermi. For 0.13 ML adsorbed FePc the spin polarization is somewhat reduced and is rotated from [110] towards [100] in the plane of the sample. We interpret this rotation as due to a strong coupling of the orbital moment of FePc with the conduction electrons of the Fe substrate. At a coverage of ~0.25 ML the polarization is reduced to ~0 and then at higher coverage (~1 ML) it increases to about 1/2 of the initial polarization. These data suggest that paramagnetic molecular species are useful for modifying the interfaces of spin-valve devices. A mechanism for this effect will be presented.

5:40pm **MI+OX-WeA12 Magnetic Configurations of $Ni_{80}Fe_{20}$/Ir Superlattices**, ***G.J. Mankey***, University of Alabama, *J. Hwang*, Lane College, *N. Pachauri, E.A. Manoharan, P.R. LeClair*, University of Alabama, *H. Ambaye, V. Lauter*, Oak Ridge National Laboratory

Antiferromagnetically coupled superlattices consisting of ferromagnetic (FM) layers separated by nonmagnetic (NM) spacer layers exhibit a wide range of magnetization behavior as a function of applied field. The magnetic configurations depend on the magnetization, thickness and anisotropy of the FM layers and the strength and type of magnetic coupling through the NM layers. The dependence of the magnetic configurations on applied magnetic field can be estimated with one-dimensional micromagnetic models that find the minimum energy configurations of the average magnetization vectors within the ferromagnetic layers1. A set of Ni80Fe20/Ir superlattice samples was designed to compare the measured magnetization curves as a function of applied field to magnetization curves generated by a micromagnetic model. The Ni80Fe20 layers were sputter deposited with an in-plane magnetic field, to induce uniaxial anisotropy within these layers. Both the FM layer thickness and number of superlattice periods were varied. FM layer thicknesses were verified by magnetometry and x-ray reflectivity analysis. The Ir NM layer thickness was tuned to the thickness for maximum antiferromagnetic coupling strength. Ir was chosen because the coupling strength has strong temperature dependence, increasing by about a factor of two as the temperature is reduced from 300 K to 5 K. A detailed comparison of the modeled and experimental magnetization curves enables a parameterization of the micromagnetic model that shows applying a magnetic field generates a complex magnetic structure in finite superlattices for multiple repeats. This complex structure, with twisted magnetic configuration is measured for a 16-repeat superlattice structure using polarized neutron reflectivity. Analysis of the polarized neutron reflectivity data for the applied magnetic field along the hard axis of the FM layers allows the determination of the detailed magnetic configuration.

1. U. K. Robler and A. N. Bogdanov, Phys. Rev. B 69, 184420 (2004).

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