Magnetic Interfaces and Nanostructures
Room: 6 - Session MI+SP+AS-ThM

Emerging Probes in Magnetic Imaging, Reflectometry and Characterization
Moderator: Z. Gai, Oak Ridge National Laboratory, V. Lauter, Oak Ridge National Laboratory

8:00am **MI+SP+AS-ThM1 Toward Microscopy with Direct Chemical and Magnetic Contrast at the Atomic Level**, ***V. Rose***, Argonne National Laboratory **INVITED**

In this talk we will discuss the development of a novel high-resolution microscopy technique for imaging of nanoscale materials with chemical, electronic, and magnetic contrast. It will combine the sub-nanometer spatial resolution of scanning tunneling microscopy (STM) with the chemical, electronic, and magnetic sensitivity of synchrotron radiation. [1] Drawing upon experience from a prototype that has been developed to demonstrate general feasibility, current work has the goal to drastically increase the spatial resolution of existing state-of-the-art x-ray microscopy from only tens of nanometers down to atomic resolution. The technique will enable fundamentally new methods of characterization, which will be applied to the study of energy materials and nanoscale magnetic systems. A better understanding of these phenomena at the nanoscale has great potential to improve the conversion efficiency of quantum energy devices and lead to advances in future data storage applications. The combination of the high spatial resolution of STM with the energy selectivity afforded by x-ray absorption spectroscopy provides a powerful analytical tool.

Work at the Advanced Photon Source, the Center for Nanoscale Materials, and the Electron Microscopy Center was supported by the U. S. Department of Energy, Office of Science, Office of Basic Energy Sciences, under contract DE-AC02-06CH11357.

[1] V. Rose, J.W. Freeland, S.K. Streiffer, "New Capabilities at the Interface of X-rays and Scanning Tunneling Microscopy", in Scanning Probe Microscopy of Functional Materials: Nanoscale Imaging and Spectroscopy, S.V. Kalinin, A. Gruverman, (Eds.), Springer, New York (2011), pg 405-432.

8:40am **MI+SP+AS-ThM3 Effect of Sub-Micrometer Scale Magnetic Inhomogeneity on the Magnetoelectric Coupling in Manganites**, ***A. Biswas***, University of Florida **INVITED**

The conventional magnetoelectric (ME) coupling in multiferroics is defined as the effect of a magnetic/electric field on the electric-polarization/magnetization. However, the strength of the ME coupling is usually small. Our recent results have revealed methods for significantly increasing the ME coupling in perovskite manganites and can be summarized in two broad categories: (1) in the phase separated manganite $(La_{1-y}Pr_y)_{1-x}Ca_xMnO_3$ (LPCMO), we have discovered that anisotropic strain leads to a fluid-like ferromagnetic material which can be manipulated using an electric field leading to an unconventional ME coupling [1,2] and (2) an ME coupling in $BiMnO_3$ (BMO) thin films which is about 30 times larger than previously observed in single phase multiferroics [3]. I will discuss the origin of the ME coupling in both multiferroic and phase-separated oxides and relate it to inhomogeneous magnetic properties of the thin films, measured using techniques such as low temperature scanning probe microscopy, spin-polarized neutron reflectometry, and strain dependent electric polarization. Acknowledgement: NSF DMR-0804452

1. Dhakal et. al., *Phys. Rev. B***75**, 092404 (2007)

2. Jeen et. al., *Phys. Rev. B***83**, 064408 (2011)

3. Jeen et. al., *J. Appl. Phys.***109**, 074104 (2011)

9:20am **MI+SP+AS-ThM5 Impact of Interfacial Magnetism on Magnetocaloric Properties of Thin Film Heterostructures**, ***C.W. Miller***, University of South Florida **INVITED**

In an effort to understand the impact of nanostructuring on the magnetocaloric effect, we have grown and studied gadolinium in $W(5nm)/Gd(30nm)/W(5nm)]_8$ heterostructures. The entropy change associated with the second-order magnetic phase transition was determined from the isothermal magnetization for numerous temperatures and the appropriate Maxwell relation. The entropy change peaks at a temperature of 284 K with a value of approximately 3.4 J/kg K for 30 kOe field change; the full width at half max of the entropy change peak is about 70 K, significantly wider than that of bulk Gd under similar conditions. The relative cooling power of this nanoscale system is about 240 J/kg, somewhat lower than that of bulk Gd (410 J/kg). Polarized neutron reflectometry was used to determine the depth profile of the magnetic moment per Gd atom, m_{Gd}. Despite sharp interfaces observed by transmission electron microscopy, m_{Gd} is systematically suppressed near the Gd-W interfaces. Because the peak magnetic entropy change is proportional to $m^{2/3}$, the maximum achievable magnetocaloric effect in Gd-W heterostructures is reduced. By extension, our results suggest that creating materials with Gd-ferromagnet interfaces may increase the m_{Gd} relative to the bulk, leading to enhanced magnetocaloric properties. Together, these observations suggest that nanostructuring may be a promising route to tailoring the magnetocaloric response of materials.

Supported by AFOSR and NSF.

10:40am **MI+SP+AS-ThM9 Polarized Neutron Reflectometry on Exchange Biased Thin Films**, ***K. Temst***, KU Leuven, Belgium **INVITED**

Polarized neutron reflectivity has established itself as an important tool in the study of magnetic thin film systems. It provides a high-resolution magnetic depth profile and it offers vectorial probing of the magnetization. In recent years polarized neutron reflectivity has played an influential role in elucidating the magnetic structure of exchange bias systems, i.e. structures in which a ferromagnetic layer is coupled to an antferromagnetic layer. Exchange bias leads to a remarkable shift of the hysteresis loop, an increase in coercivity, and often a pronounced asymmetry of the hysteresis loop shape as wellas a complex magnetic history. With this contribution we will take a closer look at two such exchange bias systems and highlight the role of polarized neutron reflectivity.

As a first model system, the archetypal exchange bias system Co/CoO will be highlighted. The antiferromagnetic CoO layer is prepared by oxidizing the surface of a Co thin film, by exposing it to a reduced oxygen atmosphere. We will review the properties of exchange bias in surface-oxidized Co thin films, with the emphasis on the asymmetry of the magnetization reversal mechanism and the training effect. We will also discuss how the training effect can be (partially) restored by applying a magnetic field perpendicular to the initial cooling field direction. Recently we explored an alternative way to establish exchange bias between Co and CoO: rather than creating the antiferromagnetic CoO layer by oxidizing a metallic Co layer, the antiferromagnetic CoO is produced by implantation of oxygen ions into a Co layer. Polarized neutron reflectivity (PNR) is used to determine the magnetic depth profile and to probe the magnetization reversal mechanism. Simultaneously with the PNR measurements, in situ anisotropic magnetoresistance measurements were carried out.

The second example is a ferromagnet/antiferromagnet $FePt/FePt_3$ bilayer in which complementary use is made of polarized neutron reflectivity (for studying the magnetic depth profile in the ferromagnetic layer) and nuclear resonant scattering of synchrotron x-rays (making use of the Mössbauer effect) to probe the antiferromagnetic FePt3 layer. Below the Néel temperature, antiferromagnetic order appears in the $FePt_3$ layer with a spin wavevector pointing along the [100] axis. A net magnetization of the $FePt_3$, which increases towards the $FePt/FePt_3$ interface is found.

This work was supported by the Fund for Scientific Research-Flanders (FWO), the KULeuven Concerted Research Action program (GOA/09/006), the Belgian Interuniversity Attraction Poles research programs (IAP P6/42), and the KULeuven BOF (CREA/07/005) program.

11:20am **MI+SP+AS-ThM11 Soft X-ray Microscopy to Study Complexity, Stochasticity and Functionality in Magnetic Nanostructures**, ***P. Fischer***, *M.-Y. Im*, Lawrence Berkeley National Lab, *S.-K. Kim*, Seoul National University, Republic of Korea

Research in magnetism is motivated by the scientific curiosity to understand and control spins on a nanoscale and thus to meet future challenges in terms of speed, size and energy efficiency of spin driven technologies. Imaging magnetic structures and their fast dynamics down to fundamental magnetic length and time scales with elemental sensitivity in emerging multi-element and nanostructured materials is highly desirable. Magnetic soft X-ray microscopy is a unique analytical technique combining X-ray magnetic circular dichroism (X-MCD) as element specific magnetic contrast mechanism with high spatial and temporal resolution [1]. Our approach is to use Fresnel zone plates as X-ray optical elements providing a spatial resolution down to currently 10nm [2] thus reaching out into fundamental magnetic length scales such as magnetic exchange lengths. The large field of view allows to investigate both the complexity, but also the stochasticity of magnetic processes, such as nucleation or reversal. Utilizing the inherent time structure of current synchrotron sources fast magnetization dynamics such as current induced wall and vortex dynamics in ferromagnetic elements can be performed with a stroboscopic pump-probe scheme with 70ps time resolution, limited by the lengths of the electron bunches.

We will present studies of magnetic vortex structures, where we found a stochastic character in the nucleation process, which can be described within a symmetry breaking DM interaction [3]. We will also present time resolved studies of dipolar coupled magnetic vortices, where we find an efficient energy transfer mechanisml, which can be used for novel magnetic logic elements [4].

This work was supported by the Director, Office of Science, Office of Basic Energy Sciences, Materials Sciences and Engineering Division, of the U.S. Department of Energy under Contract No. DE-AC02-05-CH11231.

[1] P. Fischer, *Exploring nanoscale magnetism in advanced materials with polarized X-rays*, Materials Science & Engineeering R72 81-95 (2011)

[2] W. Chao, P. Fischer, T. Tyliszczak, S. Rekawa, E. Anderson, P. Naulleau, Optics Express **20(9)** 9777 (2012)

[3] M.-Y. Im, P. Fischer, Y. Keisuke, T. Sato, S. Kasai, Y. Nakatani, T. Ono, *Symmetry breaking in the formation of magnetic vortex states in a permalloy nanodisk*, (2012) submitted

[4] H. Jung, K.-S. Lee, D.-E. Jeong, Y.-S. Choi, Y.-S. Yu, D.-S. Han, A. Vogel, L. Bocklage, G. Meier, M.-Y. Im, P. Fischer, S.-K. Kim, NPG - Scientific Reports 1 59 (2011)

11:40am **MI+SP+AS-ThM12 Elemental and Magnetic Contrast using X-ray Excited Luminescence Microscopy**, ***R.A. Rosenberg***, *S. Zohar, D. Keavney,* Argonne National Laboratory, *A. Mascarenhas, M. Steiner,* National Renewable Energy Laboatory, *D. Rosenmann, R.S. Divan,* Argonne National Laboratory

We have developed an imaging technique based on x-ray excited luminescence microscopy (XELM), that will enable elemental and magnetic specific imaging of a wide range of materials such as those used in solar cells, magnetic materials, spintronic devices, ferroelectrics, and solid-state lighting. This new scientific tool utilizes the benefits of pulsed, polarized, tunable synchrotron radiation excitation with microscopic detection of the resulting optical emission. A unique offshoot of the microscope is the ability to perform element specific magnetic microscopy of micron-sized features or domains in magnetic fields. X-rays transmitted through thin films are attenuated and the resultant absorption spectrum can be determined by changes in the substrate luminescence. Since many substrates, such as $SrTiO_3$ and GaAs, used in thin film growth have intense optical emission, this tool should impact many materials where photoelectron emission microscopy (PEEM) cannot be performed since it is not useable on insulating materials or if magnetic or electric fields are required. This approach will be especially useful at low temperatures where luminescence yields are highest, and PEEM has difficulties. In this presentation we will present some initial results from the microscope on some prototype solar cell materials and lithographically patterned Permalloy/GaAs and Permalloy/Cu/Co/GaAs samples. The results demonstrate the potential of XELM for elemental and magnetic specific imaging.

This work was performed at the Center for Nanoscale Materials and the Advanced Photon Source. It was supported by the U.S. Department of Energy, Office of Science and Office of Basic Energy Sciences under the contract number DE-AC02-06CH11357 and by the Department of Energy, Energy Efficiency and Renewable Energy, Solid State Lighting Program.

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