Magnetic Interfaces and Nanostructures
Room: 230A - Session MI-TuM

Oxides, Fluorides, and Spin Structures
Moderator: Greg Szulczewski, The University of Alabama

8:00am **MI-TuM1 Magnetic Interactions at Perovskite Oxide Interfaces**, ***Yayoi Takamura**, B. Li, R.V. Chopdekar,* University of California, Davis, *E. Arenholz,* Lawrence Berkeley National Laboratory, *A. Mehta,* SLAC National Accelerator Laboratory, *M.D. Biegalski, H.M. Christen*, Oak Ridge National Laboratory **INVITED**

Perovskite-structured oxides possess a wide range of intriguing and technologically relevant functional properties including ferromagnetism, ferroelectricity, and superconductivity. Furthermore, the interfaces of perovskite oxides have been shown to exhibit unexpected functional properties not found in the constituent materials. These functional properties arise due to various structural and chemical changes as well as electronic and/or magnetic interactions occurring over nanometer length scales at the interfaces, and they have the potential to be harnessed to enable new, more versatile, and energy efficient devices. In particular, magnetic exchange coupling at ferromagnetic/ antiferromagnetic (FM/AFM) and FM/FM interfaces are crucial due to their applications in magnetic technologies such as magnetic read heads and nanostructured permanent magnets. In this talk, we report on a unique spin-flop coupling observed at FM $La_{0.7}Sr_{0.3}MnO_3$ (LSMO)/AFM $La_{0.7}Sr_{0.3}FeO_3$ (LSFO) interfaces and contrast these interfaces to FM/FM interfaces consisting of hard FM $La_{0.7}Sr_{0.3}CoO_3$ (LSCO) and soft FM LSMO where exchange-spring behavior has been observed. Detailed structural and magnetic characterization of the individual layers was carried out using a combination of resonant x-ray reflectometry and element-specific soft x-ray magnetic spectroscopy, which provide more insight into interfacial effects over conventional characterization techniques such as bulk magnetometry. Our results indicate that the complex interplay between the charge, lattice, spin and orbital degrees of freedom at perovskite oxide interfaces provides a versatile route to control magnetic switching behavior as required for advanced magnetic device applications.

8:40am **MI-TuM3 X-ray Imaging of Magnetism at the Nanoscale**, ***Stefano Bonetti**,* Stockholm University, Sweden, *R. Kukreja, Z. Chen,* Stanford University, *F. Macia, J.M. Hernandez,* Universitat de Barcelona, Spain, *A. Eklund,* KTH Royal Institute of Technology, Sweden, *D. Backes,* New York University, *J. Frisch,* SLAC National Accelerator Laboratory, *Y. Acremann,* Laboratorium für Festkörperphysik, ETH Zürich, Switzerland, *J. Katine,* HGST, *G. Malm,* KTH Royal Institute of Technology, Sweden, *S. Urazhdin,* Emory University, *A.D. Kent,* New York University, *Ohldag, J. Stöhr, H.A. Dürr*, SLAC National Accelerator Laboratory **INVITED**

In this talk, I will describe the new scanning x-ray transmission microscope instrument that we recently built at the Stanford Synchrotron Radiation Lightsource (SSRL), at the SLAC National Accelerator Laboratory. In a single experiment, we are now able to measure extremely small magnetic, elemental and chemical signals at the nanoscale (with 35 nm resolution), in buried layers. We can also achieve a temporal resolutions of 50 ps, and synchronize our instrument to a microwave generator in order to detect excitations of up to 10 GHz in frequency. In order to show the capabilities of our technique, I will present two of our most recent results.

At first, I will discuss our successful attempt to directly image the injection of spins from a thin film ferromagnet into a non-magnetic Cu layer, when a bias current is fed through the ferromagnet/non-magnet interface. The elemental and chemical specificity of x-rays allows us to distinguish spin accumulation on Cu atoms located at the interface from those within the bulk of the Cu film. Spin accumulation in the film gives rise to an average transient magnetic moment per Cu atom of 3×10^{-5} μ_B around the Fermi level, which we explain using Mott's two current model. We also find a greatly enhanced transient moment on the Cu interface atoms, which we attribute to enhanced spin dependent scattering via localized interface states.

Then, I will present the first time-resolved x-ray images of the spin-wave soliton generated by spin-torque when a spin-polarized current is injected from a nano-contact into an extended magnetic layer, a 5-nm thick permalloy ($Ni_{80}Fe_{20}$) film. The circular polarization of the photons, tuned at the resonant L_3 absorption edge of Ni, allows for selectively probing the dynamics of the magnetization in the film. By synchronizing the spin waves oscillations to the RF cavity of the synchrotron, we are able to create a phase resolved map of the magnetic excitation, i.e. a spin-wave "movie." The unprecedented combined temporal and spatial resolution, and the ability to look through the thick metal electrodes that provide the current necessary to excite the dynamics, reveal intriguing details of the spin-wave dynamics. In particular, we observe the emergence of a novel localized spin-wave soliton with a nodal line, i.e. with *p*-like symmetry, qualitatively different from the predicted solitonic excitation with essentially cylindrical symmetry (i.e. *s*-like).

Our studies provide a deeper understanding of magnetism at the nanoscale, and highlight the importance of nanoscale time-resolved techniques to tackle the challenges of modern magnetism.

9:20am **MI-TuM5 Complex Fluorides: A New Class of Multiferroic and Magnetoelectric Materials**, ***David Lederman**, A. KC, T.A. Johnson, C. Cen, A.H. Romero, P. Borisov*, West Virginia University **INVITED**

Transition metal fluoride antiferromagnets have been used to study the fundamental properties of exchange bias and magnetism at the interface between antiferromagnets and ferromagnets. The highly ionic nature of these compounds makes them ideal candidates for studying fundamental magnetic properties. Less studied are multiferroic fluoride compounds such as the orthorhombic $BaMF_4$ or the perovskite $NaMF_3$ materials, where M is a transition metal. Recent theoretical and computational work has suggested that the some of the $BaMF_4$ compounds should be magnetoelectric and that the perovskite fluoride compounds in particular should have large canting of the antiferromagnetic structure which results in strong weak ferromagnetism. In this talk I will describe recent work in the growth of thin films of these materials using molecular beam epitaxy. Their magnetic properties were measured using SQUID magnetometry and their ferroelectric properties were measured using scanning probe microscopy and direct ferroelectric polarization measurements. For the $BaMF_4$ compounds, we were able to confirm that the Ni and Co compounds are multiferroic, while the Fe compound is definitely not multiferroic. I will also discuss the growth of $NaMnF_3$ thin films and their magnetic and dielectric properties as a function of temperature and magnetic fields.

11:00am **MI-TuM10 Spin-Dependent Size of Interband Hybridization Gap: The Interplay of Adlayer and Substrate States in Pb/Cu(111)**, ***Markus Donath**, S.N.P. Wissing, K.T. Ritter, A.B. Schmidt, P. Krueger*, Muenster University, Germany

In view of spintronics applications, spin-polarized valleys are a key issue to realize spin-polarized currents. To date, spin-polarized valleys have been discovered in surface states at high-symmetry points in momentum space (see, e.g., [1]). We propose and have discovered an alternative way of producing spin-polarized valleys via hybridization gaps induced by spin-orbit interaction. So far, spin-orbit-influenced hybridization led to spin-dependent avoided band crossings, yet with no energy gap of spin-dependent size, i.e., no spin-polarized valleys.

We investigated the unoccupied electronic structure of Pb/Cu(111) by spin- and angle-resolved inverse photoemission. In these studies, we discovered a hybridization gap with spin-dependent size, about 200 meV for the one and even larger than 500 meV for the other spin direction, although not in a fundamental band gap at the Fermi level. Yet more importantly, we revealed the mechanism behind the formation of this spin-dependent valley-like gap structure by a tight-binding model based on *ab initio* calculations: The way of how adlayer and substrate states interact [2].

[1] K. Sakamoto et al., Nat. Commun. **4**, 2073 (2013).

[2] S.N.P. Wissing et al., Phys. Rev. B (Rapid Communications), accepted (2015).

11:20am **MI-TuM11 Energy Dispersion and Spin Structure of Unoccupied Electronic States of BiTeI: A Matter of Surface Termination?**, ***Christian Langenkämper****, *K. Miyamoto, A.B. Schmidt, P. Krüger, M. Donath*, Westfälische Wilhelms-Universität Münster, Germany

Recently, a new class of "Rashba materials" has been discovered: Non-centrosymmetric materials like MoS_2 [1] and BiTeI [2] show a lifting of the spin degeneracy in the electronic structure due to the bulk Rashba effect. So far, studies on BiTeI are limited to the occupied band regime and its Rashba-type spin dependence. For future applications, e.g. opto-spintronics, a substantiated knowledge about the complete spin-dependent electronic structure, occupied as well as unoccupied, is needed.

We present a combined experimental and theoretical study on the unoccupied electronic structure of BiTeI along the Γ-K direction. In our spin-resolved inverse photoemission measurements, we found a strong influence of the sample quality on the energy dispersion around the Γ point. Based on band structure calculations, we attribute this effect to different

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surface terminations, Te or I. Due to band bending, the different terminations have a direct consequence for the band dispersion. This effect is not observed at K, where the spectra do not depend on the surface quality. We will discuss this result in the context of *ab initio* band structure calculations. - In addition, we studied the spin structure of the bands along Γ-K. Around the Γ point, we found in-plane spin polarization in agreement with previous photoemission experiments for the occupied states [2]. Upon approaching K, the direction of the spin polarization rotates from in-plane to fully out-of-plane in accordance with the crystal symmetry.

[1] Suzuki *et al*., Nature Nanotechnology **9**, 611 (2014)

[2] Ishizaka *et al*., Nature Materials **10**, 521 (2011)

11:40am **MI-TuM12 Abnormal Asymmetric Domain Expansion and Skyrmion Bubble Stability in Thin Films with Strong Dzyaloshinskii-Moriya Interaction**, ***Lucas Caretta****, M. Mann, AJ. Tan, G.S.D. Beach*, Massachusetts Institute of Technology

The Dzyaloshinskii-Moriya interaction (DMI) at heavy-metal/ferromagnet interfaces can stabilize chiral spin textures [1]. It has recently been shown that field-driven bubble domain expansion in perpendicularly-magnetized thin films is asymmetric under the application of an in-plane field, which can be used to quantify the DMI effective field in the domain wall (DW) [2]. We have imaged domain expansion in Pt(3nm)/Co(0.9nm)/Pt(x)/GdOx(3nm) films using wide-field Kerr microscopy to characterize this behavior systematically as a function of DMI strength. In the case of null or weak DMI, realized when top and bottom Pt layers are of similar thickness, the in-plane field dependence of the DW velocity is well-described by the simple expansion model derived in Ref. [2]. However, in the case of strong DMI, we find a strongly nonmonotonic behavior due to flattening of the DW, minimizing Zeeman energy and DMI energy. Moreover, we show that when the ratio of the DMI effective field to the perpendicular anisotropy field is large, expanding bubble domains leave behind fine-scale dendritic structures, consisting of coupled 360 degree DWs. These dendritic structures can be manipulated to form stable skyrmion bubbles. We show that the stability of skyrmion bubbles is a strong function of the applied in-plane field near the DMI field. The skyrmion bubble annihilation field becomes deterministic at large in-plane fields.

1. A. Fert et al., Nat. Nano., 8, 152-156 (2013)

2. S.G. Je et al., PRB 88, 214401 (2013)

12:00pm **MI-TuM13 Control and Characterization of Magnetic Domain Patterns in Complex Oxide Microstructures**, ***Michael Lee****, T. Wynn, R.V. Chopdekar,* University of California, Davis*, E. Folven, J. Grepstad,* Norwegian University of Science and Technology*, A. Scholl, A. Young,* Lawrence Berkeley National Laboratory (LBNL)*, S. Retterer,* Oak Ridge National Laboratory*, Y. Jia, B. Li, Y. Takamura*, University of California, Davis

Future memory devices must achieve improved storage density, stability, and low power consumption. To this end $La_{0.67}Sr_{0.33}MnO_3$ (LSMO) is a promising material due to the confluence of many scientifically interesting functional properties, including ferromagnetism, colossal magnetoresistance, and high spin-polarization. The ability to tune these properties through a number of different stimuli is equally encouraging. In order to utilize LSMO the magnetic behavior of nanostructures must be well characterized, but due to the vast array of energetically competitive interactions present, size effects play a significant role in oxide nanostructures.

In this work we investigated the evolution of domain structure as a function of temperature in micromagnets patterned into epitaxial films of LSMO via x-ray photoemission electron microscopy (XPEEM). Results showed transitions from vortex to Landau patterns in circular patterns (2μm in diameter) indicating that saturation magnetization and magnetocrystalline anisotropy (K_1) have different dependence on temperature. Additionally, squares (also 2μm) with edges aligned along the hard magnetization axis began in the Landau state dictated by shape anisotropy, but developed distinct inner and outer flux closure structures as K_1 becomes stronger at lower temperatures. This could mean the creation of magnetic domain structures in devices that have more fine-tuned and efficient behavior. The presence of these novel spin-textures has been used to extract approximate fundamental magnetic parameters for LSMO at micro- and nano-dimensions. We have developed a method to extract values of K_1 from simulations of the observed XPEEM images. Parameters obtained from circular micromagnets were used to simulate other experimentally observed magnetic domain structures and confirm the validity of the procedure. This is a new analysis technique making it possible to locally measure magnetic properties in structures that would otherwise be difficult or impossible to characterize.

Novel spin-textures have been observed as a direct result of studying materials systems that express magnetocrystalline anisotropy. Using the newly developed technique, approximate values of magnetocrystalline anisotropy have been uncovered for the micromagnets studied to more clearly describe the magnetic behavior of LSMO nanostructures. The outcome of this project will improve the quality of future research due to a deeper understanding of the delicate balance of energies.

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