Magnetic Interfaces and Nanostructures Division
Room On Demand - Session MI-Contributed On Demand
Magnetic Interfaces Contributed On Demand Session

MI-Contributed On Demand-1 Direct Imaging of the Ac Component of the Pumped Spin Polarization With Element Specificity,
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For the development of novel spintronic devices, it is important to understand the dynamic magnetic processes on the micro- and nanoscale [1]. In spintronics the generation and manipulation of pure spin currents is in the focus of research activities. Amongst the utilized fundamental effects is spin pumping where a precessing magnetization of a ferromagnet being at ferromagnetic resonance (FMR) transfers angular momentum to an adjacent nonferromagnetic layer [2], i.e. spin current. By using lithographically fabricated micro-resonators it is possible to measure FMR of the small samples with a detection sensitivity of down to 10^6 spins [3]. These micro-resonators allow combining STXM with XMCD spectroscopy and FMR (STXM-FMR). The STXM-FMR setup enables the visualization of the high frequency magnetization dynamics in the GHz regime with a high lateral resolution of nominally 35 nm and a time resolution of 17.4 ps [4]. In this contribution we present the STXM-FMR results for thin magnetic Py ($Ni_{80}Fe_{20}$) microstrips with the lateral dimensions: 5x1 μm^2 measured individually and adjacently to the Co-doped ZnO thin film.

Two types of samples were investigated: single Py microstrips and a heterostructure consisting of Co-doped ZnO thin film with the Py microstrip placed on top (Co:ZnO/Py) in order to investigate the ac component of the pumped spin polarization directly inside the nonferromagnet with ultimate spatio-temporal resolution and elemental selectivity. For FMR and STXM-FMR measurements a static magnetic field was applied in the plane of the strips. Both FMR and STXM-FMR measurements confirm that quasi-uniform and spin-wave modes can be excited in the Py microstrips. The results for the single Py strip show, that with increasing the static magnetic field it is possible to observe the transition from one mode to another and additionally observe superposition of the modes in-between the FMR signals. When superposition of the modes occurs, a non-standing character of the spin-waves can be observed for the Py strip. For the Co:ZnO/Py sample we demonstrate the feasibility to investigate the lateral distribution of the pumped ac spin polarization inside the adjacent non-ferromagnet, when Py microstrip is driven into quasi-uniform main FMR excitation or a spin-wave excitation [5].

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MI-Contributed On Demand-4 Breaking Time-Reversal Symmetry at the M Point: Spin Signal from a Surface State on Tl/Ge(111),
***Markus Donath**, P. Eickholt, P. Krüger, S. Stolwijk, A. Schmidt,* Westfälische Wilhelms-Universität Münster, Germany

We report on an additional effect influencing the observed spin polarization in SARPES (spin- and angle-resolved photoemission) and SRIPE (spin-resolved inverse photoemission) experiments. We detected and analyzed a spin-dependent intensity asymmetry for spin-degenerate surface states at the M point in the unoccupied electronic structure of Tl/Ge(111)-(1x1) [1]. Approximating the initial state by a plane wave, we calculated the SRIPE process and obtained good agreement with the experimental data [2]. Our model reveals that this spin asymmetry at a point of time-reversal invariant momentum (TRIM) is of different origin than other effects discussed in the literature, which are based on the light detection geometry, photon energy, and experimental probing depth of the electrons. Instead, the spin asymmetry in this nonmagnetic material with spin-orbit interaction is caused by breaking the initial-state time-reversal symmetry in the experiment. Since SARPES and SRIPE are based on time-reversed processes, the effect is also expected for SARPES experiments where the outgoing photoelectrons break the time-reversal symmetry in the same way as the incoming electrons in SRIPE experiments. Understanding and considering such experimentally induced spin asymmetries is essential for correctly interpreting spin-resolved (inverse) photoemission data.

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MI-Contributed On Demand-7 Spin-orbit-induced effects in VLEED experiments from MoS_2/Au(111),
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The influence of spin-orbit interaction on low-energy electron reflection from MoS_2 on Au(111) was studied by VLEED (very-low-energy electron diffraction) [1,2,3]. Maps of the electron reflectivity and the spin asymmetry of the reflected

electron intensities were measured for a wide range of electron incidence angles and kinetic energies. To account for an adlayer coverage of about 30%, maps of the Au(111) substrate and for a MoS_2 bulk sample were measured as well.

The adlayer and substrate signals were distinguished by a comparison of the maps.

For MoS_2/Au(111), we obtained a spin asymmetry of the reflected intensities, which shows a characteristic feature with alternating sign in the energy region of a VLEED fine structure [1]. The Au(111) substrate, in contrast, shows qualitatively

different spin-asymmetry features, partially with reversed sign compared with MoS_2/Au(111). The results of bulk MoS_2 resemble the single-layer data to a great extend. The influence of the substrate on the results will be discussed.

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MI-Contributed On Demand-10 Direct Observation of Spin Accumulation in Cu Induced by Spin Pumping,
J. Ding, Argonne National Laboratory*; W. Zhang,* Oakland University*; B. Jungfleisch, J. Pearson,* Argonne National Laboratory*; **Hendrik Ohldag,*** Lawrence Berkeley Lab, University of California, Berkeley*; V. Novosad,* Argonne National Laboratory*; A. Hoffmann,* University of Illinois at Urbana Champaign

Pure spin currents have been ubiquitous in contemporary spintronics research. Despite its pro-found physical and technological significance, the detection of pure spin current has largely remained indirect, which is usually achieved by probing spin-transfer torque effects or spin-to-charge conversions. By using scanning transmission X-ray microscopy, we report the direct detection and spatial mapping of spin accumulation in a nonmagnetic Cu layer without any direct charge current injection. Such a pure spin current is induced by spin pumping from a $Ni_{80}Fe_{20}$ layer and is not accompanied by concomitant charge motion. The observed frequency dependence indicates that the signal is dominated by a coherent, pure spin current, but the magnitude of the spin accumulation suggests also possible additional thermal contributions. Our technique takes advantage of the X-ray magnetic circular dichroism and the synchronization of microwave with X-ray pulses, which together provide a high sensitivity for probing transient magnetic moment. From the detected X-ray signals, we observe two distinct resonance modes induced by spin pumping, Based on micromagnetic simulations, we attribute these two resonances to non-linear microwave excitations. Our result provides a new pathway for detecting pure spin currents that originate from many spintronics phenomena, such as spin Hall and spin Seebeck effects, and which can be applied to both metal and insulator spin current sources [1].

Work at Argonne, including experimental design and measurement, sample fabrication, data analysis, and manuscript preparation, was supported by the U.S. Department of Energy (DOE), Office of Science, Basic Energy Sciences, Materials Science and Engineering Division under Contract No. DE-AC02-06CH11357. Use of the Stanford Synchrotron Radiation Light source, SLAC National Accelerator Laboratory, is supported by the U.S. Department of Energy, Office of Science, Office of Basic Energy Sciences under Contract No. DE-AC02-76SF00515. W.Z. acknowledges the DOE visiting FacultyProgram.

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MI-Contributed On Demand-13 Spatially Resolved Ferromagnetic Resonance of a Single Fe_3O_4 Nanoparticle Chain Using Scanning Transmission X-Ray Microscopy*, **Thomas Feggeler**, B. Zingsem, R. Meckenstock,* University of Duisburg-Essen, Germany*; H. Ohldag,* Lawrence Berkeley National Laboratory (LBNL)*; M. Farle, H. Wende, K. Ollefs,* University of Duisburg-Essen, Germany

Scanning Transmission X-Ray Microscopy imaged Ferromagnetic Resonance (STXM-FMR) [1, 2] at the Fe L_3-edge was used for the first-time detection of the magnetization dynamics of a bi-segmented chain of 19 Fe_3O_4 nanoparticles (particle diameter: 40-50 nm), naturally grown inside a bacterium Magnetospirillum Magnetotacticum MS-1. A uniform resonant excitation within the chain segments was measured element specifically with a spatial resolution of about 50 nm and pico second time resolution. Micromagnetic simulations of a corresponding nano particle chain agree well to the observations made in the experiment. The combination of conventional Ferromagnetic Resonance, micromagnetic simulations and STXM-FMR allows the comprehensive characterization of magnetization dynamics on the nanoscale, necessary for the development of genetically engineered spin wave computing devices, as suggested in [3].

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MI-Contributed On Demand-16 Scanning NV Magnetometry for Semiconductor Device Analysis*, U. Celano,* IMEC, Belgium*; **Peter Rickhaus**, H. Zhong,* Qnami AG, Switzerland*; F. Ciubotaru,* IMEC, Belgium*; L. Stoleriu,* Alexandru Ioan Cuza University, Romania*; A. Stark, F. Favaro de Oliveira, M. Munsch,* Qnami AG, Switzerland*; P. Favia, M. Korytov, P. Van Marcke,* IMEC, Belgium*; P. Maletinsky,* Qnami AG, Switzerland*; C. Adelmann, P. van der Heide ,* IMEC, Belgium

Scanning NV magnetometry (SNVM) is an emerging quantum sensing technique which allows to measure minute magnetic fields with nanoscale resolution. We present a specific use-case of SNVM: the characterization of magnetic nanowires. Magnetic nanowires are among the essential building-blocks of contemporary spintronic devices since their magnetic properties can be tuned by their geometry, and their fabrication is compatible with standard semiconductor fabrication schemes. While their topography and homogeneity can be well characterized with established techniques, it remains difficult to access their microscopic *magnetic* properties which are key to improve device performance.

Here, we demonstrate magnetic imaging of ultra-scaled magnetic nanowires by SNVM. The imaging reveals the presence of weak magnetic inhomogeneities inside in-plane magnetized nanowires that are largely undetectable with standard metrology. In this context, we will discuss the potential of SNVM for semiconductor device analysis.

MI-Contributed On Demand-19 $Co_2Fe_{1.25}Ge_{0.75}$: Single-Phase, Highest Magnetic Moment, Highest Curie Temperature*, **Shambhu KC**, R. Mahat,* The University of Alabama*; S. Regmi,* University of Alabama*; J. Law,* The University of Alabama*; V. Franco,* Universidad de Sevilla, Spain*; G. Mankey, W. Butler, A. Gupta, P. LeClair,* The University of Alabama

Spintronic device performance is compromised when thermal effects impact magnetic properties and spin polarization of the materials [1]. One way of mitigating this problem is to find materials having a very high saturation moment (MS) and high Curie temperature (TC). The full Heusler alloy Co2FeGe theoretically has promise to meet this demand. However, its inability to form a single-phase compound makes it problematic for application. The addition of a fourth element is sometimes useful in stabilizing a single-phase compound [2], but it can be detrimental to some properties, particularly due to the increased probability of chemical disorder. In this talk, we present the successful synthesis of a single-phase compound based on Co2FeGe, viz Co2Fe1.25Ge0.75, by altering the stoichiometry rather than adding a fourth element. For the single-phase compound, MS as high as 6.7 ± 0.1 μB/f.u. at 5K and a Curie temperature of 1135 ± 5 K are measured – to our knowledge the highest reported for full Heusler alloys. In addition, thin films of Co2Fe1.25Ge0.75 deposited on Al2O3(110) and MgAl2O4(100) substrates are highly epitaxial. The structural quality of the films can be argued to be among the best reported for Heusler films to date. The thin film MS values also agree with the bulk MS. First principle calculations suggest the system exhibits total energy minimum at the experimental lattice parameter. These calculations also predict an enhancement in magnetization with a value closer to the experimental value. Hence, the highest moment, highest Curie temperature, and the ability to grow excellent quality single crystal films make Co2Fe1.25Ge0.75 a strong candidate for many device applications.

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MI-Contributed On Demand-22 Defects in Magnetic Weyl Semimetal $Co_3Sn_2S_2$*, **Zheng Gai**, Q. Zou, M. Fu, L. Zhang,* Oak Ridge National Laboratory*; R. Xue,* University of Tennessee Knoxville*; J. Yan,* Oak Ridge National Laboratory*; M. David,* University of Tennessee Knoxville*; M. Yoon,* Oak Ridge National Laboratory, USA

Co3Sn2S2 is a magnetic Weyl semimetal with kagome-lattice. In such samples, the existence of bulk Weyl nodes, which are formed under broken inversion or time-reversal symmetry, creates nontrivial topological properties like robust Giant anomalous hall effect. The surface–bulk correspondence ensures the bulk bands related topological "Fermi arc" surface bands dispersion. In this presentation, we use low temperature high magnetic field scanning tunneling microscope, spin polarized STM, and quasiparticle interference (QPI) to study the influence of local defects to the Weyl nodes movement, including magnetic and nonmagnetic vacancies and adatoms. S, Co and Sn vacancies and adatoms are identified, their behavior under magnetic field are studied. The interplay among topology, defects and magnetism are discussed for the understanding of the involved quantum phenomena.

This research was conducted at the Center for Nanophase Materials Sciences, which is a DOE Office of Science User Facility.

MI-Contributed On Demand-25 Optimizing Magneto-Elastic Coupling in Multilayer Fega/NiFe Thin Films for Magneto-electric Applications*, **Adrian Acosta**, J. Chang,* UCLA

Magnetoelectric (ME) materials provide the ability to efficiently control magnetism with electric fields, offering the potential to circumvent the size and efficiency limitations of traditional electronic devices. One barrier towards enhancing the efficiency in ME devices is the need for ferromagnetic materials that exhibit both a large magnetostriction and soft magnetic properties to yield a high magneto-elastic coupling. Additionally, for microwave ME applications, a low Gilbert damping is needed for low loss operation whereas materials with large magnetostriction typically exhibit high Gilbert damping coefficients due to their large spin lattice coupling (α ~ 0.2 vs ~ 0.03 for most ferromagnetic metals).

FeGa is a material of interest due to its large magnetostriction (~275 ppm in polycrystalline bulk) and large piezomagnetic coefficient (>2 ppm/Oe) but is highly lossy at high frequencies and exhibits a large magnetic hysteresis. Recent studies of FeGa/NiFe (1:1 volume fraction) multilayer (ML) thin films [1-2] have found that these nanolaminates can achieve a low coercivity (<10 Oe) and can reach a >4x increase in magnetoelectric coefficient compared to single phase FeGa films. However, prior work on FeCo/NiFe suggests that only a thin interlayer of NiFe is required to achieve a significant enhancement in soft magnetic properties [3]. In this work, we explore a multilayering strategy of FeGa with NiFe – (100 nm FeGa / N)/ (2.5 nm NiFe) – where N represents the total number of bilayers. It was found that 2 bilayers optimized the lowest in-plane coercivity (7 Oe) and Gilbert damping coefficient (0.014). Compared to multilayers with an insulating layer insertion, this is less than an order of magnitude lower than reported FeGaB(25 nm)/Al2O3/FeGaB(25 nm) (α = 0.24) [4] and within the same order of magnitude for MLs we have previously studied of FeGa(10 nm)/NiFe(10 nm)/FeGa(10nm) with an Al2O3 insertion (α = 0.006).

Furthermore, it is expected that the magnetostriction increases linearly with the number of bilayers as the contribution from interfacial magnetostriction also increases. XRD and AFM imaging are used to correlate the coercivity, gilbert damping, and magnetostriction with the grain size and surface roughness of the composite film with increasing number of bilayers. This ML strategy shown here can be used to help design materials with a higher magneto-elastic coefficient for strain-mediated magnetoelectric devices.

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MI-Contributed On Demand-28 Large Temperature Dependent Spin Torque Efficiency in Antiferromagnetic FeRh*, Jonathan Gibbons,* University of Illinois at Urbana Champaign*; T. Dohi,* Tohoku University, Japan*; H. Saglam,* Yale University*; J. Pearson,* Materials Science Division, Argonne National Laboratory*; S. Fukami,* Tohoku University, Japan*; A. Hoffmann,* University of Illinois at Urbana Champaign

Magnetic ordering is an attractive trait in spin source materials for spintronics applications, as this ordering can break the material's symmetry and allow for ordinarily forbidden exotic spin torques ideal for efficiently controlling perpendicularly magnetized nanomagnets or driving spin torque oscillators for energy-efficient neuromorphic computing. In ferromagnetic materials, controlling the magnetic ordering direction can control the spin polarization of the generated spin currents. Iron rhodium (FeRh) exhibits a transition between a low-temperature antiferromagnetic (AFM) state and a high-temperature ferromagnetic (FM) state. For appropriate growth parameters, this transition can be found close to 300K, such that both the FM and AFM states are stable at room temperature, making it an ideal material for probing the influence of magnetic ordering on spin geometry. We investigate the influence of magnetic ordering and present measurements of the spin torque efficiency in iron rhodium over a range of temperatures, and report large exotic spin torques in anti-ferromagnetic FeRh that grow significantly as the temperature is varied, and consider the possible influence of magnetic ordering on these findings.

This work was supported as part of Quantum Materials for Energy Efficient Neuromorphic Computing, an Energy Frontier Research Center funded by the U.S. DOE, Office of Science.

MI-Contributed On Demand-31 Effect of Sn Doping on Surface States of Bi_2Se_3 Thin Films*, Jennifer DeMell,* *G. Stephen,* Laboratory for Physical Sciences*; I. Naumov,* Howard University*; S. Tyagi,* University of Maryland, College Park*; O. Vail,* Army Research Laboratory*; M. Dreyer,* University of Maryland, College Park*; R. Butera, A. Hanbicki,* Laboratory for Physical Sciences*; P. Taylor,* Army Research Laboratory*; I. Mayergoyz,* University of Maryland, College Park*; P. Dev,* Howard University*; A. Friedman,* Laboratory for Physical Sciences

Bi_2Se_3, widely studied as a topological insulator, has great potential for applications in low-power electronics and quantum computing. Intrinsic doping, however, presents a persistent challenge, leading to predominantly bulk conduction. In this work, we use substitutional Sn dopants to control the Fermi level in Bi_2Se_3 films. Scanning tunneling microscopy (STM) shows a shift in the local density of states toward the Dirac point as more Sn is incorporated. Density functional theory calculations elucidate the STM results, showing that Sn adds metallic states near the Fermi level that are localized to the defect sites while leaving the Dirac cone undisturbed. Electronic transport measurements demonstrate that the Sn defects increase the separation between bulk and surface states, though bulk conduction remains a dominant component.

MI-Contributed On Demand-34 Control of Domain Wall Patterning and Anomalous Response Functions in Ferrimagnetic Spinels*, Lazar Kish,* University of Illinois at Urbana-Champaign*; A. Thaler,* Oak Ridge National Laboratory*; M. Lee,* Los Alamos National Laboratory*; A. Zakrzewski,* University of Illinois at Urbana-Champaign*; D. Reig-i-Plessis,* University of British Columbia, Canada*; B. Wolin, X. Wang,* University of Illinois at Urbana-Champaign*; K. Littrell,* Oak Ridge Natinal Laboratory*; R. Budakian,* University of Waterloo, Canada*; H. Zhou,* University of Tennessee Knoxville*; Z. Gai, M. Frontzek,* Oak Ridge National Laboratory*; V. Zapf,* Los Alamos National Laboratory*; A. Aczel, L. DeBeer-Schmitt,* Oak Ridge National Laboratory*; G. MacDougall,* University of Illinois at Urbana-Champaign

The ferrimagnetic spinels are known for anomalous magnetoresponsive behaviors which stem from strong spin-lattice coupling and orbital ordering effects. Single crystals of these materials (Mn3O4, MnV2O4, FeV2O4) display a nanometer length-scale patterning of magnetostructural domains which is strongly correlated with these effects. The domain patterns are remarkably sensitive to environmental stress and controllable by applied magnetic fields. In this talk, we present reciprocal-space characterizations of these mesoscale patterns using small-angle neutron scattering, which allows us to correlate various response functions including inverse magnetoelastic effect and magnetodielectric effects with the onset and field response of domains. Meanwhile, neutron diffraction and small-angle X-ray scattering reveal a strong intertwining of these effects with lattice degrees of freedom, collectively establishing strain as an important tuning parameter for anomalous behavior in these materials.

MI-Contributed On Demand-37 Anomalous Hall Effect in Heterostructures Based on $MnBi_2Te_4$ Grown by MBE*, Seul-Ki Bac,* *L. Riney, J. Wang,* University of Notre Dame*; K. Koller,* Saint Mary's College*; X. Liu, M. Zhukovskyi, T. Orlova, M. Dobrowolska, J. Furdyna, B. Assaf,* University of Notre Dame

The intrinsic magnetic topological insulator $MnBi_2Te_4$ provides a great platform to explore quantum phenomena, such as quantum anomalous Hall effect and axion insulators, as reported earlier. However, the search of interesting electromagnetic effects in this material was hindered by the difficulty of preparing its high-quality films with well-controlled composition and thickness. In this study, we compare three different types of Mn-Bi-Te samples grown by molecular beam epitaxy: a heterostructure of $MnBi_2Te_4$ and Bi_2Te_3, a single $MnBi_2Te_4$ layer, and a heterostructure of $MnBi_2Te_4$, Bi_2Te_3, and MnTe. We measured the anomalous Hall effect (AHE) in each case and demonstrate its evolution from a two-component AHE contain the contribution of the MnTe and $MnBi_2Te_4$, to single component AHE resulting from few-layer $MnBi_2Te_4$ scattered out in a Bi_2Te_3 matrix, and finally to an antiferromagnetic AHE, characteristic of the pure phase of $MnBi_2Te_4$. Our work provides an understanding of the AHE for all three possible heterostructure compositions and paves the way for the realization of new quantum phenomena in pure $MnBi_2Te_4$ thin films.

MI-Contributed On Demand-40 Magnetic Transition Behavior of Epitaxial $Fe_{47}Rh_{47}Pd_6$ Films*, Gary Mankey,* University of Alabama*; H. Sato,* Tohoku University, Japan*; N. Pachauri,* Intel*; S. Keshavarz,* University of Alabama*; H. Lee,* Trinity College Dublin, Ireland*; P. LeClair,* University of Alabama*; O. Mryasov,* Department of Physics and Astronomy

The structural and magnetic properties of Fe-Rh-Pd epitaxial thin films grown on MgO(001) were studied as a function of growth temperature. Films grown above 400 C exhibit a first-order antiferromagnetic to ferromagnetic magnetic phase transition with a transition temperature that decreases as the growth temperature is increased. The chemical order parameter of the Fe-Rh-Pd films is nearly independent of the growth temperature, while the lattice constants change slightly. A comparison of our structural, magnetic, and electrical transport results with first-principles-based calculations as well as literature results indicate that the transition temperature of Fe-Rh-based alloy films depends sensitively on the lattice parameters, and is of electronic origin. The transition temperature and its width can be tuned over a wide range by controlling the crystal structure via growth conditions or post-deposition annealing.

MI-Contributed On Demand-43 The Critical Role of Checkerboard Spin Fluctuations in High-Tc Single Layer Iron Chalcogenide Superconductors*, Qiang Zou,* *H. Zhang,* West Virginia University*; T. Shishidou, M. Weinert,* University of Wisconsin Milwaukee*; L. Li,* West Virginia University

Single layer FeX (X=Te, Se, S) epitaxially grown on $SrTiO_3$ (STO) substrate represents a model system for probing a host of quantum phenomena due to the interplay of topology, magnetism and superconductivity.

For example, single layer FeTe exhibits long-range bi-collinear antiferromagnetic (AFM) order, which is not superconducting. We found that the AFM order, however, can be suppressed by alloying with Se at >10% concentrations, where enhanced superconductivity emerges [1]. Our spin spiral calculations further showed that the ground state is magnetically disordered paramagnetic, where local checkerboard (CB) AFM fluctuations is critical to the high Tc superconductivity in FeSe [2].

In this work, the impact of S incorporation into single layer FeSe is investigated. Our calculations indicate that the energy difference between CB and co-linear (CL) AFM order increases with increasing S. Fits of the spin-spiral dispersion to spin models leads to Heisenberg parameters J2/J1 of 0.55 for FeSe and 0.72 for FeS, placing the FeS system closer to the CL phase boundary and possibly decreasing the importance of CB fluctuations [3]. Experimentally, we synthesize high quality single layer $FeSe_{1-x}S_x$ films on STO(001) substrates by molecular beam epitaxy, and probe their electronic properties using scanning tunneling microscopy/spectroscopy and angle-resolved photoemission spectroscopy [3]. We observe that with increasing S concentration x, the Fermi surface at M point becomes more anisotropic and the effective mass decreases from 4.3 to 1.2 m_e, while the hole pocket at Γ point stays at 60 meV below the Fermi level. More importantly, no Tc enhancement is observed for films with x > 0.7. Our findings demonstrate that the CB AFM fluctuations plays an essential role in the enhanced superconductivity in epitaxial single layeriron chalcogenidesuperconductors on STO.

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MI-Contributed On Demand-46 Magnetic Anisotropy in a Single Crystal Antiferromagnetic Thin Film, ***Saima Siddiqui,*** University of Illinois at Urbana Champaign*; J. Pearson,* Argonne National Laboratory*; A. Hoffmann,* University of Illinois at Urbana-Champaign

Antiferromagnetic materials promise to show magnetization dynamics, including switching, at ultra-high frequency and thus are of immense interest for next generation memory and logic applications. Besides, spin waves in an antiferromagnetic insulators propagate very efficiently. However, electrically reading the states of the antiferromagnetic materials is not easy. Recently, spin Hall magnetoresistance (SMR) has been identified as one of the promising ways to access the surface states of the antiferromagnetic insulators. In this work, we focus on α-Fe_2O_3 insulator. We grow a 200-nm thick α-Fe_2O_3 film on (11-20) Al_2O_3 by reactive sputtering at 5 mTorr. A 6-nm thick Pt film is deposited in-situ on the Fe_2O_3 film. We measure the SMR of the patterned Hall bar structure of Pt at low temperatures and room temperatures. Below the Morin transition, we observe positive and negative magnetoresistance in the Pt/Fe_2O_3 bilayers depending on the direction of the current flow at the spin flop transition. This identifies that SMR can clearly determine the anisotropy of a thin film antiferromagnetic insulator. Moreover, we observe the spin-flop field of α-Fe_2O_3 using the Hall measurement in addition to the SMR measurement. The Hall magnetoresistance is 100x higher than the SMR at the spin-flop field. We will show a detailed study of the dependence of magnetoresistance on angular fields at different temperatures. Our study reveals important physical phenomena in the antiferromagnetic Fe_2O_3 thin film, which in turn will help to design energy efficient antiferromagnetic devices.

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MI-Invited On Demand-1 From Spin Spirals to Spin Glasses - Imaging Complex Magnetism on the Atomic Scale, ***Daniel Wegner,*** Radboud University, Nijmegen, Netherlands **INVITED**

I will present recent developments and discoveries in atomically resolved magnetic microscopy based on scanning probes (SPM). (a) A novel method we call SPEX microscopy combines spin-polarized scanning tunneling microscopy (SP-STM) with magnetic exchange force microscopy (MExFM), and enables the disentanglement of structural, electronic and magnetic contributions to the SPM signal [1]. This way, we were able to resolve the antiferromagnetic chiral spin spiral structure of a Mn monolayer on W(110) with unprecedented resolution [2]. (b) Our recent development of a dilution-fridge UHV SP-STM allows for the interrogation of in situ MBE-grown magnetic samples down to a temperature of 30 mK and in fields up to 9 T [3].

As a showcase, I will present the first atomic-scale magnetic microscopy results on the surface of the rare-earth element neodymium (Nd), whose complex magnetic ground state is still under debate after more than half a century of experiments. We surprisingly found evidence that Nd manifests the first example of a recently predicted new state of matter referred to as self-induced spin glass [4]. Contrary to the accepted paradigm that a spin glass requires structural disorder (as found in dilute magnetic alloys), self-induced glassiness can also occur in defect-free single crystalline materials. SP-STM experiments on extremely clean MBE-grown Nd(0001) films on W(110), combined with *abinitio* calculations and atomistic spin-dynamics simulations, reveal very complex non-collinear spin structures with local but no long-range order. By performing measurements at various temperatures (30 mK - 7 K) and as a function of magnetic field, we observed and quantified the aging phenomenon, which distinguishes spin glasses from quantum spin liquids or spin ice. We relate the glassy behavior to the crystalline symmetry, leading to competing magnetic interactions. This not only resolves the long-standing debate on the magnetic ground state of neodymium, but suggests that glassiness may arise in elemental solids without disorder if certain symmetry conditions are met.

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MI-Invited On Demand-7 Magnetic Exchange and Anisotropy in Perpendicular Magnetic Tunnel Junction Nanopillars: Experiment and Micromagnetic Modeling, ***Jamileh Beik Mohamadi,*** Loyola University New Orleans*; A. Kent,* New York University **INVITED**

Perpendicular magnetic tunnel junctions, pMTJs, are extensively used in industry for sensing and data storage applications. pMTJs are multilayered structures composed of several ferromagnetic and non-magnetic thin films, including a free layer with switchable magnetization. Reducing the dimensions of pMTJs, including the thickness of layers and the lateral size, is desirable to enhance the energy efficiency, speed, and data storage density. As the dimensions, mainly the thickness, of the magnetic film decrease, interfacial effects dominate, and the magnetic properties change. Of particular interest are the interfacial perpendicular magnetic anisotropy, PMA, and the exchange interaction of the pMTJ free layer that serves as write media. The reason is: 1) strong PMA is needed to obtain higher thermal stability of the device, and 2) exchange interactions set the length scale for micromagnetic inhomogeneities. Therefore, they both have a significant effect on the spin torque switching dynamics and the switching time[1, 2].

Interfacial anisotropy of the free layer drops inversely with its thickness. This implies that any spatial inhomogeneities of the film thickness alter the magnetic energy landscape, such as in the form of a higher-order perpendicular anisotropy. Moreover, the magnetic exchange interaction

(Heisenberg model) of the free layer thin film is reduced significantly compared to bulk values. We have observed this effect when we used VSM analysis used to determine the exchange constant of CoFeB thin film. Exchange interaction is reduced further for a composite CoFeB/W/CoFeB free layer in pMTJ stack. This reduction of exchange energy is also observed when dynamic methods such as spin-torque ferromagnetic resonance, ST-FMR, are used.

The higher-order anisotropy and the reduced exchange interaction in the free layer thin film also have significant effects on the spin-torque switching dynamics of the free layer. On the one hand, the presence of higher-order anisotropy reduces the switching time[2]. On the other hand, the reduced exchange interaction results in delayed switching[3]. I will present some of the implications of the above-mentioned effects on the switching dynamics and switching speed of pMTJ free layers.

Acknowledgments

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MI-Invited On Demand-13 Utilizing Vacuum States Above Surfaces for Imaging and Manipulation of Atomic-Scale Magnetism*, Anika Schlenhoff,* University of Hamburg, Germany **INVITED**

Non-collinear spin textures in ultra-thin film systems are in the focus of ongoing research. Specifically, atomic-scale magnetic skyrmions raise expectations for their application in information technology as logic spin-electronic devices or in recording media. For their characterization and manipulation spin-sensitive techniques with ultimate spatial resolution are required. Spin-polarized scanning tunneling microscopy (SPSTM) can resolve magnetic surface structures down to the atomic-scale. However, based on spin-polarized tunneling of electrons, this imaging technique is restricted to tip-sample separations of only a few Ångstroms, making the technique very fragile in terms of sensitivity to vibrations or for accidental, destructive tip-sample collisions. Ångstrom distances are also technically challenging for practical applications in future spin-electronic devices.

Spin-polarized vacuum resonance states (sp-RS) are unoccupied electronic states in the vacuum gap between a probe tip and a magnetic sample. As I will show in this talk, these states exhibit the same local spin quantization axis as the spin texture of the underlying sample surface, even when the spins are rotating on the atomic-scale [1]. In an SP-STM setup, the sp-RS can be addressed by spin-polarized electrons that tunnel resonantly from the magnetic tip into the surface, resulting in a magnetic image contrast governed by the spin-polarized electron tunneling into the sp-RS [1]. Our SP-STM experiments on ultrathin films with non-collinear spin textures demonstrate that this resonant tunneling allows for atomic-scale spin-sensitive imaging in real space at tip-sample distances of up to 8 nm. This technique provides a loophole from the hitherto existing dilemma of losing spatial resolution when increasing the tip-sample distance in a scanning probe setup [2]. Experimental results will be discussed in terms of the sp-RS' spin-splitting and the magnetic contrast as a function of bias and tip-sample distance, as well as in terms of the atomic-scale nature of the resonant tunneling condition between the probe tip and the sample.

The tip-sample distances demonstrated in this talk are in the range of present flying heights of read-write heads in data storage devices. In combination with thermally-assisted spin-transfer torque switching via sp-RS [3], our approach qualifies for a spin-sensitive read-write technique with ultimate lateral resolution in future spin-electronic applications.

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MI-Invited On Demand-19 Magnetism in Topological Crystalline Insulator Heterostructures*, Badih Assaf,* University of Notre Dame **INVITED**

Topological crystalline insulators (TCI) arise in the PbSnSe and PbSnTe material family and host valley degenerate surface states protected by mirror symmetry. The rocksalt crystal structure of these materials, and the wide tunability of their energy gap enables the realization of epitaxial heterostructures of TCIs and normal insulators, where topological interface states have been probed by magnetooptics. In this talk, I will discuss the recent growth and electrical magnetotransport characterization of heterostructures of TCI(Pb0.7Sn0.3Se)/EuSe, where the normal insulator is replaced by the magnetic insulator EuSe to obtain an interfacial Zeeman effect. Strong Shubnikov-de-Haas oscillations are observed in these structures evidencing their high carrier mobility. The oscillations coexist with the magnetism of EuSe, but further tuning of the Fermi level is likely needed to measure the impact of the Zeeman exchange on Landau levels. The realization of these heterostructures enables a direct determination of the exchange interaction energy induced by proximity, not yet measured for any topological insulator. Work supported by NSF-DMR-1905277.

MI-Invited On Demand-25 Moving Toward Antiferromagnetic Straintronics*, Michelle Jamer,* United States Naval Academy **INVITED**

Strain-coupled multiferroics are currently being pursued due to their enhanced tunability towards room temperature applications. [1] The artificial systems are proposed to augment intrinsic (single-phase) multiferroics, since they can be optimized for proposed systems via magnetoelectric coupling. Information storage needs are dramatically increasing and require sub 10 nm magnetic feature sizes and lower energy writing. [2] Traditional magnetic memory writing systems are plagued by large current densities for switching the magnetization, which causes the magnetic size for information storage to remain above this 10 nm magnetic feature ideal. [3]

Antiferromagnetic multiferroics are attractive or spintronic applications, since there is no external magnetic moment to interfere with surrounding components. In this talk, the systems with magnetostrictive Galfenol, Terfenol, and $Co_{1-x}Tb_x$ coupled to a piezoelectric PMN-PT will be discussed. Polarized neutron reflectometry (PNR) has been used in these systems to understand the unique reversal dynamics and the effect of voltage on the magnetization.[4] Overall, these measurements have shown that the strain-coupling could lead to the next generation of straintronic materials. Most interestingly, $Co_{1-x}Tb_x$ is a fully compensated ferrimagnetic material when x= 0.22, and has shown to have a fairly large magnetostriction, which could be the material of future straintronic devices.

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MI-Invited On Demand-31 A Two-Dimensional Atomically-Thin Manganese Gallium Nitride Magnetic Monolayer*, Y. Ma,* Ohio University*; D. Hunt,* GIyA, CAC-CNEA and Consejo Nacional de Investigaciones Cient´ıficas y T´ecnicas - CONICET, Argentina*; K. Meng,* The Ohio State University*; T. Erickson,* Ohio University*; F. Yang,* The Ohio State University*; M. Barral, V. Ferrari,* GIyA, CAC-CNEA and Consejo Nacional de Investigaciones Cient´ıficas y T´ecnicas - CONICET, Argentina***; Arthur R. Smith,*** Ohio University **INVITED**

Two-dimensional (2D) magnetic materials are of great interest for fundamental science as well as advanced applications. Besides 2D materials, the dilute magnetic semiconductors (DMS) have also captured worldwide interest by combining magnetism with electronic properties. MnGaN-2D is the ultimately-thin limit of a novel DMS material, but having a densely concentrated and well-ordered structural design. With 1/3 of the monolayer being magnetic manganese atoms, MnGaN-2D shows room-temperature ferromagnetism as demonstrated with spin-polarized scanning tunneling microscopy as a function of applied magnetic field, and as predicted by first-principles theoretical calculations which reveal the origins of the ferromagnetism through its highly spin-split and spin-polarized electronic structure.[1]

These results are backed up by SQUID magnetometry measurements which reveal a high spin-polarization of ∼79% at room temperature as well as perpendicular magnetic anisotropy. But this intriguing system shows even more interesting behavior as it turns out that its electronic structure is strain-dependent leading to the possibility of magneto-elasticity. Theoretical calculations reveal a high sensitivity of the spin-polarized electronic structure to lattice strain, offering one explanation for results from tunneling spectroscopy (*dI/dV*) measurements, which reveal unexpected variations in the electronic properties.

Simulations, including both isotropic and anisotropic cases, confirm a highly strain-dependent manganese partial density of states. Spin-orbit coupling is included which indicates either *out-of-plane* perpendicular magnetic anisotropy (PMA) or *in-plane* magetic anisotropy, dependent on the type of strain whether compressive or tensile. Clear evidence for both compressive and tensile local lattice strains is found by detailed analysis of atomic resolution STM images which reveal a highly non-Gaussian lattice spacing distribution.

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MI-Invited On Demand-37 Topological Multiferroics*, **Sinéad Griffin,*** Lawrence Berkeley Lab, University of California, Berkeley **INVITED**

Multiferroic materials that combine magnetism and ferroelectricity are described by order parameters in real space under the Landau's phenomenological theory. The recent strides in topological order -- described by reciprocal space invariants -- have identified several new classes of materials including topological insulators and Weyl/Dirac semimetals. In this talk I will address the question: how can topological order in reciprocal space be combined with, and possibly controlled by, real space order parameters such as magnetism and ferroelectricty? I will identify the fundamental design rules for their coexistence in several classes of materials and give examples how topological order can be controlled via multiferroic order parameters.

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