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

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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