Wednesday Afternoon, October 17, 2007

Magnetic Interfaces and Nanostructures

Room: 619 - Session MI-WeA

Nanomagnetic Imaging and Spectroscopy

Moderator: D. Pappas, National Institute of Standard and Technology

1:40pm **MI-WeA1 L10 Phase FePt Magnetic Force Microscopy Probes for Magnetic Domain Images**, ***S.H. Liou***, *L. Nicholl, R. Zhang,* University of Nebraska, *L. Yuan, D. Pappas,* National Institute of Standard and Technology, *B.S. Han,* State Key Laboratory of Magnetism, China

Selecting an appropriate probe for the sample type is important when imaging magnetic domains using magnetic force microscopy (MFM). We have developed a process for fabricating probes with L10 phase FePt that can image the domain structure of both hard and soft magnetic materials. Commercially available batch fabricated probes with micromachined tips are coated with 5 nm to 30 nm of FePt. After annealing at 650 oC for 1 hour to obtain the L10 phase, the probes are magnetized in a SQUID along a direction 100 from the z-axis. This produces tips with a magnetization direction perpendicular to the sample surface. The resolution of an MFM image is related to the tip-sample distance, which is less than 20 nm for high resolution images. At these distances, the stray field of a hard magnetic sample can be large enough to alter the magnetization direction of the tip, unless the tip has a high coercivity. With our technique, we produce tips with coercivities greater than 1 T—which, as we will demonstrate in this work, is suitable for imaging the domain structure of permanent magnets. Imaging soft magnetic materials presents a different problem; namely, if the stray field of the tip is larger than the coercivity of the sample, the tip will alter the domain structure of the sample—especially at the lift heights necessary for high resolution images. Our process produces tips with a stray field low enough for imaging the domain structure of soft magnetic materials at lift heights less than 20 nm. We have tested our tips on an array of NiFe dots in the vortex state; each element in the array having a diameter of around 600 nm. Since the center of the vortex is easy to move, the stray field from the tip must be small in order to obtain images with an unperturbed vortex center. In this work, we will show images of the dots with an undisturbed vortex in the center of each dot. These results show that our probes are suitable for imaging both hard and soft magnetic materials.

2:00pm **MI-WeA2 Magnetic Structures of Frustrated Square Lattices**, ***L. Gao***, *Z. Gai, S. Retterer, J.D. Fowlkes, J. Shen,* Oak Ridge National Laboratory

Thin films of ferromagnetic magnetic materials with lithographically designed geometries are model systems for the study of artificial spin ice or frustrated systems.[1] In this work, the square lattices, which are composed of four rectangular elements, were fabricated using electron beam lithography and lift-off technique. The frustrated magnetic domain structures of the square lattices were investigated using magnetic force microscope (MFM) and scanning electron microscope with polarization analysis (SEMPA). The magnetic structure of individual permalloy element is dominated by the shape anisotropy. Single domain can be obtained by optimizing the size and the aspect ratio of the element. The lattice spacing and size of elements were changed to investigate the interactions between elements and their effects on the moment configurations. The correlations between the elements decrease with increasing spacing and decreasing size of elements. The temperature and magnetic field dependences of the moment configuration of the lattices will be presented at the meeting. This research was conducted at the Center for Nanophase Materials Sciences, which is sponsored at Oak Ridge National Laboratory by the Division of Scientific User Facilities, U.S. Department of Energy.

[1] R. F. Wang, C. Nisoli, R. S. Freitas, J. Li, W. McConville, B. J. Cooley, M. S. Lund, N. Samarth, C. Leighton, V. H. Crespi, and P. Schiffer, Nature 439, 303 (2006).

2:20pm **MI-WeA3 Time Resolved X-ray Imaging of Magnetic Nanostructures Driven by Spin-transfer Torque**, ***J.P. Strachan****, Stanford Univ., *Y. Acremann,* Stanford Synchrotron Radiation Lab., *V. Chembrolu, X.W. Yu,* Stanford Univ., *A. Tulapurkar,* Stanford Synchrotron Radiation Lab., Stanford Univ., *T. Tyliszczak,* Lawrence Berkeley National Lab., *J. Katine, M. Carey,* Hitachi Global Storage Tech., *H.C. Siegmann, J. Stöhr,* Stanford Synchrotron Radiation Lab., Stanford Univ.

Spin-torque (or spin-transfer torque) is a novel phenomenon involving the transfer of angular momentum from a spin-polarized current to a ferromagnet. There is much excitement in the use of this effect for developing non-volatile, high density magnetic RAM, as well as for DC current-driven microwave oscillators. Indeed, steady-state precessional modes as well as full magnetization reversal of nanoscale magnetic elements driven by spin-torque have been observed. These observations have been via giant magneto-resistance measurements, using a reference "fixed" magnetic layer, which also serves as the spin-polarizer. Given the experimental challenges in probing thin, buried nanomagnets, the detailed magnetic configuration of the element has remained unknown. I describe a high resolution, time-resolved x-ray microscopy technique which provided the first direct images of the nanostructure during the switching process. Motion pictures with 200 ps time resolution and 35 nm spatial resolution reveal that the process is based on the transient formation of a vortex configuration. The vortex moves across the magnetic element, leaving behind a switched magnetization in its wake. A physical understanding of this unexpected mechanism is discussed, as well as the dependence on sample size and shape. It is seen that the sample dimensions are well within the single-domain regime. The highly non-uniform magnetic configuration which is transiently taken is initiated by the presence of the Oersted field, but primarily formed by the spin-torque. It is seen that other non-uniform switching mechanisms may dominate for smaller length scales.

2:40pm **MI-WeA4 Local Detection and Manipulation of Single Spins and Spin-Orbit Coupling at Surfaces**, ***K. Kern***, Max-Planck-Institut für Festkörperforschung, Germany **INVITED**

The spin state of single magnetic atoms and molecules at surfaces is not only of fundamental interest but may play an important role in future atomic-scale technologies. It can be determined via the Kondo resonance by low-temperature scanning tunneling microscopy. The Kondo effect originates from the screening of the spin of a magnetic impurity by the surrounding conduction band electrons and is characterized by a peak in the impurity's density of states near the Fermi level. As a second impurity is brought into proximity, magnetic interactions between the impurities become important and can modify the Kondo resonance considerably. Here, I demonstrate that it is possible to determine the magnetic interaction between single Co atoms adsorbed on a noble metal surface by measuring the modified Kondo spectrum. The results are compared to theoretical predictions of the magnetic interactions between single atoms. Increasing the interatomic distance of a Cobalt dimer from 2.56 to 8.1 Å we follow the oscillatory transition from ferromagnetic to antiferromagnetic coupling. Adding a third atom to the antiferromagnetically coupled dimer results in the formation of a collective correlated state. I will further demonstrate the ability to tune the coupling of individual cobalt adatoms with their surroundings by controlled attachment of molecular ligands. In the second part of the talk I will show that by scanning tunneling spectroscopy it is possible to extract the strength of the spin-orbit coupling in a two-dimensional energy band from the local density of states. The spin splitting of the surface state induces a singularity in the local density of states which can be detected as a distinct peak in the differential conductance spectrum. From the STS spectrum we can determine the Rashba energy as a measure of the strength of the spin splitting. Its detection and imaging are demonstrated for the surface alloys Bi and Pb on Ag(111), which exhibit particularly large spin-split band structures. The giant spin splitting in these systems opens up interesting perspectives in the field of spintronics.

4:00pm **MI-WeA8 Mapping Resonant Dissipative Behavior in Magnetic Nanostructures: The Role of Single Defects**, *S.V. Kalinin, S. Jesse,* Oak Ridge National Laboratory, ***R. Proksch***, Asylum Research

Dissipative dynamics in magnetic materials and nanostructures is directly related to the physics of wall pinning mechanisms and spin-lattice interactions. Understanding these mechanisms on the level of a single pinning center (e.g. dislocation, second phase inclusion, or other micro-structural element) is crucial for progress in magnetic device applications. Here, we report quantitative mapping of magnetic dissipation on a single

***** Falicov Student Award Finalist

defect center in single-crystal yttrium-iron garnet (YIG). The image formation mechanism in Magnetic Dissipation Force Microscopy is analyzed in detail, and it is shown that small frequency dispersion in the cantilever transfer function leads to qualitative errors if the Cleveland formula is used. This leads to cross-talk between the domain pattern and dissipation image. The correction algorithms based on (a) direct transfer function calibration and (b) statistical image analysis are suggested. To decouple the dissipation and force gradient signal, we have developed a novel excitation approach in SPM based on an excitation signal having a finite density in a frequency band in the Fourier domain. This band excitation method allows very rapid acquisition of the full frequency response at each point in an image and in particular enables the direct measurement of energy dissipation through the determination of the Q-factor of the cantilever-sample system. The use of standard MDFM and BE-MFM illustrated the presence of ring-type dissipation contrast associated with single defect centers, corresponding to energy loss of ~1 eV/oscillation. The distance dependence of the ring diameter suggests that the dissipation is resonant in nature and corresponds to well defined field magnitude. The crystallographic origins of the defects are analyzed. Similar contrast is observed in other nanomagnetic systems including nanocrystalline iron, and magnetic nanoparticles from magnetotactic bacteria. Research was sponsored by the Division of Materials Sciences and Engineering, Office of Basic Energy Sciences, U.S. Department of Energy at Oak Ridge National Laboratory, managed and operated by UT-Battelle, LLC.

4:20pm **MI-WeA9 Epitaxial Growth of Ultrathin Fe Films on Ni(111) Investigated by LEED and STM**, ***B. An***, *S. Fukuyama, K. Yokogawa*, National Institute of Advanced Industrial Science and Technology (AIST), Japan

Recently, the ultrathin Fe films on fcc substrates have attracted a great attention because of its novel magnetic properties, and thus the growth of ultrathin Fe films on Ni(111) has also been investigated by many surface techniques. However, the structures of the Fe films grown on Ni(111) have not yet been characterized in real space. In this study, we characterize the surface structures of ultrathin Fe films grown on Ni(111) at room temperature by LEED and STM. The Fe film grows first at the step edges of the Ni(111) substrate, then grows up on the large terraces of Ni(111) and the Fe films on Ni(111). The first monolayer Fe reveals two-dimensional fcc-Fe(111) on Ni(111). Some equilateral triangular lines consisting of dark spots aligned along the <1-10> direction with a spacing of 0.5 nm are observed on the monolayer Fe and interpreted by the creation of atomic vacancies in the first layer of Ni substrate due to the strain caused by the lattice misfit between the Fe monolayer and the Ni substrate. The second layer Fe reveals a striped structure consisting of parallel stripes running in the <11-2> direction with a spacing of approximately 1.7 nm. Such striped structure is attributed to the stacking fault of the second-layer Fe on the first-layer Fe. Further increasing of Fe films leads to the formation of slender islands running along the <1-10> direction. The growth processes of the ultrathin Fe films are discussed.

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