Magnetic Interfaces and Nanostructures
Room 206 - Session MI+NS+NANO 6-TuM

Magnetic Imaging I

Moderator: M. Miller, Naval Research Laboratory

8:20am **MI+NS+NANO 6-TuM1 Scanning Electron Microscopy with Polarization Analysis (SEMPA) Imaging of Surface and Thin Film Magnetic Microstructure***, **J. Unguris,*** National Institute of Standards and Technology **INVITED**

Scanning Electron Microscopy with Polarization Analysis (SEMPA) provides a direct image of a sample's magnetization by measuring the spin polarization of secondary electrons emitted in a scanning electron microscope (SEM). SEMPA therefore generates a high resolution picture of the direction and relative magnitude of the magnetization, in the same way that an SEM images topography by measuring the secondary electron intensity. With submomolayer magnetic sensitivity and probe sizes as small as 10 nm, SEMPA is sensitive to extremely small amounts of magnetic material. In particular, SEMPA's surface sensitivity makes it especially well suited for the direct, quantitative mapping of the magnetization direction in thin films and at the surface of magnetic materials. Comparisons between magnetic and physical structure in these systems are further facilitated by the natural ability of SEMPA to separate the magnetic and topographic contrast. When combined with other compatible surface analytical techniques such a Auger, RHEED and STM, SEMPA can also provide information about the relationship between the magnetic structure, the chemical structure, and the atomic scale order. SEMPA can also be used for real time, in situ imaging of magnetic structure during thin film growth and processing. This talk will describe the SEMPA technique by presenting examples of measurement applications from thin film and multilayer magnetism, surface magnetism of ferromagnets and antiferromagnets, and depth profiling of magnetic structures in multilayers. These measurements have provided a better understanding of thin film domain structures, spin reorientation transitions, interlayer exchange coupling, magnetic ordering in antiferromagnetic films, and the relationship between magnetic domain structure and magnetoresistance in multilayers.

9:00am **MI+NS+NANO 6-TuM3 'Magnetic-Laboratory' on an AFM Tip***, **B.K. Chong**[1], H.P. Zhou,* University of Glasgow, UK, United Kingdom*; G. Mills, L. Donaldson, J.M.R. Weaver,* University of Glasgow, UK

We present novel magnetic nanosensors based on the functionalisation of an AFM probe for use in measuring, imaging and manipulating magnetic specimens. The probes are fabricated using bulk silicon micromachining and electron-beam nanolithography (EBL). The use of conventional lithographic techniques and a microfabricated substrate allows the batch production of a large number of similarly functionalised probes without the need for individual processing of single probes and hence gives very good reproducibility.@footnote 1@ We have demonstrated two classes of magnetic probe. The eMFM probe is one in which the permanent magnetic coating used in conventional MFM tips is replaced by a small electro-magnetic coil to form a magnetic-sensitive AFM tip. Initial results indicate controllability of coil size (spatial resolution) to 1/4 µm diameter, demonstrated capability of magnetic imaging and possible application in local magnetic modification. The Hall bar magnetometer for SHPM, is also integrated with a tip and cantilever. This involved the development of a new fabrication technique in which the resist was supported by a lattice of sacrificial structures which spanned the spaces between probes. This allowed the use of low melting point or chemically reactive materials as the sensor. The combination of eMFM and Hall bar magnetometer forms a novel type of magnetic sensor-actuator probe, a 'Magnetic-Lab' on a tip. Such a probe will allow the magnetic imaging of a specimen without significant distortion due to stray fields from the probe using Hall probe magnetometry as well as the deliberate modification of its magnetic state using the coil. @FootnoteText@ @footnote 1@ H.Zhou, G.M. Mills, B.K.Chong, L. Donaldson & J.M.R. Weaver, 'Recent Progress in the Functionalisation of AFM Probes using Electron-Beam Nanolithography', J. Vac. Sci. Technol. A17(1) 2233-9(1999).

9:20am **MI+NS+NANO 6-TuM4 High Anisotropy, High Gradient Magnetic Tips For Magnetic Resonance Force Microscopy***, **H.J. Mamin**, B.C. Stipe, C.S. Yannoni, D. Rugar,* IBM Almaden Research Center*; T.D. Stowe, T.W. Kenny,* Stanford University*; D. Streblechenko, M.R. Scheinfein,* Arizona State University

In magnetic resonance force microscopy (MRFM), imaging is performed by detecting forces on a magnetic tip, but arising from only those spins within a thin resonant slice. To achieve the ultimate goal of single-spin detection, the tip must produce sufficient field gradients, at least 10 G/nm. At the same time, thermal fluctuations in the tip moment must be sufficiently small that the tip does not perturb the spin under study. These requirements have driven us to the use of tips based on high anisotropy, rare-earth bulk magnets. Small particles of NdFeB, PrFeB, and SmCo have been attached to cantilevers and oriented in an external magnetic field. The particles were then sculpted to the desired sub-micron size and shape with a focused ion beam. The magnetic properties have been characterized through cantilever-based magnetometry as well as electron holography. By measuring dissipation and applying the fluctuation-dissipation theorem, we have set upper limits on the low frequency fluctuations in the tip moment. Using a tip optimized for a 1 nm slice thickness, we have detected MRFM signals from on the order of 100 net spins. This work is supported, in part, by the Office of Naval Research.

9:40am **MI+NS+NANO 6-TuM5 Quantitative Magnetic Force Microscopy and Exchange Force Microscopy: New Tools for Magnetic Imaging***, **H.J. Hug**, P.J.A. van Schendel, S. Martin, R. Hoffmann, P. Kappenberger, M.A. Lantz, H.-J. Guentherodt,* University of Basel, Switzerland **INVITED**

Magnetic Force Microscopy has become a a well established technique for studying the topography and the micro-magnetic structure of various samples with a high lateral resolution. Among these are ferromagnetic and superconducting materials, and magnetic recording read/write-heads. Recently there has been growing interest in the quantitative analysis of measurement data obtained using a magnetic force microscope (MFM).@footnote 1@ Recent tip calibration procedures allow quantitative stray field measurements, the determination of the stray field distribution of the tip, and its stray field sensitivity. The best lateral resolution currently is around 30nm. However, the combination of ultra-sharp SFM-tips coated with ultra-thin magnetic layers and improved instrumental sensitivity may allow a lateral resolution around 10nm. A higher lateral resolution may be reached by the measurement of exchange forces. The principles of this new technique and first experiments will be discussed.@FootnoteText@@footnote 1@P.J.A. van Schendel et al., J. Appl. Phys. 88, 435-445 (2000)

10:20am **MI+NS+NANO 6-TuM7 Magnetic Force Microscopy of Coupled and Decoupled Micrometer Scale Permalloy Structures***, **U. Memmert**, A.N. Müller, U. Hartmann,* University of Saarbrücken, Germany*; J. Jorzick, C. Krämer, S.O. Demokritov, B. Hillebrands,* University of Kaiserslautern, Germany*; E. Sondergard, M. Bailleul, C. Fermon,* CEA Saclay, France

The magnetic structure and the magnetization reversal process of arrays of micron size rectangular magnetic permalloy islands were investigated by magnetic force microscopy in external magnetic fields. The samples were prepared by e@super -@-beam lithography and ion etching of UHV deposited 35 nm thick permalloy films. Islands of 1 µm x 1.75 µm dimensions were investigated with inter-island spacings between 0.1 µm and 1 µm. The data show a transition from not interacting islands for large inter-island spacing to interacting islands for the smallest spacing. For not interacting islands flux-closure structures were found to be present without external fields. Either a simple Landau structure with one single cross-tie within in the 180° wall or diamond structures consisting of 90° walls were found. For interacting islands the individual structures were often found in a magnetized state even in zero field. Edge domains were present on both short edges of each structure. A demagnetization of the interacting islands in an ac-magnetic field along the longer axis of the islands leaves the individual structures in a magnetized state with edge domains. Within the rows along the long island axis all structures are magnetized in the same direction. The rows show a row by row alternating magnetization resulting in a net zero magnetization for the entire sample. A demagnetization in an ac-field perpendicular to the long axis leaves each individual structure in a individually demagnetized state. Magnetization reversal for external fields along the long island axis takes place by simultaneous switching of structures being located together in the same row within the pattern.

[1] **Falicov Student Award Finalist**

10:40am **MI+NS+NANO 6-TuM8 Correlation of Structural and Magnetic Properties of Fe/Cr(001) Studied by Combined SP-STM and MFM**, ***M. Kleiber***, *R. Ravlic, M. Bode, R. Wiesendanger,* University of Hamburg, Germany

The magnetic structure of ultrahin Fe films on the (001)-surface of a chromium single crystal is the result of the competition between the antiferromagnetic coupling to the alternately magnetized Cr(001)-terraces and the ferromagnetic coupling in the iron layer. It is expected that for thin Fe-films the antiferromagnetic coupling between the Cr-substrate and the Fe-overlayer dominates the surface domain structure while Fe-exhibits a single-domain state for thicker films. By combining STM, spin-polarized STS and UHV-MFM we have correlated the structural and magnetic properties of the Fe/Cr(001) system. These microscopic techniques reveal that the domain structure depends on the local step density. On areas with high step density no domains are found which is expected as the terraces are too small to induce domains in the iron film. In contrast a low step density leads to a domain structure of the Fe-film which is directly linked to the step structure of the underlying Cr-substrate.

11:00am **MI+NS+NANO 6-TuM9 Flux Lattice Imaging of a Patterned Nb Film with a Cryogenic Magnetic Force Microscope**, ***M. Roseman,*** *P. Grutter,* McGill University, Canada; *V. Metlushko,* Argonne National Laboratory

Using our cryogenic magnetic force microscope, we have investigated a superconducting Nb thin film, 100 nm in thickness with T@sub c@ ~6.6 K. The film is patterned with a square array (1 µm by 1 µm) of antidots, which serve as artificial pinning centers for magnetic flux. We have observed the flux lattice as a function of temperature (5.5 K - 6.6 K) and applied magnetic field, for field strengths up to 62.1 G, the third matching field (a matching field is one where the flux lattice spacing is commensurate with the antidot array). Evidence of flux dragging by the tip reveals information about both tip-vortex and vortex-vortex interactions, and provides an indication of localized sample pinning potentials. Force distance curves acquired at temperatures near T@sub c@ clearly demonstrate an observable Meissner force between tip and sample, and allow for an estimation of the value of the temperature dependent London penetration depth, @lambda@@sub L@(T).

11:20am **MI+NS+NANO 6-TuM10 Magnetic Field Measurements of Current-Carrying Devices by Force Sensitive Magnetic Force Microscopy with Potential Correction**, ***R.A. Alvarez***, *S.V. Kalinin, D.A. Bonnell,* University of Pennsylvania

Magnetic force microscopy (MFM) is a well-known technique based on the detection of the dynamic response of a mechanically driven cantilever to a magnetic field. MFM image contrast of non-conductive or biased surfaces includes contributions of electrostatic forces that can in some circumstances dominate the total force gradient. Since current-carrying devices, e.g. lines or circles are recognized as convenient calibration standards to determine first and second order magnetic moments of the MFM probes, this ambiguity is not inconsequential. An approach to imaging is proposed that combines surface potential nulling measurements with magnetic force microscopy to eliminate the electrostatic forces. Unlike conventional MFM, this technique measures force rather than force gradient. The distance, line bias and modulation frequency dependence of cantilever response was found to be in excellent agreement with magnetostatic calculations. Based on these observations, a new type of MFM on current carrying devices is proposed. In this technique, the device is ac biased at the off-resonant frequency and the current induced magnetic field results in cantilever deflection. At the same time, ac voltage bias at the resonant frequency is applied to the tip and conventional SSPM feedback is used to match tip and surface potentials. This technique allows simultaneous collection of surface potential and magnetic force images. To the best of our knowledge, this is the first example of an SPM technique that utilizes simultaneous active and passive modulation of the tip and allows simultaneous measurement of magnetic and electrostatic forces.

11:40am **MI+NS+NANO 6-TuM11 Evaluation of MFM for Probing Electromigration Processes**, ***R. Yongsunthon***, *J. McCoy, E.D. Williams,* University of Maryland

The study of electromigration in metals requires correlation of current densities with the evolution of defects in current-carrying lines. In principle, magnetic force microscopy (MFM) is an appropriate tool for this purpose. Most use of MFM has concentrated upon determining magnetic polarity across magnetic domain boundaries, rather than quantification of magnetic field variation. Such quantification is non-trivial, because the extended nature of the tip-sample interaction involves complicated factors such as coupling of the system geometry. To explore the MFM capability to yield reliable analysis, we are evaluating the MFM instrument response for known structures, such as lines containing defects of simple geometry. The instrumental response function is defined by tip parameters, such as tip magnetization and shape, which make predicting the response function impractical. However, it is possible to make meaningful relative quantification and calibration, by comparison with response from structures where the behavior is well understood. To analyze the data from such known calibration samples, the fields around the lines are numerically calculated and compared with deconvolution of the measured signal. Preliminary results suggest that meaningful relative quantification of the signal can be achieved to within 20% and that current variations can be detected to at least 10%. Continuing work to relate this to the limiting levels of current crowding that will be detectable is underway. (Work supported by NSF-MRSEC, grant# DMR 96-3252.

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