Monday Morning, October 2, 2000

Magnetic Interfaces and Nanostructures
Room 206 - Session MI-MoM

Magnetic Spectroscopies
Moderator: S.D. Bader, Argonne National Laboratory

8:20am **MI-MoM1 Spin Polarized Photoemission Study of Magnetite Films: Extraction of the Bulk Polarization via a Substrate Overlayer Model***,* ***S.A. Morton****, G.D. Waddill,* University of Missouri, Rolla*; J.G. Tobin,* Lawrence Livermore National Laboratory*; S. Kim, I.K. Schuller,* University of California, San Diego*; S.A. Chambers,* Pacific Northwest National Laboratory

Many materials have been predicted to be half metallic, yet to date remarkably little truly compelling evidence for this behavior has emerged. One technique that can potentially yield a definitive result is spin polarized photoemission and it is from this technique that the most compelling evidence yet has emerged.@footnote 1@ However such experiments are hampered by the difficulty in producing clean stoichiometric surfaces with a polarisiation that is truly representative of that of the bulk. We have used the spin-resolved photoemission facility at the Advanced Light Source,@footnote 2@ to study the half-metallic candidate Fe@sub 3@O@sub 4@, which holds out the possibility of use in spintronic devices as a pure spin source. The epitaxial films were grown on MgO by UCD and PNNL and were characterized by RHEED, LEED, XRD, and magneto-transport measurements. We have demonstrated that cleaning the samples results in the loss of their polarization. However, our ability to perform spin resolved experiments at higher photon energies, (as a direct result of the high brightness of the 3rd generation source), has enabled us to study the near Fermi edge polarization of the samples "as received", without having to resort further to potentially destructive cleaning techniques. By measuring the polarization as a function of emission angle and photon energy, and combining these measurements with a substrate overlayer model, we have been able to extract the underlying polarization of the bulk material and have demonstrated that it is significantly higher than the 30% initially observed in the "as-received" samples, and may indeed be up to 100%. Furthermore, our spin resolved spectra demonstrate close agreement with simulated spectra derived from theoretical calculations.@footnote 3@ @FootnoteText@ @footnote 1@Park et al, Nature 392 794 (1998); Phys. Rev. Lett. 81 1953 (1998)@footnote 2@Tobin et al, MRS Symp. Proc. 524 185 (1998)@footnote 3@Zhang and Satpathy, Phys. Rev. B. 44 13319 (1991).

8:40am **MI-MoM2 Magnetic Dichroism in the Soft X ray Absorption Region of NiMnSb Ferromagnetic Alloy***,* ***C.N. Borca,*** University of Nebraska, Lincoln*; S. Stadler,* Naval Research Laboratory*; D. Ristoiu,* CNRS Laboratoire Louis Neel, France*; P.A. Dowben,* University of Nebraska, Lincoln*; Y.U. Idzerda,* Naval Research Laboratory*; J.P. Nozieres,* CNRS Laboratoire Louis Neel, France

We have investigated the magnetic and electronic structure of NiMnSb alloy by soft-X-ray absorption spectroscopy (XAS) and magnetic circular dichroism (MCD) measurements in the Mn 2p and Ni 2p core absorption regions. We have studied the unoccupied orbital symmetry of NiMnSb. The spectra display strong polarization dependence, especially at the Mn 2p threshold. The unoccupied orbital assignment will be presented as a function of temperature and light polarization. The apparent multiplet structures found in the Mn 2p XAS spectra corresponds to a tetragonal crystal field symmetry and is the origin of most of the moment in this Heusler alloy. The XAS spectrum in the Ni 2p core shows a doublet feature in both 2p3/2 and 2p1/2, resulting from the octahedral crystal field.

9:00am **MI-MoM3 Cu Metallic Quantum Well State Dispersions in the Cu/fccFe/Cu(100) System***,* ***A. Danese****, R.A. Bartynski,* Rutgers University

Multilayers of alternating ultrathin non-magnetic/ferromagnetic (NM/FM) films often exhibit oscillatory magnetic coupling between sequential FM layers. This phenomenon has great technological importance and is associated with the presence of metallic quantum well (MQW) states in the NM layer. To understand the influence of the FM substrate on the electronic states of the NM layer, we have performed an inverse photoemission (IPE) study of the Cu/fccFe/Cu(100) system along the @Gamma@X direction of the surface Brillouin zone (SBZ). We have also modeled this system using a phase accumulation approach. The model predicts that a subset of these states disperse slowly as a function of parallel momentum in the region of the projected spin polarized band gap of the FM layer, which for fccFe lies a few eV above the Fermi energy. We will discuss IPE results for Cu/fccFe/Cu(100) system in this region of the SBZ, both above and below the Curie temperature of the Fe layer. We have also investigated thermal desorption of CO from this system as a function of Cu film thickness to determine how the presence of MQW states influences the chemisorption bond.@footnote 1@ @FootnoteText@ @footnote 1@Supported by NSF-DMR #98-01681 and ACS-PRF #33750-AC6,5.

9:20am **MI-MoM4 On the Evolution of Magnetic Moments of Fe in FeCo(100) & FeNi(100) Alloy Films***,* ***N.A.R. Gilman****, R. Zhang, R.F. Willis,* Pennsylvania State University*; M. Hochstrasser, J.G. Tobin,* Lawrence Livermore National Laboratory

We report on the variation of the local magnetic moments with changing composition in Fe@sub x@Co@sub 1-x@ and Fe@sub x@Ni@sub 1-x@ alloy films grown epitaxially on fcc Cu(100). The elemental magnetic moments were determined from magnetic-field-induced intensity asymmetry observed in angle-dependent photoelectron spectroscopy of the 3p core-levels of the constituent atoms - "x-ray magnetic dichroism.@footnote 1@ Both the Fe and the Ni moments change in magnitude with changing composition of FeNi alloys.@footnote 2@ The 'stoichiometrically averaged moment' follows the Slater-Pauling curve up to a critical filling of the 3d bands (corresponding to ~2.5 holes in the minority-spin d-band) at which point it collapses to a lower spin-state ('Invar' effect). This is caused by a sudden change in the Fe local moment. This magnetic instability is predicted theoretically independent of what element the Fe is alloyed with ie, a similar collapse is expected for FeCo alloys at the same critical filling of the d-bands.@footnote 3@ However, to date, no such collapse of the Fe moment has been observed in similarly grown FeCo alloy films with fcc-like pseudomorphic structure. In this paper, we present new results comparing the evolution of the Fe moments in FeNi and FeCo fcc pseudomorphic films grown on Cu(100). Simultaneously, we monitor the distribution of states in momentum space at the Fermi energy. The Fermi surface topology confirms that the films are of fcc symmetry, although tetragonal distortion occurs with increasing Fe moment. The dichotomy in the magnetic behavior is discussed in the light of these, and other recent results. @FootnoteText@ @footnote 1@ C. Roth et al., Phys. Rev. Lett. 70, 3479 (1993). @footnote 2@ R.F. Willis et al., Phys. Rev. B, in press (2000) @footnote 3@ P. James et al., Phys. Rev. B 59, 419 (1999).

9:40am **MI-MoM5 X-Ray and Neutron Scattering Studies of Magnetic Roughness in Thin Magnetic Films***,* ***S.K. Sinha,*** Argonne National Laboratory*; S.A. Stepanov,* Illinois Institute of Technology & Argonne National Laboratory*; R.M. Osgood,* Argonne National Laboratory **INVITED**

It has become apparent that magnetic roughness at interfaces plays an important role in, for instance, the magnetic and transport behavior of thin film magnetic devices. Reflectivity and diffuse scattering studies of thin films using neutrons or X-rays can be used to distinguish between chemical and magnetic roughness at interfaces and to determine the parameters characterizing the latter, such as the correlation length. We discuss the theory of magnetic scattering of neutrons and resonant X-rays by rough interfaces within the Born and Distorted Wave Born Approximations and illustrate how it has been used to analyze experimental results attained on several systems so far.

10:20am **MI-MoM7 Diffuse X-Ray Resonant Magnetic Scattering (DXRMS) of Thin Magnetic Films on Anisotropic Substrates***,* ***J.J. Kelly IV****, D.E. Savage, F. Liu, F. Flack, M.G. Lagally,* University of Wisconsin, Madison

Recent applications of very thin magnetic films and magnetic multilayers, such as in magneto-electronics or magnetic data storage, have emphasized the necessity of understanding the nature of magnetism at surfaces and interfaces. For example, the effect of surface and interface morphology, both chemical and magnetic, on spin dependent electron scattering, and thus spintronics devices, is a critical question. Diffuse x-ray resonant magnetic scattering (DXRMS), a unique element-specific technique, provides information on both the chemical and magnetic morphology at surfaces and interfaces by looking at the diffuse and specular components of resonant magnetic x-ray scattering. Using DXRMS and the magneto-optical Kerr effect (MOKE), we have investigated the influence of deliberately induced anisotropic morphology on the magnetic properties of thin magnetic films and multilayers. Changes in x-ray scattering and coercivity are observed as the sample is rotated relative to the incident x-ray beam, and correlated with morphology. The results are discussed in light of previous results using DXRMS and theory. @FootnoteText@ Research supported by NSF and Seagate.

10:40am **MI-MoM8 Control of Surface Roughness during Nanoscale Multilayer Deposition by Adding Surfactants***, X.W. Zhou,* The University of Virginia*; W. Zou, H.N.G. Wadley,* The University of Virginia, usa

Nanoscale multilayers often exhibit special properties not possessed by their bulk constituents. For instance, multilayers composed of a thin (~20 Å) conductive layer (such as Cu) sandwiched between thin (~50 Å) ferromagnetic layers (e.g., Co) undergo a larger drop in electrical resistance under an external magnetic field. This property, called magnetoresistance, has been utilized in hard drive read heads to allow a significant increase in hard drive storage capacity, and are being explored for nonvolatile random access memories. The performance of these devices can be improved when the interfacial roughness and interlayer mixing of the multilayers can be reduced. While hyperthermal energy deposition techniques have been used to grow the nonequilibrium flat interfaces in the nanoscale multilayers, considerable interests are also growing in searching new multilayer material systems that intrinsically generate low interfacial roughness and interlayer mixing. Traditional material search criteria primarily based upon lattice-match, magnetic saturation, and thermal immiscibility resulted in high quality NiCo/Cu/NiCo multilayers. Better multilayers are likely to be formulated among more complex multilayer structures involving more elements. However, the tremendous possibilities of complex multilayer systems preclude a mere experimental trial and error search for the multilayer systems. Using an atomistic simulation approach, the effects of adding Ag and Au in the NiCo/Cu/NiCo multilayers have been explored. Remarkable Ag surface segregation and surface flattening effects were observed. These surfactant effects were found to be much less for Au. Analyses indicated that such effects can be attributed to the larger size (compared to Cu, Ni, and Co) and lower cohesive energy (compared to Cu, Ni, Co, and Au) of Ag atoms. This finding suggested a new set of materials that should be explored in experiments.

Magnetic Interfaces and Nanostructures
Room 206 - Session MI-MoA

Thin Films and Multilayers

Moderator: D.P. Pappas, National Institute of Standards and Technology, Boulder

2:00pm **MI-MoA1 Positive Exchange Bias Model: Fe/FeF@sub 2@ and Fe/MnF@sub 2@ Bilayers**, *M. Kiwi, J. Mejía-López,* Pontificia Universidad Católica, Chile*; **R.D. Portugal**[1],* Pontificia Universidad Católica, Chile, France*; R. Ramírez,* Pontificia Universidad Católica, Chile

Positive exchange bias (PEB) is a phenomenon that was recently observed experimentally while normal (or negative) exchange bias (NEB) had been discovered more than forty years ago. It is remarkable that both phenomena are observed in the same samples subject to different cooling fields. Here we put forward a model to explain PEB and its crossover to NEB in Fe/FeF@sub 2@ and Fe/MnF@sub 2@ bilayers. Our model incorporates recent experimental information, such as the perpendicular coupling between the ferromagnet (FM) and the antiferromagnet (AFM) and that compensated AFM interfaces show the highest NEB shifts. A freezing of the canted AFM interface spins is proposed, and thus while hysteresis loops are performed the energy is stored in an incomplete domain wall in the FM. Recent polarized neutron reflectometry experiments provide strong support for this picture.@footnote 1@ The energy minima at each point of the magnetization curve are obtained exactly, with arbitrary precision, by a new analytical formulation which is introduced in this work. The results extracted from the model are in qualitative and quantitative agreement with available experimental facts. @FootnoteText@ @footnote 1@ M R Fitzsimmons et al., Phys. Rev. Lett. 84, 3986 (2000).

2:20pm **MI-MoA2 Asymetry of Magnetization Reversal in the Fe/(Fe,Mn)F@sub 2@ Exchange Bias System as a Function of Crystallinity***, **A. Hoffmann**, M.R. Fitzsimmons,* Los Alamos National Laboratory*; C. Leighton, K. Liu, I.K. Schuller,* University of California, San Diego*; J. Nogués,* Universitat Autònoma de Barcelona, Spain*; C.F. Majkrzak, J.A. Dura,* National Institute of Standards and Technology*; H. Fritzsche,* Hahn-Meitner Institut, Berlin, Germany

Using polarized neutron reflectometry we have recently shown that the magnetization reversal can be different on both sides of the hysteresis loop for polycrystalline Fe exchange coupled to epitaxial twinned FeF@sub 2@ or MnF@sub 2@.@footnote 1@ Namely, with decreasing field (+M@sub s@ -> -M@sub s@) we observe a rotation of the magnetization indicated by the presence of spin-flip scattering, while for increasing field (-M@sub s@ -> +M@sub s@) the data suggest magnetization reversal by domain wall motion. However for epitaxial twinned films of FeF@sub 2@ and MnF@sub 2@, this difference of magnetization reversal depends on the direction of the cooling field with respect to the crystallographic orientation. In order to clarify the role of frustration between twinned antiferromagnetic domains, we examined the asymmetry of the magnetization reversal also in samples with either single-crystal (untwinned) or (110) textured polycrystalline FeF@sub 2@ films. In untwinned and textured samples we detected no significant asymmetry in the magnetization reversal. This suggests that the twinning of the antiferromagnet is essential for the asymmetry in the magnetization reversal to occur. This can be understood by a "45 degree coupling" of the Fe to the FeF@sub 2@ due to a twin-driven frustration. As a result there can be a unidirectional anisotropy due to exchange bias along the easy axis of the ferromagnet, which in turn then may give rise to the asymmetry in the magnetization reversal. This work was supported by U.S. Department of Energy, BES-DMS under Contract No. W-7405-Eng-36, grant DE-FG03-87ER-45332, and funds from the University of California Collaborative University and Laboratory Assisted Research. @FootnoteText@ @footnote 1@ M.R. Fitzsimmons, P. Yashar, C. Leighton, I.K. Schuller, J. Nogués, C.F. Maikrzak, and J.A. Dura, Phys. Rev. Lett. vol. 84, 3986 (2000).

2:40pm **MI-MoA3 Growth and Magnetic Properties of Ultrathin Fe on Pd(110)@footnote 1@**, *B. Roldan Cuenya, J. Pearson, C. Yu, **D. Li**, S.D. Bader,* Argonne National Laboratory

While it is known that initial metal growth on Pd(110) surfaces is highly anisotropic and tends to form nanoscale wires, the magnetic properties of such systems are less studied. We have investigated the growth and magnetic properties of 0-3 ML Fe on a stepped Pd(110) with SMOKE, RHEED, and LEED in order to address the correlation among morphology, structure, and magnetic properties at low dimensions. The Fe films, grown at 70 °C, are flat and epitaxial up to 1.5 ML, where 3-dimensional growth starts. RHEED oscillations with 1-ML period were observed on the (1,0) and (2,0) streaks while an oscillation with a period of 0.5-ML exists on the (0,0) streak. The initial growth is pseudomorphic. The in-plane row spacing along the [110] direction starts to relax at ~ 0.5 ML and decreases by ~ 5% at 3 ML. The submonolayer Fe films remain ferromagnetic down to ~ 0.35 ML, below which the Curie temperature (T@sub C@) may become lower than our low-temperature limit of 25K. The T@sub C@ initially increases sharply with coverage and starts to saturate at 0.8-1 ML to ~210K. The magnetic easy axis is perpendicular to the surface for 0.4-0.7ML of Fe and in-plane for Fe thicknesses > 2 ML. Between 0.7-1.2 ML, there appear to be mixed magnetic phases as indicated by the co-existence of both polar and longitudinal Kerr signals, and an increase in coercivity. @FootnoteText@ @footnote 1@ Supported by DOE BES-MS #W-31-109-ENG-38 and ANL LDRD#00-001N. @footnote 2@ J.-P, Bucher, E. Hahn, P. Fernandez, C. Massobrio, and K. Kern, Europhysics Lett., 27, 473 (1994).

3:00pm **MI-MoA4 Real Space Study of Ultrathin Fe Films on Cu(100)***, **A. Biedermann**, M. Schmid, P. Varga,* Vienna University of Technology, Austria

Ultrathin iron films deposited on Cu(100) represent a prototype system for the exploration of novel magnetic structures and thin film magnetism. We present the first atomically resolved survey of the surface/ thin film structures using scanning tunneling microscopy (STM). The clean thin films deposited at room temperature are known to be pseudomorphic (fcc) between 2 and 10 monolayer film thickness, however, with notable deviations from the ideal structure. We have identified (1) a novel "striped-bcc" phase at 4-5 monolayer film thickness and (2) the structure of the initial bcc grains at 6-8 monolayer film thickness. Locally, both the "striped-bcc" phase and the initial bcc-Fe grains show a strained bcc configuration, identifying the tendency of the Fe films to form a bcc-lattice as a common driving force for the observed structures. The appearence of the "striped-bcc" phase coincides with an increased ferromagnetism at 4-5 monolayer thickness seen by several other groups.

3:20pm **MI-MoA5 Spin Reorientation Transition in Magnetically Coupled Fe/Cu/Ni/Cu(001) System***, **H.J. Choi**[2], W.L. Ling, J.H. Wolfe,* University of California, Berkeley*; S. Anders, A. Scholl,* Lawrence Berkeley National Laboratory*; F. Nolting, H. Ohldag,* Stanford Synchrotron Radiation Laboratory*; U. Bevensiepen, R. Kawakami, Z. Qiu,* University of California, Berkeley

It is well known that low temperature grown Fe film on Cu(001) exhibits spin reorientation transition (SRT) at a critical thickness where the magnetic remanence is greatly suppressed within a pseudo-gap region. Subsequent experiments showed that the loss of the macroscopic magnetization is due to the formation of magnetic stripe domains. It is generally believed that the understanding of the strip domains will greatly advance our knowledge on the magnetic long-range order in two-dimensional Heisenberg system. With this motivation, we investigated the SRT of Fe film in Fe/Cu/Ni/Cu(001) system where the Fe layer is magnetically coupled to the perpendicular magnetization of Ni with the interlayer coupling strength being controlled by the Cu thickness. With in situ surface magneto-optic Kerr effect measurement, we show that the Fe-Ni interlayer coupling results in an alternating alignment of the Fe magnetization with Cu thickness for Fe film thinner than the SRT thickness d@sub R@, but has no effect for Fe film thicker than d@sub R@. The SRT thickness d@sub R@, defined as the onset of in-plane magnetization, was found to be independent of the Fe-Ni interlayer coupling. Within the SRT pseudo-gap region, however, the longitudinal magnetic remanence exhibits oscillatory behavior with Cu thickness with a periodicity exactly half of that of the oscillatory interlayer coupling. This result shows that the strip domains are severely modified by the strength of the Fe-Ni interlayer coupling. To provide more detailed information, element specific domain imaging was taken in this system using photoemission electron microscope at the Advanced Light Source of Lawrence Berkeley National Laboratory.

3:40pm **MI-MoA6 Magnetic Anisotropies in Ultra-Thin Films: The Spin-Reorientation Transition in Fe(110)/W(110)***, **E. Vescovo**, H.-J. Kim,* Brookhaven National Laboratory **INVITED**

Reorientation of the easy axis of magnetization are not unusual in ultra-thin films. They are generally understood as the result of a delicate energy balance between three dimensional anisotropy terms - which favor the bulk easy-axis direction - and two-dimensional surface and interface terms

[1] **Falicov Student Award Finalist**

[2] **Falicov Student Award Finalist**

- which can favor a different direction. Bulk contributions are proportional to the film thickness. Correspondingly, in thin films, there can be a critical thickness (t@sub R@) at which the two contributions balance exactly. In all those cases, a switch of the magnetization has to be expected when crossing t@sub R@. Fe(110) films epitaxially grown on W(110) display a spin reorientation phase transitions as a function of film thickness.@footnote 1@ This transition --- from the in-plane [110] direction to the [100] direction --- is characterized by a t@sub R@ of about 50 monolayers. Here we report on new spin- and angle-resolved photoemission experiments on this system. We show how t@sub R@ can be greatly varied by directly manipulating the Fe(110) surface. Furthermore, we explore the temperature dependence of the anisotropy balance and provide compelling evidence demonstrating that this in-plane spin reorientation transition can also be induced by varying the temperature, at constant thickness. @FootnoteText@ @footnote 1@ H.J. Elmers and U. Gradmann, Appl. Phys. A 51, 255 (1998)

4:20pm **MI-MoA8 Fermi Surfaces and Magnetic Behavior of Thin FeNi Alloy Films**, ***M. Hochstrasser***, *N.A.R. Gilman, R.F. Willis,* The Pennsylvania State University*; F.O. Schumann, J.G. Tobin,* Lawrence Livermore National Laboratory

We report angle-resolved and spin-resolved photoemission measurements of changes in the electronic structure with changing composition of pseudomorphic films of FeNi magnetic alloys grown epitaxially on Cu(100). With x-ray magnetic linear dichroism angle dependent (XMLDAD) 3p core-level photoemission the evolution of the elemental magnetic moments was monitored. In addition, changes occuring in the spin-polarized valence bands were observed with spin-polarized photoemission, together with changes in the k-distribution of states at the Fermi energy. A projection of the Fermi surface shows a delocalized "dogbone" feature due to sp-states and more localized "hotspots" corresponding to the emergence of minority spin d-states. Hybridization between the s p- and d-states occurs at thesse locations on the dogbone indicative to a strong nesting of wavevectors of excitations spanning the Fermi surface. The sp-dogbone states spin polarize with increasing average magnetic moment. Both elemental moments, observe d in XMLDAD, grow with increasing Fe concentration up to a maximum at the Fe concentration of 55%, that on the Fe increasing at a faster rate than the Ni moment. Beyond this point, the Fe moment shows a rapid decline to a "low-spin" value, of the order of that of the Ni monent, which tracks the behavior of the Fe moment but to a smaller degree. Spin-resolved valence band photoemission measurements show first an increase in the exchange splitting of 3d-states, followed by a decline, essentially tracking th e core-level dichrosim. The magnetic instability observed abovethe invar concentration (Fe > 65%) is characterized further by a diffuseness in the spectral distribution and an increased lifetime broadening of mainly minority-spin states, indicative of magnetic non-collinear disorder.

4:40pm **MI-MoA9 Highly Spin-Polarized Chromium Dioxide Thin Films Prepared by Chemical Vapor Deposition from Chromyl Chloride**, ***W.J. DeSisto,*** University of Maine*; P.R. Broussard,* Covenant College*; T.F. Ambrose, B.E. Nadgorny, M.S. Osofsky,* Naval Research Laboratory

Highly spin-polarized materials, and in particular thin films, are central to many magneto-electronic devices. An efficient and controlled chemical vapor deposition (CVD) process for depositing highly spin-polarized, metastable chromium dioxide (CrO@sub 2@) on (100) TiO@sub 2@ substrates has been developed using chromyl chloride (CrO@sub 2@Cl@sub 2@) as a precursor. This precursor is a liquid at room temperature with a vapor pressure adequate for CVD using conventional precursor handling equipment. The films were shiny, black, and approximately 200 nm thick. The spin polarization, as measured by the Point Contact Andreev Reflection (PCAR) technique, was 81± 3%. X-ray diffraction @theta@/2@theta@ scans indicated the films grew completely (100) oriented, in registry with the (100) oriented TiO@sub 2@ substrate. X-ray diffraction @phi@-scans on the CrO@sub 2@ (110) reflection indicated the expected two-fold symmetry, with no evidence of misaligned material. The resistivity at room temperature was 240 @micro@@ohm@cm and decreased to 10 @micro@@ohm@cm at 5K, consistent with metallic behavior. The films were ferromagnetic with a Curie temperature of 395 K and a coercivity of approximately 100 Oe at 298 K. This deposition technique enhances the possibility of fabricating a GMR and/or a tunnel junction device based on CrO@sub 2@, and thus opens up new opportunities in magneto-electronics.

5:00pm **MI-MoA10 Effect of Composition and Microstructure on Temperature Coefficient of Resistance of Polycrystalline La1-xCaxMnO3 Thin Films**, ***C.-H. Lai****, C.-F. Hsu,* National Tsing Hua University, Taiwan, R. O. C.*; Y.-C. Chin, C.-T. Jiang,* Chung-Shan Institute of Science and Technology, Taiwan

Perovskite La1-xCaxMnO3 has drawn much attention on account of the colossal magnetosistance. Due to the sharp resistivity drop around the insulator-metal transition temperature (Tp), epitaxial La1-xCaxMnO3 thin films have been demonstrated to be a promising candidate for IR detector (bolometric) application. In this work, polycrystalline La1-xCaxMnO3 films were deposited by using rf sputtering on Si/SiO2 substrates, and the dependence of the temperature coefficient of resistance (TCR) on the film composition and the structure was investigated. When the temperature is higher than Curie temperature Tc, the resistivity of our polycrystalline La1-xCaxMnO3 films follow the "small palaron model", that is, the resistivity can be expressed as R=BTexp(Ea/kT). Consequently, increasing the activation energy Ea increases the TCR value. By adjusting the Ar/O2 flux during depositions or changing the atmosphere of post-annealing, oxygen content can be manipulated. Because precise oxygen content is difficult to measure, the lattice constant of the films was used for the indicator of relative oxygen contents. When oxygen content increased, the Ea and TCR decreased accompanied with the increase in Tp. Ea and TCR value also decreased with increasing Ca content. ESCA results showed that the ratio Mn4+/Mn3+ increased with increasing oxygen (or Ca) content. Since the carrier transportation of La1-xCaxMnO3 is mainly by hopping along Mn4+-O-Mn3+, the increase in the ratio Mn4+/Mn3+ may imply that hopping probability increases, resulting in smaller resistance and Ea. The surface roughness can significantly increase the resistance but the TCR value is about the same. The resistance reduced with the grain growth but the TCR value maintained constant. The TCR value can reach 3%/K at room temperature.

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.

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

Magnetic Imaging II

Moderator: F.J. Himpsel, University of Wisconsin, Madison

2:00pm **MI+NS+NANO 6-TuA1 Correlation of Ferromagnetic and Antiferromagnetic Spin Orientation Observed by Photoemission Electron Microscopy**, ***S. Anders***, *A. Scholl, F. Nolting, H.A. Padmore,* Lawrence Berkeley National Laboratory*; J. Stohr, J. Luening,* Stanford Synchrotron Radiation Laboratory*; J.W. Seo,* University of Neuchatel, Switzerland*; J. Fompeyrine, J.-P. Locquet,* IBM Research Division, Switzerland*; M. Scheinfein,* FEI Company **INVITED**

Photoelectron emission microscopy (PEEM) using polarized x rays is a unique tool for the study of ferromagnetic (FM) and antiferromagnetic (AFM) materials. FM materials are studied using x-ray magnetic circular dichroism (XMCD) and AFM materials using x-ray magnetic linear dichroism (XMLD). The elemental specificity of PEEM allows to study individual layers in multilayer structures, and to investigate the coupling between them. Increasingly complex layered structures containing magnetic and antiferromagnetic materials are used in modern magnetic devices, and knowledge of the magnetic properties of the layers and interfaces is essential for the understanding of the properties of these devices. Of particular interest is the effect of exchange biasing at the interface of an AFM and an FM. AFM materials have been difficult to study so far because of a lack of methods with sufficient spatial resolution and surface sensitivity. We have investigated the magnetic and topographic surface structure of several AFM materials, in particular thin singlecrystalline and polycrystalline NiO and LaFeO@sub 3@ films. We were able to resolve the antiferromagnetic surface structure of those materials, showing antiferromagnetic domains, and antiferromagnetic patterns, correlated to the surface topography. Local NEXAFS spectra yielded information about the antiferromagnetic orientation at the sample surface. The study of an FM Co thin film on top of an AFM LaFeO@sub 3@ film showed for the first time a direct correlation between AFM and FM domains.

2:40pm **MI+NS+NANO 6-TuA3 Magnetic Imaging of NiO/Ag(001) Thin Film using PhotoEmission Electron Microscope**, ***W. Zhu,*** University of Connecticut, US*; L. Seve, B. Sinkovic,* University of Connecticut*; A. Scholl, S. Anders,* Lawrence Berkeley National Laboratory

PhontoEmission Electron Microscope (PEEM) combined with linearly polarized synchrotron X-rays provides a powerful way of imaging magnetic domains in antiferromagentic thin films. We have performed magnetic imaging on antiferromagnetic thin film of NiO with PEEM. The 90-Å thick NiO film is of (001) orientation, epitaxially grown on a Ag (001) single crystal substrate. The magnetic contrast is found to be correlated with the topological contrast, which is caused by the local thickness variation in the film. Micro-X-ray absorption spectra (XAS) in areas of different contrast revealed that the directions of magnetic moments within these areas are differently oriented with respect to the X-ray polarization direction. The difference in Micro-XAS from these areas disappeared at temperature of ~350 °C (above the Neel temperature), where the antiferromagnetic order disappears. Experiments with the X-ray polarization direction parallel to [100] and [110] direction of the film give similar results, which indicates that the magnetic contrast is due to the in-plane vs. out-of-plane magnetic moments orientation rather than the differently oriented in-plane moments. These results are consistent with our recent spectroscopic studies of NiO/Ag(001) films of various thickness.

3:00pm **MI+NS+NANO 6-TuA4 Magnetic Imaging by Local Tunneling Magnetoresistance - A High Resolution Technique**, ***W. Wulfhekel,*** *H.F. Ding, J. Kirschner,* MPI Halle, Germany **INVITED**

We give an overview over our recent efforts of magnetic imaging using scanning tunneling microscopy with a ferromagnetic tip. Magnetic sensitivity is obtained on the basis of local tunneling magnetoresistance between a soft magnetic tip and the sample. The imaging capacities of the technique are illustrated with exemplary studies of the surface domain structure of different itinerant ferromagnets. On Co(0001) we find surprisingly narrow sections of the walls of only 1.1nm width, over an order of magnitude less than previously observed in Co. Recording quantitative profiles of the perpendicular component of the magnetization across the wall and comparing the experimental data with micromagnetic calculation, the narrow sections are identified as 20° domain walls. Besides magnetic imaging, we focus on the influence of the stray filed of the tip on the magnetic structures under investigation. In the limit of soft magnetic materials or strong stray fields, the wall mobility and magnetic susceptibility can be studied on the local scale. Finally, measurements of magnetoresistance versus tunneling voltage and tip sample distance give deeper insight into the mechanisms of spin polarized tunneling.

3:40pm **MI+NS+NANO 6-TuA6 Self-assembled Magnetic Nanowires Studied with Spin-polarized Scanning Tunneling Microscopy**, ***T.-H. Kim,*** *W.-G. Park, Y. Obukhov, Y. Kuk,* Seoul National University, Korea

In thin film of immiscible Co and Ag alloys, nanowires have been observed. The alternating stripes, magnetic Co stripes and non-magnetic Ag stripes, are formed on W(110) substrate by the driving force of the phase separation. The film can be grown sequentially, or deposited simultaneously. The periods of the stripes are found to be 20 to 30 Å, perpendicular to the long axis of the stripes. The relations between the morphology and the magnetic contrast of the self-assembled magnetic nanowires have been studied with spin-polarized scanning tunneling microscopy. Using an electromagnet for tip magnetization, the magnetic field can be applied to the soft magnetic tip both parallel and perpendicular to the axis of the tip. With this setup, we are able to image the direction of the magnetization of the sample.

4:00pm **MI+NS+NANO 6-TuA7 Direct Visualization of Magnetic Nanowires by Spin-Polarized Scanning Tunneling Spectroscopy**, ***O. Pietzsch,*** *A. Kubetzka, M. Bode, R. Wiesendanger,* University of Hamburg, Germany

While scanning tunneling microscopy (STM) and spectroscopy (STS) are the established methods of choice for the study of structural and electronic surface properties at ultimate real space resolution, no equivalent technique for magnetic imaging was available so far. The most widely applied surface sensitive methods as, e. g., magneto-optical Kerr effect (MOKE), average over comparably large sample fractions. Here we present a recent spin-polarized STS study, carried out with an STM especially designed for magnetic imaging.@footnote 1@ We will show high resolution images of a self-organized array of Fe nanowires grown on a stepped W(110) single crystal.@footnote 2@ The magnetic wires have a periodicity of 8 nm, an average width of 4 nm, and a thickness of two atomic layers. Making use of ferromagnetically coated STM tips with the appropriate anisotropy we were able to image the magnetic domain structure in detail. The magnetism of the stripe system is governed by perpendicular anisotropy.@footnote 3@ Adjacent stripes exhibit antiferromagnetic coupling mediated by the stray field. Our images allow the investigation of the influence of local structural defects as, e. g., non-uniform stripe width or dislocation lines, on the magnetic properties on a sub-nanometer scale. The width and orientation of domain walls within single stripes is determined. We will show how the domain structure is affected by applied external fields of up to 0.5 Tesla. The contrast mechanism will be explained. The imaging method is of general applicability for the study of the surfaces of magnetic nanostructures. @FootnoteText@ @footnote 1@ O. Pietzsch et al., Rev. Sci. Instrum. 71, 424 (2000) @footnote 2@ O. Pietzsch, A. Kubetzka, M. Bode, and R. Wiesendanger, Phys. Rev. Lett. , in press. @footnote 3@ J. Hauschild, U. Gradmann, and H. J. Elmers, Appl. Phys. Lett. 72, 3211 (1998).

4:20pm **MI+NS+NANO 6-TuA8 Real-Space Imaging of Two-Dimensional Antiferromagnetism on the Atomic Scale**, ***M. Bode,*** University of Hamburg, Germany*; S. Heinze,* Forschungszentrum Jülich, Germany*; A. Kubetzka, O. Pietzsch,* University of Hamburg, Germany*; X. Nie, S. Blügel,* Forschungszentrum Jülich, Germany*; R. Wiesendanger,* University of Hamburg, Germany

The ultimate limit of two-dimensional antiferromagnetism (2D-AFM) is a magnetic monolayer of chemically equivalent atoms, where adjacent atoms at nearest-neighbor sites have magnetic moments with opposite directions, deposited on a non-magnetic substrate.@footnote 1@ Since the total magnetization of this film is zero spatially averaging techniques like spin-polarized photoelectron spectroscopy cannot be used for an experimental verification of (2D-AFM). We have resolved the two-dimensional antiferromagnetic structure within a pseudomorphic monolayer film of chemically identical manganese atoms on tungsten (110) by spin-polarized scanning tunneling microscopy (SP-STM) at 16 Kelvin.@footnote 2@ While images of the chemical surface unit-cell without any magnetic contribution were obtained using a non-magnetic W-tip, spin-polarized electrons from magnetically coated tips probe the change in translational symmetry due to the magnetic c(2x2)-superstructure of Mn/W(110). Based on fundamental theoretical arguments it will be shown that SP-STM is a powerful technique for the investigation of complicated surface magnetic configurations.

@FootnoteText@ @footnote 1@ S. Blügel, M. Weinert, and P.H. Dederichs, Phys. Rev. Lett. 60, 1077 (1988). @footnote 2@ O. Pietzsch et al., Rev. Sci. Instr. 71, 424 (2000).

4:40pm **MI+NS+NANO 6-TuA9 Ballistic Electron Magnetic Microscopy Studies of Ferromagnetic Films and Tunnel Junctions***, **W.H. Rippard,** A.C. Perrella, R.A. Buhrman,* Cornell University **INVITED**

A new magnetic imaging technique, ballistic electron magnetic microscopy (BEMM), has been developed to study the magnetic structure in ferromagnetic multilayer films and nanostructures as a function of magnetic field H. In BEMM we exploit the hot electron transport properties of the ferromagnetic films in order to probe their magnetic structure. This technique allows not only the magnetic imaging in applied fields with nm-scale spatial resolution, but also allows the direct investigation of spin dependent transport through the ferromagnetic multilayers. As we are not using a magnetic probe to image these films, we are able to investigate very thin and soft magnetic structures which are the most relevant to technological applications. The magnetization reversal process of both continuous and patterned ferromagnetic films have been investigated. Using a UHV compatible stencil-mask technique, sub-micron structures have been fabricated and imaged with BEMM. In particular, I will discuss the switching behavior of permalloy 'diamonds' and 'rectangles' (1.5 x 0.3 microns2), as well as other shapes of smaller dimension. Using this technique the nanometer scale imaging of tunnel junctions can also be performed. Ballistic current transport through magnetic tunnel junctions will be presented, both in terms of the imaging of 'pin holes' in the junctions and spin-dependent transport through the barrier. The energy dependence of the transport in the ferromagnetic multilayer structures as well as in the tunnel junction systems will also be presented.

Magnetic Interfaces and Nanostructures
Room Exhibit Hall C & D - Session MI-TuP
Poster Session

MI-TuP1 Magnetic Properties of Ultrathin Co Films on Si(111)*, H. Xu,* National University of Singapore, Singapore*; A. Wee, A. Huan,* National University of Singapore

The growth and magnetic behaviour of ultrathin cobalt films on clean(7x7) and Au covered Si(111) were investigated. All experiments including molecular beam epitaxy (MBE) were performed in an ultra-high vacuum (UHV) chamber with a background pressure of 5x10@super-11@ mbar. The Si substrates were introduced via a load-lock and firstly outgassed over night, then the substrates were further cleaned by flashing to 1500K by resistive heating for several seconds. The UHV system was equipped with Auger electron spectroscopy (AES), scanning tunneling microscopy (STM), low energy electron diffraction (LEED) and magneto-optic Kerr effect (MOKE). The growth process was studied using STM and LEED. Magnetic properties were determined with MOKE. It was found that Co nucleates in the initial stage that prefer to grow along the bunched step-edges of the Si substrate(), which leads to a strong in-plane uniaxial anisotropy (hard axis along<-110> direction). By introducing Au buffer layers, the tendency for step decoration is reduced, Co grains begin to coalesce on the terrace, so that in-plane uniaxial anisotropy is reduced. However, the magnetic characteristics were improved by the deposition of a Au buffer layer, which partially blocks the silicide reaction between Si and Co. The ferromagnetic inactive layer was found to be decreased to 2.2 ML. By using an higher flashing current, unbunched steps are created on same Si substrate. It is suggested that in this way much more regions for reaction between Si and Co grains arise and a larger amount of CoSi@sub2@ is formed which then deteriorate the magnetic properties of the film in initial layers. Furthermore, in terms of Néel domain wall model and microstructure, different dependencies of coercivity vs. film thickness were discussed.

MI-TuP2 Model Based Design of Next Generation Ion Beam Deposition Systems*, H.N.G. Wadley,* *W. Zou,* University of Virginia, usa*; X.W. Zhou, J.J. Quan, Y. Sun, S. Subha,* University of Virginia*; T. Hylton, G. Hufnagel,* CVC Commonwealth, Inc.

Ion beam deposition (IBD) is increasingly used for the growth of giant magnetoresistive (GMR) multilayers and magnetic tunnel junction (MTJ) devices. The performance of both device types is a very sensitive function of the layer thickness, the metal atom deposition rate, incident angle and energy, together with the reflected neutral flux and energy at the substrate. These in turn depend upon the ion gun, target, substrate geometry, the ion gun voltage, the ion type, the extent of target dither and substrate rotation, the background pressure, and any shaping of the metal flux. Optimally selecting these parameters for the three or more metal targets in the deposition system has become very challenging to IBD tool designers. A Multiscale model has been used to simulate the Ion Assisted Ion Beam Deposition of GMR structure. The model allows the thickness of a metal layer and the metal atom incident angle over the surface of a wafer to be optimized by selection of the ion type and energy, target placement, orientation and dither, substrate placement and rotation, and background pressure. A molecular dynamics approach based on embedded atom method potentials is used to investigate the effects of process parameters such as assisting ion energy on the interfacial roughness and the interlayer mixing during the deposition of giant magnetoresistive (GMR) multilayers. The atomic scale mechanisms of mixing and roughening at the various interfaces are identified. This simulation can then be used to identify improved deposition systems that can meet the film thickness uniformity, interface morphology and atomic scale structure, target needed for the high yield manufacture of GMR devices.

MI-TuP3 Preparation of Cross-sectional TEM Specimens of Obliquely Deposited Magnetic Thin Films on a Flexible Tape*, E.G. Keim,* *M.D. Bijker, J.C. Lodder,* University of Twente, The Netherlands

Specimen preparation is an essential part of Transmission Electron Microscopy (TEM). In general, if one is interested in interface and/or film properties one should prepare a TEM specimen in cross-section. Upon surveying the literature, no recipe is provided for the preparation of TEM cross-sections of Metal Sputtered (MS) or Metal Evaporated (ME) magnetic thin films on polymer substrates. Various private communications in the field@footnote 1,2@ reinforce our impression that no adequate preparation procedure for this class of materials is available at present, although proper quality TEM images of ME tapes in cross-section have been published previously@footnote 3-9@ without an adequate description of TEM specimen preparation though. TEM cross-sections of MS or ME tapes pose several unique problems during preparation. In this paper we will present a recipe for making cross-sectional TEM specimens which is especially benificial for brittle metal layers even on polymer base films, resulting in large homogeneous electron transparent areas and leaving the very fragile polymer tape substrate and glue layer completely intact. Our recipe proves to be a good alternative to the use of a microtome. Apart from the sample preparation method also some details of the deposition technique will be elucidated. @FootnoteText@ @footnote 1@ J. Jodge and Peng Tang, Private communication (1999), Quantum Corp., USA.,@footnote 2@ H. te Lintelo, Private communication (1999), IST Corp., Belgium.,@footnote 3@ S. Honodera, H. Kondo, and T. Kawana, MRS Bulletin. 21(9), 35 (1996).,@footnote 4@ H. Ho, G. Gau, and G. Thomas, J. of Appl. Phys. 65(8) , 3161 (1989).,@footnote 5@ K. Sato, K. Chiba, T. Ito, T. Ssaki, and J. Hokkyo, J. of Appl. Phys. 69(8), 4736 (1991).,@footnote 6@ J. Hokkyo, T. Suzuki, K. Chiba, K. Sato, Y. Arisaka, T. Sasaki, and Y. Ebine, JMMM 120, 281 (1993).,@footnote 7@ P. ten Berge, L. Abelmann, J. C. Lodder, A. Schrader, and S. Luitjens., J. of The Magnetics Society of Japan 18(S1), 295 (1994).,@footnote 8@ M.D. Bijker, E.M. Visser, and J.C. Lodder, Tribology International 31(9), 553 (1998).,@footnote 9@ H.J. Richter, IEEE Transactions on Magnetics 29(1), 21 (1993).

MI-TuP4 Magnetic Transition at the Gd(0001) Surface*, C.S. Arnold,* *D.P. Pappas,* National Institute of Standards and Technology, Boulder

Controversy surrounds the magnetic ordering properties of the Gd(0001) surface. Several reports conclude that the surface has an it\{extraordinary} transition, ordering at a Curie temperature significantly higher than that of the bulk, while others reports have failed to reproduce this result. Our experiments unambiguously prove that the Gd(0001) surface has an ordinary transition. Furthermore, by analyzing both the bulk and surface magnetization, we show that Gd(0001) films are good realizations of semi-infinite, 3-dimensional Heisenberg ferromagnets with identical exchange couplings for surface and bulk, and identical Curie temperatures.

Magnetic Interfaces and Nanostructures
Room 206 - Session MI+EL-WeM

Magnetic Semiconductors and Hybrid Structures I
Moderator: B. Jonker, Naval Research Laboratory

8:20am **MI+EL-WeM1 Characterizations of MBE Grown Single Crystal Ferromagnetic Ni@sub 2@MnGa Thin Films on (001) Ga@sub 1-x@In@sub x@As***, J.W. Dong*[1]*, J.Q. Xie, L.C. Chen, M.T. Figus, S. McKernan, C.J. Palmstrom,* University of Minnesota

Minimization of spin flip scattering at the interface of ferromagnetic metal/semiconductor is expected with the use of high quality epitaxially grown ferromagnetic metal/semiconductor heterostructures with minimal interfacial reactions. The Heusler alloy Ni@sub 2@MnGa is ferromagnetic at room temperature and has the cubic L2@sub 1@ Heusler structure with lattice parameter 3% larger than that of GaAs. We have demonstrated MBE growth of 900 Å-thick single crystal Ni@sub 2@MnGa on (001) GaAs with a 6 monolayer-thick Sc@sub 0.3@Er@sub 0.7@As interlayer, which acts as a template layer and a diffusion barrier. Reflection high energy electron diffraction, X-ray diffraction, and transmission electron microscopy (TEM) studies confirm the single crystal structure of the Ni@sub 2@MnGa films and indicate that the growth is pseudomorphic on GaAs substrates. These results suggest an epitaxially stabilized tetragonal phase of Ni@sub 2@MnGa with a = b = 5.65 Å, c = 6.12 Å, which has not been found in the bulk. High resolution cross section TEM image shows that the interface between Ni@sub 2@MnGa films and the Sc@sub 0.3@Er@sub 0.7@As interlayer is atomically abrupt. The Rutherford backscattering channeling minimum yield of 6.5% further confirms the high quality of the Ni2MnGa films. At room temperature, magnetic measurements using a vibrating sample magnetometer show that the films are ferromagnetic with a coercivity of ~50 Oe, a saturation magnetization of ~250 emu/cm@super 3@, and a weak in-plane magnetic anisotropy. Using a superconducting quantum interference device magnetometer, the Curie temperature of the films is found to be ~340 K. Our results indicate that Ni@sub 2@MnGa/GaAs can form high quality ferromagnetic metal/semiconductor heterostructures that might be used for spin injection measurements. In this talk, the effect of interlayer and strain on the structural and magnetic properties of Ni@sub 2@MnGa on Ga@sub 1-x@In@sub x@As substrates will be discussed.

8:40am **MI+EL-WeM2 Molecular Beam Epitaxial Growth of Ferromagnetic Ni@sub 2@MnGe on GaAs(001)***, **J. Lu**, J.W. Dong, J.Q. Xie, D. Carr,* University of Minnesota*; V. Godlevsky,* Rutgers University*; C.J. Palmstrom,* University of Minnesota

A number of Heusler (L2@sub 1@) structures such as Ni@sub 2@MnX (X = Ga, In, Sn, Sb) are ferromagnetic shape memory alloys. The ferromagnetic Heusler alloys show promise as single crystal ferromagnetic spin polarized injecting contacts to semiconductors. In this work, epitaxial thin films of the Heusler alloy Ni@sub 2@MnGe have been for the first time grown on GaAs(001) substrate by molecular beam epitaxy (MBE). A two step growth procedure was used which included alternate layer epitaxy at 200°C of a thin Ni@sub 2@MnGe template layer followed by codeposition at 250°C. A (2x2) surface reconstruction was observed by in-situ reflection high energy electron diffraction. X-ray diffraction studies show that the Ni@sub 2@MnGe film is epitaxially grown on GaAs(001) with the crystallographic relationship: (001)@sub Ni2MnGe@//(001)@sub GaAs@, (110)@sub Ni2MnGe@//(110)@sub GaAs@ . X-ray diffraction was used to determine both the out of plane and in plane lattice parameters. These confirmed that the film had a tetragonal structure, with a = 5.65 ±0.02 Å c = 5.897 Å, and c axis perpendicular to film surface, suggesting pseudomorphic growth on the GaAs surface. The magnetic properties were measured using superconducting quantum interference device magnetometry (SQUID). The coercivity of the film is ~50 Oe, and the saturation magnetization Ms is ~ 200 emu/cm3. The Curie temperature was 330 ± 10 K. In this talk, the magnetic and structural properties of Ni@sub 2@MnGe/GaAs heterostructures as a result of growth procedures and composition will be discussed. Results from Rutherford backscattering and transmission electron microscopy studies will be correlated with the magnetic properties.

9:00am **MI+EL-WeM3 Demonstration of Electrical Spin Injection: The Spin-LED@footnote 1@***, **Y.D. Park**, B.R. Bennett, B.T. Jonker,* Naval Research Laboratory*; H.-D. Cheong, G. Kioseoglou, A. Petrou,* SUNY, Buffalo

Electrical spin injection into a semiconductor is a prerequisite for realizing the potential of semiconductor-based spintronic devices. This has been an elusive goal, however, and only modest effects (@<=@ 1%) have been obtained. We report here highly efficient electrical spin injection from a magnetic contact into a GaAs quantum well-based light emitting diode (LED) heterostructure (a spin-LED@footnote 2,3@) in which the spin injection efficiency exceeds 50%. Radiative recombination of spin polarized carriers in quantum wells results in the emission of circularly polarized light. The degree of optical polarization is proportional to the carrier spin polarization, enabling a direct, quantitative measure of the spin injection efficiency. The samples consist of ZnSe/ZnMnSe/AlGaAs/GaAs/AlGaAs heterostructures grown by MBE on p-GaAs(001) substrates, where the semimagnetic semiconductor ZnMnSe serves as a source of spin-polarized electrons which are injected via an applied bias voltage into the GaAs quantum well. Standard optical lithography and chemical etch procedures were used to define surface emitting LED mesa structures. The measured circular polarization of the electroluminescence (EL) exceeds 50%, and demonstrates that highly efficient spin transport occurs across the ZnMnSe/AlGaAs interface despite the large 0.5% lattice mismatch. Data are reported as a function of injection current, magnetic field, and temperature. The EL lineshape consists of multiple components whose relative polarization provide insight into spin relaxation mechanisms. We compare results from ex situ and in situ contacts, and with those obtained for carefully lattice matched systems.@footnote 4@. @FootnoteText@ @footnote 1@ This work was supported by the Office of Naval Research. @footnote 2@ US patent #5,874,749 (filed 6/93; awarded 2/99) @footnote 3@ Jonker, et al., submitted for publication. @footnote 4@ Fiederling, et al., Nature 402, 787 (16 December 1999).

9:20am **MI+EL-WeM4 Ferromagnetism and Spin Related Phenomena in Semiconductor Heterostructures***, **H. Ohno**,* Tohoku University, Japan **INVITED**

Alloys between non-magnetic III-V semiconductors and Mn have been grown by molecular beam epitaxy and shown to exhibit ferromagnetism at reduced temperatures. These alloys, (Ga,Mn)As, (In,Mn)As, and (Ga,Mn)Sb are quasi-lattice matched to their host semiconductors and thus offer new and unique opportunities to combine ferromagnetism and high quality III-V heterostructures being widely used in frontiers of semiconductor physics and also in commercially available devices. This talk covers the following topics: (1) Preparation and properties of ferromagnetic semiconductors, particularly (Ga,Mn)As, where transition temperature can be as high as 110 K for 5% Mn concentration.@footnote 1@ (2) The origin of carrier-induced ferromagnetism based on a mean field theory using kp approximation.@footnote 2@ (3) Ferromagnet/non-magnet tri-layer semiconductor structures exhibiting inter-layer magnetic coupling and spin-dependent scattering.@footnote 3@ (4) Resonant tunneling structures with ferromagnetic emitters.@footnote 4@ (5) Spin-injection experiments using ferromagnetic semiconductor heterostructures.@footnote 5@ (6) Spin relaxation in nonmagnetic (110) GaAs quantum wells, where prolonged spin relaxation times are observed,@footnote 6@ which can be over 10 ns from room temperature down to 5 K when modulation doped. @FootnoteText@ @footnote 1@ H. Ohno, Science, 281, 951 (1998), J. Mag. Mag. Materials, 200, 110 (1999). @footnote 2@ T. Dietl, H. Ohno, F. Matsukura, J. Cibert, and D. Ferrand, Science, 287, 1019 (2000). @footnote 3@ N. Akiba, D. Chiba, K. Nakata, F. Matsukura, Y. Ohno, and H. Ohno, J. Appl. Phys., 87, 6436 (2000). @footnote 4@ H. Ohno, N. Akiba, F. Matsukura, A. Shen, K. Ohtani, and Y. Ohno, App. Phys. Lett., 73, 363 (1998). @footnote 5@ Y. Ohno, D. K. Young, B. Beschoten, F. Matsukura, H. Ohno, and D. D. Awschalom, Nature, 402, 790 (1999). @footnote 6@ Y. Ohno, R. Terauchi, T. Adachi, F. Matsukura, and H. Ohno, Phys. Rev. Lett., 83, 4196 (1999).

10:00am **MI+EL-WeM6 Properties of Mn@sub x@Ge@sub 1-x@, Cr@sub y@Ge@sub 1-y@ and Mn@sub x@Cr@sub y@Ge@sub 1-x-y@ Semiconductor Films Grown by Molecular Beam Epitaxy@footnote 1@***, **J.E. Mattson**,* Naval Research Laboratory, US*; Y.D. Park, T.F. Ambrose, A.T. Hanbicki, A. Wilson, G. Spanos, B.T. Jonker,* Naval Research Laboratory

Mn doped GaAs exhibits ferromagnetic ordering along with semiconducting behavior.@footnote 2,3@ Recent theory@footnote 4@ suggests that low concentrations of Mn (10@super 20@ cm@super -3@). We describe here the structural, magneto-transport, and magnetic properties of Ge@sub 1-x@Mn@sub x@, Ge@sub 1-y@Cr@sub y@ and

[1] **Falicov Student Award Finalist**

$Ge_{1-y-x}Cr_yMn_x$ thin films (with $x < 0.15$, and $y < 0.15$) in which Mn and Cr act as acceptors. Samples were grown by MBE on GaAs(001) and Si(001) substrates at substrate temperatures ranging from 175 to 350°C and growth rates of 4-5 Å/min. For all growth conditions studied, the GeMn films show a largely diffuse RHEED pattern and lack of structural order as determined by XRD. The temperature dependence of the resistivity shows non-metallic behavior with room temperature hole concentrations as high as $3x10^{20}cm^{-3}$. The magnetic properties determined from SQUID magnetometry are similar to those of Ge_8Mn_{11} bulk alloys, suggesting the formation clusters of Ge_8Mn_{11} rather than a homogeneous alloy. Plan-view TEM confirms the presence of clusters. The GeCr films exhibit single crystal growth and are p-type with p

10:20am **MI+EL-WeM7 Characterizations of Fe Thin Films on GaAs (001) Grown at Cryogenic Temperatures by Molecular Beam Epitaxy***, **Y. Chye**, P Petroff,* University of California, Santa Barbara

One of our research objectives is to fabricate hybrid structures by integrating ferromagnetic materials into semiconductors. It has been demonstrated that molecular beam epitaxy (MBE) can be used to fabricate single crystalline Fe directly upon GaAs.[1] However, the intermixing between Fe and GaAs at the interface forms a "magnetically dead layer"[1] which will badly affect polarized transport and thus make efficient "spintronics" devices hard to realize. In an effort to circumvent this problem, we propose to grow Fe on GaAs at cryogenic temperatures (below -100 ° C). At these temperatures, the deposited Fe atoms and the GaAs surface atoms are less likely to react with each other through interdiffusion. To implement these ideas, we grow Fe thin films on GaAs (001) semi-insulating substrates at -150 ° C in an EPI-620 MBE with a liquid-nitrogen cooled sample stage. It is indicated by the streaky RHEED pattern that single crystalline Fe is grown on GaAs. The surface morphology, interface properties, crystal structure, film orientation and magnetic behavior of the samples have been characterized by atomic force microscopy (AFM), transmission electron microscopy (TEM), x-ray diffraction, and superconductivity quantum interference device (SQUID), respectively. To examine the interdiffusion at the interface, we perform photoluminescence (PL) measurements for samples with very thin Fe films grown at different temperatures above GaAs quantum wells. Our results show that the PL peaks for the quantum wells do not significantly change for the cryogenic temperature grown samples, whereas the room temperature grown samples show a dramatically reduced luminescence efficiency and energy emission shift. These results suggest that the cryogenic temperature deposition strongly suppress the interdiffusion between the Fe and GaAs at the interface. @FootnoteText@ [1] J. J. Krebs, B. T. Jonker, G. A. Prinz, J. Appl. Phys., 61 (1987) 2596.

10:40am **MI+EL-WeM8 Growth and Magnetic Properties of Epitaxial Fe-N Films[1]***, **F. Liu**, S.-C. Byeon, C. Alexander, G.J. Mankey,* University of Alabama

Reported values of magnetic moments in epitaxial $Fe_{16}N_2$ films vary from 2.3 to 3.5 Bohr magnetons per atom.[2] These discrepancies arise from the fact that the films are multiphase mixtures which decompose upon heating.[3] To study this problem, 40 nm thick Fe-N films were produced using reactive sputtering in an ultra clean sputtering system with in situ RHEED. First, an S-terminated GaAs surface is prepared by wet chemical etching. After annealing at 450 C, a 3 nm thick Fe seed layer is deposited to promote epitaxial growth of a 20 nm thick Ag(100) buffer layer. The Fe-N film is then grown on this Ag(100) buffer. The sputtering power, Ar + N_2 pressure, and the substrate temperature were varied systematically to produce the optimal RHEED pattern. The films were capped with a 5 nm thick Ru layer for ex situ structural and magnetic analysis. XRD is used to identify the degree of N-site ordering and the unit cell volume. XPS depth profiling is used to determine the chemical composition of the Fe-N film. The structural and chemical measurements are correlated with ferromagnetic resonance and vibrating sample magnetometry measurements of the saturation magnetic moment. These results are used to clarify the origin of the "giant magnetic moment" in the ordered $Fe_{16}N_2$ phase. @FootnoteText@ [1]Funded by ARO #DAAH 04-96-1-0316 and NSF #DMR-9809423. [2]G.W. Fernando et al., Phys. Rev. B 61, 375(2000). [3] Migaku Takahasi and H. Shoji, J. Magn. Magn. Mater. 208, 145(2000).

Magnetic Interfaces and Nanostructures
Room 206 - Session MI+EL-WeA

Magnetic Semiconductors and Hybrid Structures II

Moderator: P.N. First, Georgia Institute of Technology

2:00pm **MI+EL-WeA1 Spin-dependent Behavior in Magnetic / Semiconductor Heterostructures*, B.T. Jonker,*** Naval Research Laboratory **INVITED**

Magnetic / semiconductor heterostructures offer many exciting opportunities for spintronic applications, ranging from hybrid device structures to direct spin injection. We describe here recent results of each. We have fabricated hybrid logic cells which provide fully reprogrammable, nonvolatile logic operation by combining GMR elements with InAs/AlSb/GaSb resonant interband tunneling diodes (RITDs). Such programmable cells allow the use of a low component count common building block for multiple logic functions, and combine the low power, high speed operation of the RITD with the nonvolatile character of GMR elements. Electrical spin injection and transport in semiconductors is another promising avenue to add spin-dependent functionality to the many attractive device properties of semiconductor compounds -- it provides a very simple means of spin injection, and significantly broadens the potential for practical applications.@footnote 1-3@ We have recently demonstrated highly efficient electrical injection of spin-polarized electrons into a AlGaAs/GaAs-based quantum well LED heterostructure using a non-lattice matched epilayer of the semimagnetic semiconductor ZnMnSe as the spin injecting contact. The electroluminescence (EL) from the quantum well is strongly polarized, and provides a quantitative measure of spin injection across the ZnMnSe/AlGaAs interface. Other components of the EL spectrum exhibit little polarization, and provide insight into spin relaxation mechanisms. Ferromagnetic semiconductors provide an ideal contact for electrical spin injection and/or transport -- they are closely matched in conductivity and band structure, and require no large magnetic bias field to produce spin polarized carriers. Several candidate materials will be discussed. ** Supported by ONR and the DARPA SPINS program.@FootnoteText@ @footnote 1@ B.T. Jonker et al, submitted. @footnote 2@ R. Fiederling et al, Nature 402, 787 (1999) @footnote 3@ Y. Ohno et al, ibid p. 790.

2:40pm **MI+EL-WeA3 MBE Growth of Ni@sub 2@MnIn/InAs (001) Heterostructure*, J.Q. Xie*[1]**, *J.W. Dong, L.C. Chen, J. Lu, C.J. Palmstrom,* University of Minnesota

InAs is the semiconductor of choice for spintronic applications due to the ease of forming ohmic contacts and its high electron mobility. The former arises from the fact that the Fermi level tends to be pinned in the conduction band at the metal/InAs interface. Although no elemental ferromagnetic metals are lattice matched to InAs, Ni@sub 2@MnIn is nearly lattice matched. In the bulk, stoichiometric Ni@sub 2@MnIn is ferromagnetic at room temperature and has the cubic L2@sub 1@ Heusler structure with a lattice parameter 0.2% larger than that of InAs. In this talk, we report on the growth of ferromagnetic Ni@sub 2@MnIn films on (001) InAs by molecular beam epitaxy (MBE). Both in situ reflection high energy electron diffraction and ex situ X-ray diffraction measurements indicate that Ni@sub 2@MnIn films grow epitaxially on MBE-grown (001) InAs substrates. Vibrating sample magnetometer and superconducting quantum interference device magnetometer measurements show that the deposited films are ferromagnetic with a Curie temperature ~300 K. Our initial results indicate that Ni@sub 2@MnIn grows in a hexagonal Ni@sub 2@In@sub 3@-type structure, which probably results from either interfacial chemistry or composition. In this talk, the effects of interfacial layers on the growth, structure and magnetic properties of Ni@sub 2@MnIn thin films will be discussed.

3:00pm **MI+EL-WeA4 Investigation of the Microstructural Dependence of Magnetic Properties for MnSb/Bi Multilayers Grown on Sapphire*, M.L. Reed*,** *H.H. Stadelmaier, N.A. El-Masry,* North Carolina State University

The microstructural dependence of the magnetic properties for MnSb/Bi multilayer films grown on sapphire substrates by pulsed laser deposition were investigated by X-ray diffraction(XRD), vibrating sample magnetometer (VSM), and magnetoresistance measurements. Typical hysteresis loops for the MnSb/Bi multilayers are characteristic of ferromagnetic materials. However, altering the growth parameters produces a second coercive field indicating the formation of a second magnetic phase. XRD analysis identified the presence of a peak centered between (0002)MnSb and (0002) MnSb, which in previous samples had not been observed. A change in the relative planar Hall resistance from 1% to 16% with applied magnetic field was also observed in the films that exhibit this second phase. We discuss the nature of this phase and its effect on the magnetic properties of MnSb/Bi.

3:20pm **MI+EL-WeA5 Ferromagnetic Fe/Ag-GaAs Waveguide Structures for Wideband Microwave Notch Filter Devices*, W. Wu,*** University of California, Irvine*; C.S. Tsai,* University of California, Irvine and Academia Sinica, Taiwan*; C.C. Lee, H.J. Yoo, J. Su,* University of California, Irvine

Ferromagnetic Fe/Ag thin films were epitaxially grown on GaAs substrate by molecule beam epitaxy (MBE) system. Magneto-optic kerr effect (MOKE) experiment was used to measure the magnetization and sample magnetic anisotropy. Ferromagnetic resonance (FMR) peak-to-peak linewidths @delta@H@sub pp@ are identified with the narrowest linewidth of 23 Oe. Wideband electronically tunable microwave band-stop filters were successfully fabricated utilizing both the flip-chip and the integrated configurations, using Fe/Ag-GaAs waveguide structures. The coupling between the microwave signal and the spin excitations happened in ferromagnetic Fe films. Maximum coupling and thus strong attenuation of the microwave power occur at the FMR frequency of Fe, as determined by the applied magnetic fields. A frequency tuning range of 10.6 to 27.0 GHz has been measured with the flip-chip type filter. For the integrated type filter, a tuning range as large as 10.7 to 36 GHz for the peak absorption carrier frequency of a propagating microwave has been accomplished by varying a magnetic field from 0 to 4,600 Oe. Our studies show that Fe/Ag-GaAs waveguide structure is a very promising system for use in future microwave magnetoelectronics as they have well-defined magnetic properties, as well as favorable electrical properties.

3:40pm **MI+EL-WeA6 Non-Volatile Reprogrammable Logic Elements using a Hybrid RTD-GMR Circuit@footnote 1@*, A.T. Hanbicki*,** *R. Magno, S.-F. Cheng,* Naval Research Laboratory*; J.E. Mattson,* Naval Research Laboratory, US*; Y.D. Park, A.S. Bracker, B.R. Bennett, B.T. Jonker,* Naval Research Laboratory

Programmable logic devices and gate arrays are increasingly important in new computation and digital logic systems. The resonant tunneling diode (RTD) is an especially attractive device component for such applications because it offers high frequency and low power operation due to its unique IV characteristics. It has been shown that memory, multi-value logic and monostable-bistable logic elements (MOBILE)@footnote 2@ can be constructed using RTDs and FETs. We describe here the fabrication and operation of programmable gates and logic cells based on the combination of RTDs with magnetic elements, yielding fully reprogrammable, nonvolatile functions. The circuits discussed are constructed with resonant interband tunneling diodes (RITD) combined with giant magneto-resistance (GMR) elements. The RITDs are fabricated from MBE-grown InAs/AlSb/GaSb/AlSb resonant tunneling structures using standard processing techniques, and provide a peak current of 1.4 x 10@super 4@ A/cm@super 2@. The GMR elements consist of Co/Cu multilayers, and exhibit a value of @DELTA@R/R = 28% at 300 K (CIP). Simple series and parallel circuit combinations demonstrate continuous or 2-state tunability of the RITD I-V characteristic. Threshold detection is demonstrated, for the RITD and GMR in series, by ramping the magnetic field. With the elements we have chosen, the output can be switched by 0.5 V. MOBILE-like inverter operation is observed in a GMR/2-RITD circuit. Specifics of several other circuits will also be discussed. Work is in progress to fabricate an on-chip GMR/RITD integrated circuit. @FootnoteText@ @footnote 1@This work was supported by the Office of Naval Research. @footnote 2@K. Maezawa and T. Mizutani, Jpn. J. Appl. Phys., 32 (1993) L42.

4:00pm **MI+EL-WeA7 Magnetization-Controlled Resonant Tunneling in Magnetic Heterostructures**, *D.O. Demchenko, A.N. Chantis,* ***A.G. Petukhov,*** South Dakota School of Mines and Technology

Recent advances in molecular beam epitaxial growth made it possible to fabricate exotic heterostructures comprised of magnetic films or buried layers (ErAs, Ga@sub x@Mn@sub 1-x@As) integrated with conventional semiconductors (GaAs) and to explore quantum transport in these heterostructures.@footnote 1,2@ It is particularly interesting to study spin-dependent resonant tunneling in double-barrier resonant tunneling diodes (RTD) with magnetic elements such as GaAs/AlAs/ErAs/AlAs/GaAs, Ga@sub x@Mn@sub 1-x@As/AlAs/GaAs/AlAs/GaAs, and GaAs/AlAs/Ga@sub x@Mn@sub 1-x@As/AlAs/GaAs. We present the results of our theoretical studies and computer simulations of transmission

[1] **Falicov Student Award Finalist**

coefficients and current-voltage characteristics of resonant tunneling diodes based on these double-barrier structures. Interband resonant tunneling of electrons (ErAs-based RTDs) and resonant tunneling of holes (Ga@sub x@Mn@sub 1-x@As-based RTDs) is considered. Our approach is based on 8x8 k.p perturbation theory with exchange splitting and strain effects taken into account. We analyze Zeeman splittings of different resonant channels as a function of magnetization. We found that resonant tunneling I-V characteristics of the double-barrier magnetic heterostructures strongly depend on the doping level in the emitter as well as on the orientation of the magnetization. The peculiarities spin-dependent tunneling in GaAs/ErAs- and GaAs/GaMnAs-based heterostructures are explained in terms of strong interaction of confined hole states with magnetization, spin-orbit interaction and angular momentum selection rules. @FootnoteText@ @footnote 1@ D. E. Brehmer, K. Zhang, C. J. Schwartz, S. P. Chau, and S. J. Allen, Appl. Phys. Lett. 67, 1268 (1995). @footnote 2@ H. Ohno, N. Akiba, F. Matsukura, K. Ohtani, A. Shen, and Y. Ohno, Appl. Phys. Lett. 73, 363 (1998).

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

Nanomagnetism
Moderator: P.N. First, Georgia Institute of Technology

8:20am **MI+NS+NANO 6-ThM1 New Directions for Semiconductors*, D.D. Awschalom*[1]**, UC Santa Barbara **INVITED**
PLEASE SEND US AN ABSTRACT. Thank you.

9:00am **MI+NS+NANO 6-ThM3 Electron Spin Relaxation at Nanometer Length Scales Near a Ferromagnet*, B.C. Stipe*,** *D. Rugar, H.J. Mamin, C.S. Yannoni,* IBM Almaden Research Center*; T.D. Stowe, T.W. Kenny,* Stanford University
Long spin relaxation times will be important to the success of many proposed solid-state quantum computing devices, spintronic devices, and to the detection of single spins by magnetic resonance force microscopy (MRFM). However, spin relaxation may be strongly influenced by thermal magnetic fluctuations in nearby materials such as conductors and ferromagnets. We have employed MRFM with 100 spin sensitivity and 20 nm spatial resolution to study the behavior of E' centers in SiO@sub 2@ near a micron-size ferromagnetic PrFeB particle tip. Magnetic resonance was induced within a 1 nm thick selective slice at 6 GHz and 3 Kelvin in a field gradient of 1 Gauss/nm. For detection, spins were manipulated by adiabatic inversion to produce oscillatory forces on the magnetic particle mounted on a sensitive cantilever. A typical spin ensemble consisted of 2000 spins with a net polarization of 100 µ@sub B@. T@sub 1@ was measured as a function of distance from the tip and was found to systematically decrease from 13 seconds when the spins were far from the tip to about 2 seconds within 500 nm of the tip. We interpret our results in terms of magnetic noise at the spin due to small-angle, thermal magnetic moment fluctuations in the particle. No relaxation effect due to proximity to the sample surface was found for depths greater than 50 nm. This work is supported, in part, by the Office of Naval Research.

9:20am **MI+NS+NANO 6-ThM4 Ferromagnetic Resonance of Monodisperse Co Particles*, M. Farle*,** *U. Wiedwald,* Technische Universitaet Braunschweig, Germany*; M. Hilgendorff, M. Giersig,* Hahn-Meitner-Institut Berlin, Germany
Quasi- twodimensional regular arrays of monodisperse 6 nm diameter Co particles can be produced on Carbon substrates by a monophoretic deposition technique from colloidal suspensions. Transmission electron microscopy reveals hexagonal ordering on micrometer scales for deposition at 0.8 Tesla and a bcc crystalline structure of the particles.@footnote1@ Ferromagnetic resonance (FMR) spectra at 296 K show a weak angular dependence near the paramagnetic resonance field with an easy in-plane magnetization axis . This shows a preferential alignment of the superparamagnetic particles in the film plane. A symmetric lineshape and linewidth dH < 0.1 Tesla is observed which indicates the high monodispersity in magnetic and geometric properties of the individual particles. Characteristic differences of the FMR spectra for different substrates and deposition parameters are observed and will be discussed in terms of simple dipolar coupling models. Supported through EC - grant no. HPRN-CT-1999-00150. @FootnoteText@ @footnote 1@ M. Giersig and M. Hilgendorff, J. Phys. D: Appl. Phys. 32 (1999) L111.

9:40am **MI+NS+NANO 6-ThM5 Magnetic Mirages*, H.C. Manoharan*,** *C.P. Lutz, D.M. Eigler,* IBM Almaden Research Center **INVITED**
While the correlated electron physics underlying the diverse manifestations of magnetism and spin have long been studied via macroscopic behavior, only recently have novel local probes opened the door to a new class of studies on the nanometer length scale. On top of these technological advances, the advent of controlled atomic and molecular manipulation provides a unique opportunity not only to detect spin phenomena at atomic length scales, but to manipulate spins as well. This talk will detail new results that exploit these techniques using low-temperature scanning tunneling microscopy.@footnote 1@ We have directly imaged the electronic perturbation arising from the spin-compensation cloud formed around isolated magnetic moments on a metal surface. Utilizing the detection of this many-body state, known as the Kondo resonance, we demonstrate that the spectroscopic signature of an atom may be sampled and projected to a remote location by means of a surrounding two-dimensional electron gas confined in an engineered nanostructure. The ``quantum mirage'' thus cast by a single magnetic atom can be coherently refocused at a distinct point where it is detected as a phantom atom around which the electronic structure mimics that at the real atom. Once materialized, this phantom can interact with real matter in intriguing ways. We have also been developing a novel communication method based on this effect. @FootnoteText@ @footnote 1@ H. C. Manoharan et al., Nature 403, 512 (2000).

10:20am **MI+NS+NANO 6-ThM7 Correlation of Structural and Magnetic Properties of Ultra-Thin Fe-Films on W(110) by Spin-Polarized STM/STS*, A. Kubetzka*,** *O. Pietzsch, M. Bode, R. Wiesendanger,* University of Hamburg, Germany
To investigate magnetism at the nm-scale and to improve the understanding of its underlying principles, a magnetic imaging technique with ultra-high resolution is of vital importance. Recently, spin-polarized scanning tunneling microscopy/spectroscopy has been developed to a reliable tool to allow such investigations down to the atomic level.@footnote 1,2@ We investigated Fe-films on W(110) at T = 15 K in a coverage range of 1 to 2 ML. In this regime Fe grows as double layer islands interconnected by a closed ML, where the island size can be tuned by the amount of evaporated Fe. By using ferromagnetically coated tips with a magnetization direction along the tip axes, we are sensitive to the out-of-plane component of the sample magnetization. Our measurements reveal that above a critical width of about 2.5 nm along the [1-10] direction, the islands are magnetized perpendicularly to the film plane. Below this width we do not observe a magnetic contrast which we attribute to a reorientation of magnetization to in-plane. Whereas the small perpendicularly magnetized islands are in a single domain state, we observe domain walls above a coverage of 1.5 ML, with wall widths of w = 7±1 nm. @FootnoteText@ @footnote 1@ Pietzsch et al., Phys. Rev. Lett. 84, (2000). @footnote 2@ Heinze et al., Science (accepted).

10:40am **MI+NS+NANO 6-ThM8 Current-driven Magnetization Reversal in Nanopillars*, F.J. Albert*,** Cornell University*; J.A. Katine,* IBM Almaden*; R.A. Buhrman,* Cornell University*; R.H. Koch,* IBM Research Division*; E.B. Myers, D.C. Ralph,* Cornell University
As reported elsewhere, we have successfully fabricated functional F/N/F thin film nanopillar devices with lateral dimensions down to 60 nm, and with one ferromagnetic layer considerably thicker (magnetically harder) than the other. A substantial shape anisotropy has been introduced by patterning a 2 to 1 aspect ratio into these nanopillars. This shape anisotropy is confirmed with the behavior of the measured switching field as a function of angle to the elongated axis. The resistance of these devices shows abrupt, single-domain-like switching when the spin-polarized current flowing through the nanopillar exceeds a critical value and forces the two F layers either into parallel or anti-parallel alignment, depending on the current direction. Here we will report on the results of detailed studies of this spin-transfer switching effect as a function of magnetic field, magnetic orientation and nanopillar composition. Also we will report on the spin-transfer switching dynamics of these devices, measured by probing them with extremely short pulses of current. We are also pursuing the thickness dependence of the switching behavior and will report these results.

11:20am **MI+NS+NANO 6-ThM10 Patterning of Co/Pt Multilayers: Topological vs. Magnetic*, V. Metlushko*,** *G. Crabtree, V. Vlasko-Vlasov, P. Baldo, L. Rehn, M. Kirk,* Argonne National Laboratory*; B. Ilic,* Cornell University*; S. Zhang, S.R.J. Brueck,* University of New Mexico*; B.D. Terris,* IBM Almaden Research Center
Using magnetron sputtering for Pt and e-beam deposition for Co the [Co4/Pt10]n multilayers were prepared on a Si/SiO2 substrate. The patterning of submicron periodic arrays were done in two ways, using traditional interference- or e-beam lithography and lift-off which modulates the material composition of the film, and using 30 keV He ion irradiation through a mask which leaves the chemical composition and topography unchanged but reduces the magnetic anisotropy. The results of systematic characterization of arrays for different doses ranging from 1e15 to 5e16 ions/cm2 with SQUID magnetization to determine the magnetic anisotropy and moment size, with atomic force microscopy (AFM) and magnetic force microscopy (MFM) to determine the topography and the magnetic order in the periodic arrays, and with magneto optical imaging to visualize the moment reversal process during a magnetization cycle will be presented. @FootnoteText@ This work was supported by the U.S. DOE, BES-Materials Sciences, under contract W-31- 109-ENG-38 (V.M., G.C.) and by DARPA (S.Z., S.R.J.B.).

[1] **Featured Speaker - Science and Technology in the 21st Century**

Magnetic Interfaces and Nanostructures
Room 206 - Session MI-ThA

Magnetic Devices: GMR & Tunneling
Moderator: B.A. Everitt, Seagate Technology

2:00pm **MI-ThA1 The Determination of Magnetostriction for Spin-Valve Devices with 5.0 nm and 10.0 nm Permalloy Layers***, **T.J. Gafron,*** Boise State University*; S.E. Russek,* National Institute of Standards and Technology*; S.L. Burkett,* Boise State University

The objective of this study is to determine the extent of magnetostriction in spin-valves. Spin-Valves were constructed on a silicon substrate using dc magnetron sputter deposition techniques with the following structure: Ta@sub 5.0@ /NiFe@sub 5.0 or 10.0@ /Co@sub 1.0@ /Cu@sub 3.0@ /C0@sub 3.0@ /Ru@sub 0.6@ /Co@sub 2.0@ /FeMn@sub 10.0@ /Ta@sub 5.0@, where the subscripts denote the layer thickness in nanometers. The films were deposited with a magnetic field applied parallel to the substrate to align the pinned and free layers. Spin-valves were designed in a serpentine shape to maximize magnetostriction effects by increasing the device length. Device widths between 1 and 40 microns and lengths between 100 and 2000 squares were fabricated. Spin-valves tested exhibited a 5-7% change in magnetoresistance and an average ferromagnetic exchange coupling of 0.4 kA/m at 300°K. Devices were subjected to an external magnetic field while a mechanical stress was applied to the backside of the substrate. A four-point probe technique was used to measure device resistance as a function of applied field and mechanical stress. An increase in the anisotropy field, H@sub k@, is observed with increasing mechanical stress. This increase is observed for all devices tested but more distinct for those containing the 5.0 nm Permalloy. Using the curvature of the stressed sample and the thickness of the spin-valve and substrate, magnetostriction is calculated as a function of the applied stress. Results show that maximum magnetostriction occurs abruptly at lower stress values for the 10.0 nm Permalloy while magnetostriction for the 5.0 nm permalloy occurs gradually over a wider range of stress values. Magnetostriction is small (1.50 microns for the 20 micron by 1K square, 5.0 nm NiFe), but the effect is pronounced and impacts device performance as demonstrated by a shift in H@sub k@. Magnetostriction analysis becomes critical as both device complexity and integration levels increase.

2:20pm **MI-ThA2 Properties of GMR Multilayers Grown by RF Diode Sputtering***, **W. Zou,*** University of Virginia, usa*; X.W. Zhou, R.A. Johnson,* University of Virginia*; H.N.G. Wadley,* University of Virginia, usa*; D.J. Brownell, D. Wang,* Nonvolatile Electronics, Inc.

RF diode sputtering techniques are used for the growth of giant magnetoresistive (GMR) multilayers. The performance of devices synthesized in this manner is a sensitive function of the nanoscale structure and interfacial morphology created during the condensation step of the deposition process. Systematic series of experiments have been conducted to evaluate the dependence of film morphology upon composition of conducting layer. Atomic force microscopy (AFM) shows when CuAgAu is used (instead of pure Cu) the RMS roughness is reduced but occasional hillocks are also formed. By using a newly developed embedded atom method (EAM) alloy potential, a Molecular Dynamics study has been used to investigate the layer by layer growth phenomena and to identify the origin of the relationships between the experimental observations and layer composition. The use of the copper silver gold alloy is found to promote smoother interfaces because silver acts as a surfactant. Surface Auger results reveal the hillocks to be rich in silver a consequence of surface segregation into islands. Novel deposition strategies for morphology control have been proposed.

2:40pm **MI-ThA3 GMR Sensing Elements for the Detection of Magnetic Microbeads in Biosensor Array***, **M. Miller,*** Naval Research Laboratory **INVITED**

Giant magnetoresistance (GMR) magnetoelectronics has been an area of growing technological and commercial interest. GMR hard disk read heads have enabled a order-of-magnitude increase in storage density. Nonvolatile random access memory (NVRAM) utilizing GMR technology is an area of intense research and prototype devices are being introduced. Still other devices include magnetic field sensors as well as rotation and displacement sensors. A unique application for GMR devices is in the detection of magnetic microbeads commonly used in biological research for cell and biomolecule separation. We are developing a biosensor, the Bead ARray Counter (BARC),@footnote 1@ that uses these microbeads as labels to detect DNA hybridization at specific areas over an array of GMR sensors micro-fabricated on a chip. Eventually, the BARC chip is envisioned to be akin to GMR NVRAM, with millions of sub-micron GMR elements enabling simultaneous detection of thousands of DNA sequences with high sensitivity and dynamic range. We will discuss the special magnetotransport, micromagnetics, and microfabrication issues required for the development of high-density GMR-based biosensor arrays. This work was done in collaboration with P.E. Sheehan, R. L. Edelstein, C. R. Tamanaha, L. Zhong, S. Bonnak, R. J. Colton, L. J. Whitman, and G.A. Prinz. @FootnoteText@@footnote1@Edelstein et al., Biosensors & Bioelectronics 14, 805 (2000).

3:20pm **MI-ThA5 Preparation of Magnetic Tunnel Junctions by Ionized Atom Beams***, **S.O. Demokritov**, B.F.P. Roos, B. Hillebrands,* University Kaiserslautern, Germany

A new oxidation technique for the preparation of thin insulating barriers for magnetic tunnel junctions combined with in-situ resistivity and optical reflectivity measurements is studied. A highly dissociated low energy (30 eV-80 eV) ionized oxygen atom beam from a novel type of an electron cyclotron wave resonance controlled plasma reactor is used to oxidize metallic Al layers and to form an insulating barrier for tunnel junctions. The oxidation process is found to be self limiting. The oxidation depth variate from 1.5 to 2 nm in agreement with performed Monte Carlo simulations.

3:40pm **MI-ThA6 Nonlinear Magneto-Optical Investigations of Magnetic Interfaces***, **Th. Rasing***, University of Nijmegen, The Netherlands **INVITED**

Magnetization induced second harmonic generation (MSHG) is a new nonlinear magneto-optical technique that combines interface sensitivity with huge magneto-optical effects. These effects are due to the simultaneous breaking of inversion symmetry (at interfaces) and time-reversal symmetry (by the magnetization). Because most magnetically ordered materials are centrosymmetric in their bulk form, MSHG is a particularly interesting probe to study the magnetization structure of the interfaces in magnetic multilayer systems. Using MSHG, we have found e.g. that the spin orientation at the interface of CoNi/Pt multilayers can be different from the bulk due to specific preparation conditions. Due to both very high magneto-optical contrast and interface sensitivity, fine details of magnetization reversal become visible with MSHG imaging that are not detectable by usual magneto-optics. MSHG also appears to be highly sensitive for the step induced anisotropy in magnetic thin films grown on vicinal surfaces. In addition, effects of interface annealing and oxidation can be observed in situ, which is of great importance for sensor multilayer structures. By using phase sensitive spectroscopic MSHG experiments, the spin-dependent interface density of states can be probed, as was recently demonstrated in a study on a Ni(110) surface. This is of great importance for the understanding of e.g. the spin dependent tunnel current in magnetic tunnel devices. Finally, the use of fs laser excitation allows the probing of ultra fast magnetization dynamics, using pump-probe techniques. Recent results of this will be discussed. Part of this work was supported by FOM, the TMR Network NOMOKE and INTAS 97-0705 (ERBFMRXCT960015) and INTAS 97-0705.

4:20pm **MI-ThA8 "Acoustical" and "Optical" Spin Modes of a Fe/Cr/Fe/Cr/Fe Multilayer with Ferro- and Anti-ferromagnetic Couplings***, **F. Nizzoli**, L. Giovannini, P. Vavassori, R. Zivieri,* University of Ferrara and INFM, Italy

A study of the in-phase ("acoustical") and of the out-of phase ("optical") spin modes in layered ferromagnetic structures with both ferromagnetic and antiferromagnetic coupling is presented, in particular for the system Fe(20Å)/Cr(20Å)/Fe(20Å)/Cr(9Å)/Fe(100Å), for which experimental Brillouin scattering data are available@footnote 1@ In our model we take magnetocrystalline, uniaxial and shape anisotropies, Zeeman interaction, bilinear and biquadratic exchange interlayer couplings into account. The magnetization equilibrium configuration is calculated as a function of the external field using the steepest descent technique. A calculation of the dynamic magnetization assumed constant in each film gives an explanation of the behavior of the two kinds of modes at different magnetic fields applied along the easy axis. The "acoustical" mode is the lowest frequency one at low applied fields, but frequency exchanges with the "optical" modes occur at higher fields. It is found that the competition between the Zeeman and the biquadratic exchange terms is responsible for the appearance of a soft mode at a critical field marking a second-order phase transition.

4:40pm **MI-ThA9 Analysis of Tunneling Magnetoresistance Structures by Low Energy Electron Nanoscale Luminescence Spectroscopy**, ***S.H. Goss,*** The Ohio State University; *S.S.P. Parkin,* IBM Almaden Research Center; *L.J. Brillson,* The Ohio State University

The performance of state-of-the-art tunneling magnetoresistive (TMR) heads depends sensitively on the thickness of insulating layers less than a few nanometers thick which separate two magnetic films. We have used low energy electron nanoscale luminescence (LEEN) spectroscopy to observe optical emission from TMR test structures with buried insulating oxides less than a few nm thick. TMR structures grown by DC magnetron sputtering consisted of a 0.8 - 3 nm Al oxide layer on a 2.4 nm CoFe alloy (84:16) sandwiched between a multilayer metal-on-Si substrate and a 4.4 nm CoFe plus Pt overlayer. LEEN excitation energies ranging from 0.5-3 keV enabled us to distinguish between emissions from the buried oxide layers vs. the free surface. We used different compositions, thicknesses, and oxidation exposures to separate Al oxide from transition metal oxide emissions, as well as from the ambient-exposed Pt surface. A broad peak centered at 2.7 eV increased with increasing oxygen plasma exposure at constant Al thickness. It also increased with increasing Al thickness and commensurate oxygen exposure. Emission from oxidized CoFe without Al consists of a featureless emission extending from 1.5 - 3.7eV. Common to all these spectra is emission at 1.8 eV, which energy-dependent LEEN demonstrates is due to the ambient-exposed Pt. Finally, spectral changes of the buried, oxidized Al/CoFe sandwich layers as a function of thickness and oxygen exposure reveal the regime separating oxidation of the Al layer alone from over-oxidation that extends into the CoFe base layer. These results suggest that optical emission from nanometer - thick tunnel layers within TMR structures can be used to assess the extent of oxidation as well as to optimize deposition and process conditions.

5:00pm **MI-ThA10 Magneto-optical and Optical Spectroscopies of Fe/Si Multilayered Films**, ***Y.P. Lee,*** *T.-U. Nahm, C.O. Kim,* Hanyang University, Korea; *Y.V. Kudryavtsev,* Institute of Metal Physics, Ukraine; *K.W. Kim,* Sunmoon University, Korea; *J.Y. Rhee,* Hoseo University, Korea; *J. Dubowik,* Institute of Molecular Physics, Poland

Fe/Si multilayered films (MLF) exhibiting a strong antiferromagnetic (AF) coupling were studied by optical and magneto-optical spectroscopies. The first set of Fe/Si MLF with a fixed Fe sublayer thickness of 3.0 nm and a variable thickness of Si sublayers (1.0 - 2.2 nm) was prepared by rf-sputtering onto glass substrates at room temperature with the number of repetition of 50. To replicate the spacer silicide layers in the MLF, the second set of Fe/Si MLF with very thin Fe and Si sublayers (0.3 - 0.8 nm and 0.4 - 0.8 nm, respectively) was also deposited. The results were compared with the computer-simulated spectra based on various structural models of the MLF. Neither semiconducting FeSi@sub 2@ nor @epsilon@-FeSi turned out to be considered as the spacer layer for a strong AF coupling. The optical properties of the spacer extracted from the effective optical response of the MLF strongly support its metallic nature. A reasonable agreement between experimental and simulated equatorial-Kerr-effect spectra was obtained with the fitted optical parameters of the spacer for the FeSi or Fe@sub 5@Si@sub 3@ stoichiometry. A comparison of the extracted optical properties for the spacer with the calculated ones based on the first principles showed that a B2-phase metallic FeSi compound is spontaneously formed at the interfaces of MLF during deposition. For the Fe/Si system with ultrathin Fe and Si sublayers, our optical data reveal that the overall structure of MLF is close to an amorphous and semiconducting @epsilon@-FeSi.

Magnetic Interfaces and Nanostructures
Room 206 - Session MI-FrM

Magnetic Recording: Media and Heads

Moderator: D.K. Weller, IBM Almaden Research Center

8:20am **MI-FrM1 Focused Ion Beam Patterning of Magnetic Films***, **B.D. Terris**, C.T. Rettner, M.E. Best,* IBM Almaden Research Center **INVITED**

In the future it may be necessary to pattern magnetic recording media to achieve data densities beyond 100 Gb/sq. in. The required patterning should have minimal cost and leave a surface suitable for flying a recording head. One promising approach to achieving such patterning is to use ion beams to directly modify the magnetic properties of thin films. It has been shown previously that Co/Pt multilayers can be modified magnetically by exposure to a uniform beam of ions (eg. He+, N+), where the easy magnetization axis of the film is rotated from out-of-plane in the as grown film to in-plane in the irradiated film. Local areas of in-plane magnetization can thus be produced by exposing the film through masks.@footnote 1-3@ We have now demonstrated that such films can be also be patterned using a focused ion beam (FIB) of Ga+ ions without the use of a mask. In addition to patterning the multilayer Co/Pt films by easy axis rotation, films of granular CoPtCr have been patterned by removal of the magnetic film by Ga+ milling. The remanent magnetization state of square islands ranging from 80 nm to 230 nm in size was studied by MFM and the smallest islands appear to be single domain. Remanent hysteresis loops generated from MFM data show that the coercivity of the CoPtCr films is unchanged by the FIB patterning, in contrast to the FIB patterning of Co/Pt multilayers where the coercivity decreases with increasing ion dose and decreasing island size. @FootnoteText@ @footnote 1@C. Chappert et al., Science 280, 1919 (1998) @footnote 2@B. D. Terris et al., Appl. Phys. Lett.75, 403 (1999) @footnote 3@T. Devolder et al., Appl. Phys. Lett. 74, 3383 (1999)

9:00am **MI-FrM3 Interface Reactions between Quaternary Cobalt Alloys and Carbon Overcoats in Thin Film Disk Media***, **J.-U. Thiele**, D.J. Pocker, R.L. White,* IBM Storage Technology Division

In the magnetic disk drive industry's quest for ever higher data storage areal densities, the head-to-disk spacing and consequently the film thicknesses of all functional layers of magnetic media continue to decrease. In the future the thicknesses of magnetic storage layers and carbon overcoat can be expected to approach the typical thicknesses of chemical interface reactions, i.e. thicknesses of the order of a few nanometers. Here we present a core level X-ray photoelectron spectroscopy study of interface reactions between CoPtCrB and CoPtCrTa magnetic alloy layers and 35 Å thick protective hydrogenated and nitrogenated carbon overcoats on metal hard disks. In comparing CoPtCrTa alloy films with a nitrogenated carbon overcoat to the same media with hydrogenated carbon overcoats we find a drop in coercivity of up to 200 Oe. The formation of tantalum nitride as well as small amounts of chromium nitride was detected in the photoelectron spectra. Conversely, spectra of nitrogenated carbon films on B-containing alloys showed the formation of boron nitride and small amounts of chromium nitride at the interface. The amount of boron nitride varies depending on substrate bias voltage and temperature. Surprisingly, no effects of these interface reactions on the magnetic properties of the disks could be detected. In summary, while the formation of boron nitride at the interface of CoPtCrB media and protective carbon overcoat does not affect the magnetic properties of the disks in the range of boron and nitrogen concentrations investigated here, small changes in the chemical environment of Ta and/or Cr can lead to significant changes in the magnetic properties of the CoPtCrTa media.

9:20am **MI-FrM4 Corrosion Behavior of CoSm Based Magnetic Media***, **I. Zana**, G. Zangari,* The University of Alabama

Future state-of the-art magnetic recording media require high coercivity and magnetization and from a low noise stand point, a small grain size. To achieve these properties, alloys and compounds with high anisotropy are being considered. Among them, we previously reported on rare-earth transition metal CoSm thin films@foontote 1@ with very good magnetic properties. Despite these attractive magnetic properties, the potentially high susceptibility to corrosion, due particularly to the rare-earth element, rises the question of chemical stability for these alloys and therefore on the practicality of CoSm system. In order to investigate the chemical stability of a CoSm system, we fabricated a series of samples on glass substrates, by sputtering. To evaluate the influence of the roughness of both underlayer and magnetic layer, we sputter Cr as underlayer with thickness of 20, 60 and 100 nm. Onto each Cr underlayer, the magnetic layer has a thickness of 8 and 16 nm. These samples were further coated, without breaking the vacuum, with a protective layer of C-N and Si3N4 (2 to 8 nm thickness). A series of samples has been left intentionally unprotected. Corrosion resistance of the samples has been tested by high temperature /humidity accelerated aging and annealing under various atmospheres. Structural and chemical uniformity, roughness as well as stability of the magnetic properties of aged samples have been evaluated by use of x-ray photoelectron spectroscopy, electron microscopy, x-ray diffraction and magnetometry. By comparison with unprotected samples and with commercial disk structure, we found that (a) Si3N4 protective layer strongly improve the corrosion resistance and stability of the magnetic layer and (b) CoSm layers protected by Si3N4 exhibit stability comparable or superior to commercial hard disk. @FootnoteText@@footnote 1@I. Zana, G. Zangari, "Magnetic Interactions and Thermal Stability in CoSm Thin Films", accepted to publication in IEEE Transactions on Magnetics.

9:40am **MI-FrM5 Preparation and Characterization of High-Coercivity Cobalt Ferrite Particles Using Microemulsions***, **H. Du**, Y. Kim, S.L. Lim, L. Si, J. Ding,* National University of Singapore*; W.S. Chin,* National University of Singapore, Singapore

Ferrite materials in nano-scale are potential candidate for application on magnetic recording in high density and the study of nanoscale magnetic domains is of both fundamental and technical interest. In order to get uniform particles in nanosize, we attempted to separate the nucleation and growth processes. The nuclei of precursor hydroxides were formed in reverse micelles of sodium dioctyl sulfosuccinate (AOT). After separation from the microemulsion, the nanoparticles of about 10nm were calcined and the growth process was monitored. Transmission Electron Microscopy (TEM) results show that the irregular precursor nuclei will tend to form cubic shape and the particles grow larger to 20-30nm when the calcinations temperature is increased to 600°C. Lower temperature and longer calcination duration were favorable for the formation of monodispersed smaller particles. X-ray Diffraction (XRD) confirmed the crystalline nature of the ferrite particles. The compositions of the products was found to be determined by both the feed ratio of metal salts and the pH values of the microemulsion, which were analyzed through X-ray Photoelectron Spectroscopy (XPS) and Elemental Analysis. The magnetic properties of the nano-ferrites were measured using a Superconducting Vibration Sample Magnetometer (VSM). The cobalt ferrites nanoparticles synthesized had a relatively high coercivity (1555 Oe) and a saturation magnetization (77.32emu/g). The relationship between the magnetic properties and the crystal structure as well as the domain size will be discussed.

10:00am **MI-FrM6 Measuring Drive and Media Performance using Quantitative Analysis of MFM Images***, **D.A. Chernoff**, D.L. Burkhead, C.S. Cook,* Advanced Surface Microscopy, Inc.

MFM imaging of magnetic hard disks provides a direct physical examination of magnetic marks that complements electrical measurements made on test stands. Valuable information can be obtained because the MFM is free of interference from cross-talk and other read head limitations. Such images have mostly been used for qualitative analyses, such as bit shape, erase band structure, and missing information (defects). However, quantitative analysis of track and bit position and of bit signal amplitude can provide important information to aid in the design and engineering of higher density drives. To assess the accuracy of disk drive servo tracking or of the disk servo writer, we captured several MFM images, each showing 10-15 tracks in the data or the servo mark areas of an ordinary disk. We have demonstrated that our proprietary method@footnote 1@ for calibration and measurement can measure track pitch with precision better than 0.3% (1 s.d.) on calibration specimens and on optical discs.@footnote 2@ For data tracks on a magnetic disk, track pitch variation (1 s.d.) was 3% of the mean track pitch. Drive system engineers can use this information to set target values and tolerances for track pitch. To assess media performance and noise, we captured images of a special test disk, written with constant frequency test patterns. Using similar tools, we analyzed the bit position and amplitude data. Bit position variation (1 s.d.) was 1.5% of the bit spacing and bit amplitude variation was 6.3% of mean amplitude. The variation in bit position (jitter) and in bit amplitude are fundamental sources of digital errors and can be a figure of merit for media response at a given spatial frequency. @FootnoteText@ @footnote 1@ MagneTrack and DiscTrack Plus Media Measurement Systems, www.asmicro.com. @footnote 2@ Automated, high precision measurement of critical dimensions using the Atomic Force Microscope, D. A. Chernoff and D. L. Burkhead, J. Vac. Sci. Technol. A 17, 1457 (1999).

10:20am **MI-FrM7 Femtosecond Spin Dynamics in Ferromagnetic Layered Systems*, B. Koopmans,*** Eindhoven University of Technology, The Netherlands **INVITED**

Ultrafast spin dynamics in ferromagnetic metals is an issue of great current interest. Pump-and-probe pulsed laser techniques have been successfully applied to study magnetism down to femtosecond time scales. Several groups have reported on an almost instantaneous (< 100 femtosecond) loss of magneto-optical contrast in nickel and cobalt films after excitation by a short laser pulse.@footnote 1@ These observations have triggered fundamental discussions as to the ultimate magnetic time scales, and the responsible scattering processes. In this presentation an introduction to time-resolved magneto-optical techniques and an overview of the rapidly developing field will be presented. In particular, it will be shown that ultimate care has to been taken in the interpretation of these experiments. Using a novel configuration we were able to demonstrate that during the first hundreds of femtoseconds a direct relation between magneto-optics and magnetism in ferromagnetic nickel does not exist. Nevertheless, using the distinct temperature dependence of the true demagnetization and that of optical artifacts, such as state-filling effects, we have been able to access the genuine magnetization dynamics. In our experiments on epitaxially grown Cu/Ni/Cu wedges evidence was found that the equilibration of the electron and spin systems takes place within approximately 0.5-1 picosecond. Oscillations on a much slower time scale, hundreds of picoseconds, were interpreted as a precession of the magnetization vector, triggered by the optical heating pulse. The latter phenomenon may be applied as all-optical real-time ferromagnetic resonance for the investigation of magnetic devices with a sub-micrometer spatial resolution. . @FootnoteText@ @footnote 1@ See e.g. E. Beaurepaire et al., Phys. Rev. Lett. 76, 4250 (1996); J. Hohlfeld et al., Phys. Rev. Lett. 78, 4861 (1997); J. Gadde et al., Phys. Rev. B 59, R6608 (1999).

11:00am **MI-FrM9 Magnetic Force Microsopy on Inductive Recording Heads*, A. Moser,*** *M.E. Best, D.K. Weller,* IBM Almaden Research Center

Magnetic Force Microscopy (MFM) has been used to characterize the magnetic stray field generated by the inductive write elements of heads as a function of the amplitude and the pulse width of the write current. The permeability of the write element has been quantified by energizing the head with an offset current that is modulated with a sinusoidal waveform. This current modulation leads to a periodic change in the resonance frequency of the cantilever which has been monitored using a lock-in amplifier. 2D maps of the cantilever resonance frequency show that the write head first saturates at the gap. The saturation current is discussed for different materials and physical structures of the write poles. In a second experiment, the energizing current has been additionally pulsed with pulse widths as short as few nanoseconds to measure the high-frequency behavior of write heads. Here, we observe that larger write current are needed to saturate the write heads at higher frequencies.

11:20am **MI-FrM10 Surface Processing with Gas Cluster Ions to Improve GMR Films*, D.B. Fenner,*** *J. Hautala, L.P. Allen, J.A. Greer, W.A. Skinner,* Epion Corporation*; A. Al-Jibouri,* Nordiko Limited, England*; J.I. Budnick,* University of Connecticut

Reduction of roughness and removal of contamination on surfaces of substrates and films for giant magneto-resistance (GMR) will be essential in the development of advanced devices. Tools and methods to accomplish this are limited at present. Gas-cluster ion beam (GCIB) technology shows promise as a dry process that can provide substantial improvement, and can be integrated into GMR-film deposition-and-etch tools. Here we describe recent work developing GCIB techniques and processes for tantalum, alumina, copper, permalloy and other types of GMR-device films relevant to the spin valve, tunneling-MR (TMR) and nano-oxide layer (NOL) technologies. With argon GCIB it is possible to reduce the roughness of tantalum films to well below a nanometer (rms), and the roughness falls exponentially with dose. The exposure to GCIB rapidly reduces the presence of asperities on surfaces and removes other contamination. @FootnoteText@ Supported by NIST-ATP.

11:40am **MI-FrM11 Study of Exchange Anisotropy of Ni@sub 80@Fe@sub 20@/Fe@sub 60@Mn@sub 40@(111) Epitaxial Films@footnote 1@*, C. Liu,*** *G.J. Mankey,* University of Alabama

Ferro-antiferromagnetic interfacial exchange anisotropy has been studied extensively.@footnote 2,3@ We have grown Ni@sub 80@Fe@sub 20@/Fe@sub 60@Mn@sub40@ fcc (111) films on epitaxial Cu(111) buffer layers on Si(110). With increasing Cu buffer layer thickness, LEED and RHEED show improving film crystal quality while atomic force microscopy reveals an increase in interfacial roughness. Films with Cu buffer layers thinner than 10 nm had coercivities less than 13 Oe, and the exchange anisotropies deduced from the hard axis initial susceptibility were consistent with the results of hysteresis loop measurements. Films with thicker Cu buffer layer had coercivities and exchange anisotropies deduced from hard axis initial susceptibility that were larger than the results of hysteresis loop measurements. For all films, the angular dependencies of exchange bias H@sub eb@ were not sinusoidal, and surprisingly, all films showed a deviation of pinned direction from the direction of the applied field during film growth. Specifically, the film with thickest Cu buffer layer (100 nm) had the largest deviation (57Â°). This film also exhibited the largest coercivity (47 Oe). Magnetic force microscopy measurements showed a strong ripple pattern for this film, with a length scale of 2 microns, characteristic of a strong stray field in the film. All the results revealed the inhomogeneous nature of the pinning in the films which is closely related to the canting of interfacial spins. We interpret these results based on the combination of effects of roughness and structure induced change of intrinsic magnetic properties. @FootnoteText@ @footnote 1@Funded by ARO #DAAH 04-96-1-0316 and NSF #DMR-9809423. @footnote 2@A.E. Berkowitz and Kentaro Takano, J. Magn. Magn. Mater. 200, 552(1999). @footnote 3@Joo-Von Kim, et al., Phys. Rev. B 61, 8888(2000).

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