The Science of Micro-Electro-Mechanical Systems Topical Conference

Room 610 - Session AS+MI+VM-MoM

Magnetic Recording: Chemical Integration and Tribology

Moderator: R.L. Opila, Bell Labs, Lucent Technologies

8:20am **AS+MI+VM-MoM1 Disk Drive Chemical Integration: Influence of Outgassing on Stiction**, ***D.E. Fowler***, *R.H. Geiss, E. Ghelichkhani,* Maxtor Corporation **INVITED**

Beyond optimizing the magnetic read/write sensor and the magnetic storage media, the successful introduction of a new disk drive product requires the integration of the best electronics and a great mechanical design to surround this magnetic interface. However, all of this effort will be for naught, if the disk drive cannot spin-up because the interface is stuck together or if contamination at the interface causes the sensor-to-media spacing to be a few nanometers greater than the designed fly height. Failure to spin-up can be the result of stiction and, in some cases, a phenomenon called fly stiction. We briefly discuss the distinguishing physical features of stiction induced by the disk lubricant as compared to stiction induced by in-drive outgassing, before focussing on outgassing-induced fly stiction. Various analytical methods have been used to identify the important outgassing sources and materials within the drive. The formation of liquid droplets on the read/write sensor during drive operation has been documented as an important contributor to increased stiction of the sensor-to-media interface following a period of nonoperation. We describe a real time visualization setup which monitors these processes in experimental, but fully functioning disk drives. This offers the opportunity to study the phenomenon and the mechanisms of fly stiction in a realistic drive environment. Results of these visualization experiments are presented. The goal of these studies is to develop a low-stiction interface through the optimization of the chemical integration of the drive. This allows the high-performance magnetic interface to function according to its design.

9:00am **AS+MI+VM-MoM3 The Evolution of the Corrosion Process on Thin-Film Media**, ***J. Ying***, *T. Anoikin, C. Martner,* MMC Technology Inc.

Thin-film hard disks have been exposed to elevated temperature/humidity, and dilute acidic vapor environment. These tests are designed to simulate possible galvanic corrosion, which, for the thin-film media, is characterized by the formation of Co and Ni containing corrosion nodules. The evolution of the corrosion process was elucidated by inducing different degrees of corrosion on the media, and these distinct corrosion stages were characterized morphologically by SEM and chemically by AES compositional analysis. In addition, an XPS chemical state study on the reactivity of Co, Cr, and Ni to ambient and chlorinated environments was conducted. A probable galvanic corrosion mechanism is proposed to understand the chemistry observed during the evolution of the corrosion process. In particular, the effects of ionic contaminants as corrosion accelerators and the role of the Cr underlayer as a corrosion-preventing barrier layer are discussed.

9:20am **AS+MI+VM-MoM4 Tribochemistry of Monodispersed ZDOL with Hydrogenated Carbon Overcoats**, ***C.-Y. Chen***, *W. Fong,* University of California, Berkeley*; D.B. Bogy,* University of California, Berkeley, U.S.

Tribo-chemical studies of the lubricant molecular weight effect on the tribology of the head/disk interface (HDI) were conducted using hydrogenated (CHx) carbon disks coated with ZDOL lubricant. The studies involved drag tests with uncoated and carbon-coated Al2O3-TiC sliders and thermal desorption experiments in an ultra-high vacuum (UHV) tribochamber. The studies showed that the lubricant interaction with the carbon overcoat varies as a function of lubricant molecular weight. The friction coefficient increases as the molecular weight increases. The higher friction is due to the higher viscosity. The friction and catalytic decomposition mechanisms of ZDOL are described. In general, the PFPE polymers are decomposed by chain scission involving the breakage of the backbone bonds to yield free-radical segments. Chain scission can occur by three mechanisms: (1) random degradation, (2) depolymerization, and (3) weak-link degradation. Our studies further support previous observations that catalytic reactions occurred at the endgroup functionals. The lower number of endgroup functionals for ZDOL with higher molecular weight reduces the possibility of the occurrence of catalytic reactions. Moreover, the ZDOL desorbed peak temperatures shifted to lower temperatures with increasing molecular weight in thermal desorption tests. The spreading diffusion coefficient of ZDOL decreases with increasing molecular weight. As the mobility of the lubricant chain decreases, the desorption energy needed to break the lubricants increases, resulting in higher desorption peak temperatures. In addition, the longer chain length of the higher molecular weight ZDOL causes higher degrees of crosslinking. The crosslinking restricts chain mobility and causes an increase in the desorption peak temperatures.

9:40am **AS+MI+VM-MoM5 Thermal Effects on Magnetic Head/Disk Interface Materials**, ***R. Koka***, Read-Rite Corp.*; L. Zhang,* Seagate Technology, Singapore **INVITED**

The materials interacting at the head/disk interface of a rigid disk drive are primarily the disk carbon overcoat, lubricant on the disk, and the head ceramic,Al2O3.TiC. The interface materials can be subjected to high, localized temperatures when the head is flying or sliding on the disk or when wear debris is trapped in the interface. The head or disk by itself can be exposed to high temperatures during the manufacturing process. This presentation addresses some of the changes that occur in the interface materials when they are individually subjected to high temperatures. Raman spectroscopy of thermally annealed disks will be presented to show that the carbon overcoat tends to become slightly graphitic. At 350C in air, the overcoat oxidizes rapidly and completely disappears. The widely used PFPE lubricants (ZDOL & AM) used on disks, degrade at high temperatures (~350C). In the presence of Lewis acids, the degradation process occurs at lower temperatures (~200C) and the rate of degradation is very high. The products of thermal degradation are different for the two lubricants because of the functional end groups. With respect to tribology, a head made of a passive ceramic such as SiC tends to perform relatively better than a material such as Al2O3.TiC, which is known to be an aggressive catalyst for lube degradation. Annealing of the Al2O3.TiC head ceramic shows that around 350C, carbon diffuses from the TiC grains and titanium oxides are formed. The diffused carbon is amorphous with a mixture of sp2 and sp3 bonds and it becomes nanocrystalline graphite above 600C. Thin, diamond-like, carbon coatings (60A thick) on the surface of the head effectively protect the Al2O3.TiC from oxidation and carbon diffusion at temperatures below 500C. A few examples of disk wear and smear formations on heads and disks will be presented. Some similarities between the Raman spectra of smears on heads and annealed disk overcoats and degraded lubricant will be discussed.

10:20am **AS+MI+VM-MoM7 The Process Induced Changes on the Co-alloy Films and the Tribological Effects on Magnetic Recording Heads**, ***Y.S. Chaug***, *R. Adams,* Storage Technology Corporation

The ferromagnetic alloys of Co-metal systems are soft magnetic materials having large saturation magnetization and low coercive force. Sputter deposited Co@sub 1-x@(Zr,Ta)@sub x@ (0.05<x<0.16) amorphous films have been used as magnetic pole material in magnetic inductive heads for its zero magnetostriction. In the wafer process, the Co@sub 1-x@(Zr,Ta)@sub x@(CZT) films were patterned through the photolithography process and then treated with an oxygen plasma for cleaning. The surface changes on the processed CZT surface were studied using x-ray photoelectron spectroscopy. The migration of Co ions to the CZT surface was found after the oxygen plasma treatment. Atomic force microscope, scanning electron microscope and Nano-Triboscope were used to examine the changes of the Co rich CZT surface in a high humid environment. The process induced changes on the CZT surface which impacted the ABS (air bearing surface) lapping process in manufacturing the magnetic inductive heads. The tribology of the magnetic recording heads using CZT as magnetic pole will be discussed.

10:40am **AS+MI+VM-MoM8 Study of Tribochemical Processes at the Head-disk Interface Using Photoemission Electron Microscopy**, ***S. Anders***, *A. Scholl, F. Nolting,* Lawrence Berkeley National Laboratory*; W. Fong, C.-Y. Chen,* University of California, Berkeley*; D.B. Bogy,* University of California, Berkeley, U.S.*; C.S. Bhatia,* SSD/IBM*; J. Stohr,* IBM Almaden Research Center

Photoemission electron microscopy (PEEM) has been applied to study the tribochemical processes at the head-disk interface of magnetic storage devices. High resolution PEEM imaging is based on several contrast mechanisms (topographical, elemental, chemical, and various forms of polarization contrast) which makes it a unique tool for the study of tribochemical processes. We have studied surfaces of hard disks and sliders after various kinds of wear tests performed in ambient atmosphere and UHV. It was observed that the disk surface in the wear tracks is chemically modified if visible wear occurred and if a lubricant was present. In the case of unlubricated disks no chemical modifications were observed but a reduction in the hard carbon overcoat thickness. The chemical modifications consist of lubricant oxidation and fluorine removal. The

lubricant oxidation and fluorine removal is enhanced with enhanced wear. It was found that degraded lubricant is transferred to the sliders and accumulated in scratches of the slider surfaces. The hard carbon overcoat on sliders was found to be reduced in thickness after the wear tests, but not chemically altered.

11:00am **AS+MI+VM-MoM9 Tribo-Chemistry of the Head-Disk Interface in Hard Disk Drives**, ***D.B. Bogy,*** University of California, Berkeley, U.S.*; C.S. Bhatia,* IBM SSD*; C.-Y. Chen, W. Fong,* University of California, Berkeley **INVITED**

Tribo-chemical studies of the lubricant thickness effect on the tribology of the head/disk interface (HDI) were conducted using hydrogenated (CHx) carbon disk samples coated with perfluoropolyether ZDOL lubricant. The studies involved drag tests with uncoated and carbon-coated Al@sub 2@O@sub 3@-TiC sliders and thermal desorption experiments in an ultra-high vacuum (UHV) tribochamber. The studies showed that the lubricant interaction with the carbon overcoat varies as a function of lubricant thickness. Wear durability improves considerably for thicknesses greater than a monolayer. However, in the sub-monolayer thickness regime, the adhesion of the lubricant to the carbon overcoat is much stronger, as indicated by the fact that a much higher temperature is required to desorb the lubricant. When the lubricant thickness is around or above a monolayer, cohesion among the lubricant molecules plays a greater role and a much lower temperature is needed for lubricant desorption. In addition, we observed that hydrogen evolution from CHx overcoat initiates lubricant catalytic decomposition, forming CF3 and C2F5. The generation of HF during the thermal desorption experiments provides the formation mechanism of HF, which is the necessary component for catalytic reaction.

11:40am **AS+MI+VM-MoM11 Phase Transitions in Two-dimensional Ferroelectric Films**, ***C.N. Borca,*** *J. Choi, S. Adenwalla, P.A. Dowben, M. Poulsen,* University of Nebraska, Lincoln*; J.L. Robertson,* Oak Ridge National Laboratory*; V.M. Fridkin, S.P. Palto, N. Petukhova, S.G. Yudin,* Russian Academy of Science*; S. Ducharme,* University of Nebraska, Lincoln

We studied ferroelctric copolymer films of vinylidene fluor ide with trifluoroethylene, P(VDF-TrFE) 70:30. The films exibit ferroelectric switching properties and can be used in a variety of piezoelectric devices. In addition to the first order ferroelectric to paraelectric bulk transition at 80 degrees C, we report two other phase transitions. One appears at 20 degrees C and is related entirely to a surface ferroelectric transition.@footnote 1@ The third transition around 150 degrees K is due to a stiffening of the lattice and a change in the bulk electronic structure. For P(VDF-TrFE), there is a negligible density of states at the Fermi level making this phonon related transition very unusual. This last transition was observed using neutron diffraction, @footnote 2@ X-ray diffraction, photoemission spectroscopy and EELS. The effective Debye temperature decreases from a value of about 250 K to 50 K with increasing temperature across the 150 K lattice stiffening transition. @FootnoteText@ @footnote 1@J. Choi, P.A. Dowben, S. Pebley, A.V. Bune, S. Ducharme, V.M. Fridkin, S.P. Palto, N. Petukhova, Phys. Rev. Lett. 80, 1328 (1998) @footnote 2@C.N. Borca, J. Choi, S. Adenwalla, Stephen Ducharme, P.A. Dowben, Lee Robertson, V.M. Fridkin, S.P. Palto, and N. Petukhova, Appl. Phys. Lett. 74, 347 (1999).

Magnetic Interfaces and Nanostructures Technical Group
Room 618/619 - Session MI-MoM

New Magnetic Materials

Moderator: B.T. Jonker, Naval Research Laboratory

8:20am **MI-MoM1 Role of Intergrowths in the Naturally Layered Manganites**, ***S.D. Bader,*** Argonne National Laboratory **INVITED**

Doped LaMnO@sub 3@ yields the colossal magnetoresistance (CMR) family of perovskite materials. The physics is governed by competing interactions that include double exchange, super-exchange, Jahn-Teller effects, polarons, charge and spin ordering. To gain further insights, we have been exploring the properties of the related two-dimensional (2D) analogues that form a Ruddlesden-Popper series denoted SrO(LaMnO@sub 3@)@sub n@ where SrO barrier layers separate n-layers of Mn-containing oxygen octahedra. As in the perovskites, the La@super +3@ doped with Sr@super +2@ to yield the requisite mixed valent Mn@super +3@ and Mn@super +4@ needed for the CMR. We focus on n=2 (bilayers) and x=0.4 and 0.3, denoted SrO[(La@sub 1-x@Sr@sub x@)MnO@sub 3@)@sub 2@, which can be viewed as naturally occurring superlattices. They have reduced Curie temperatures relative to the 3D perovskites. Bulk single crystals grown in an optical image furnace are used. These structures are instructive because the competing interactions are now anisotropic. We illustrate examples of fascinating intrinsic and extrinsic behavior, including the intrinsic CMR values and the role of the extrinsic intergrowths on the magnetic properties. Intergrowths are stacking faults, such as occasional missing and/or extra octahedral layers. We find that intergrowths with extra octahedral layers can simulate 2D magnetic inclusions. Their magnetic and scaling properties provide a link to the 2D magnetism of artificially layered ultrathin ferromagnetic films. This work is supported by U.S. DOE BES-MS under contract #W-31-109-ENG-38.

9:00am **MI-MoM3 XPS Study of CMR Perovskite Thin Films: La@sub 0.65@D@sub 0.35@MnO@sub 3@ (D=Ca,Sr,Pb)**, *P.A. Dowben,* University of Nebraska, Lincoln*; **H. Dulli,*** University of Tennessee, Knoxville*; B. Xu, Q.L. Xu, S.H. Liou,* University of Nebraska, Lincoln

Surface segregation phenomenon has been investigated in crystalline films of La@sub 0.65@D@sub 0.35@MnO@sub 3@ (D=Ca,Sr,Pb) by angular resolved XPS. We found that surface concentration of the dopant atoms is different from the bulk. Using a binary alloy model, we constructed depth profiles for the above dopants. The surface segregation was most significant in the case of Sr-doped films which also exhibit a surface insulating phase at low temperature as can be seen clearly from the binding energy shift in the core level spectra.

9:20am **MI-MoM4 Orientational Dependence of CMR Manganite Thin Films Observed with Ferromagnetic Resonance Spectroscopy**, ***E.S. Gillman,*** Norfolk State University and Thomas Jefferson National Accelerator Facility*; N. Noginov,* Norfolk State University

Previously we have observed that transport properties depend on crystal orientation and morphology in CMR manganite thin films.@footnote 1@ Here we present ferromagnetic resonance (FMR) data that shows that these films exhibit different properties that depend on thier relative orientation in an applied magnetic field. Single crystal films exhibit larger saturization magnetization when the applied field is perpendicular to the surface, but in polycrystalline films the opposite is true. On all films there is a broadening of the resonance peak near the ferromagnetic-paramagnetic transistion temperature that is characteristic of critical fluctuations. @FootnoteText@ @footnote 1@"Crystallinity and Magnetoresistance in La@sub x@Ca@sub 1-x@MnO@sub 3@ Thin Films'', E. S. Gillman, M. Li and K. -H. Dahmen, J. Appl. Phys., 84, 6217 (1998).

9:40am **MI-MoM5 Ferromagnetic Semiconductor Heterostructures Based on (GaMn)As**, ***M. Tanaka,*** University of Tokyo, Japan **INVITED**

We have studied magnetic semiconductor (Ga@sub 1-x@Mn@sub x@)As thin films and III-V based magnetic heterostructures, and present their molecular beam epitaxial growth, structure, magnetic, transport, and magnetooptic properties. The present work, we believe, will give new opportunities to explore an interdisciplinary field between semiconductors and magnetics. (Ga@sub 1-x@Mn@sub x@)As thin films were grown by low-temperature molecular-beam epitaxy (LT-MBE) at 200C - 300C on GaAs(001) substrates. Homogeneous ternary alloys with the Mn content x up to ~0.10 were obtained, and the lattice constants of the zinc-blende (GaMn)As are slightly larger (< 0.4 %) than that of GaAs.@footnote 1@ The (GaMn)As thin films showed a ferromagnetic order with the Curie temperature of 10 K - 100 K. Systematic study indicates that the ferromagnetism of GaMnAs is induced by carriers (holes). The concept of bandgap engineering is well established in nonmagnetic semiconductors. Here, we demonstrate the successful growth of III-V based superlattice (SL) structures consisting of ferromagnetic semiconductor (GaMn)As and nonmagnetic semiconductor AlAs.@footnote 2,3@ Both x-ray diffraction and transmission electron microscopy showed that the SLs are formed with excellent crystal quality and abrupt interfaces. Magnetooptic spectra of these SLs have revealed that, due to quantum confinement effect, the interband transition is systematically blue-shifted with decreasing the thickness of GaMnAs, and that some higher subbands are formed. Furthermore, we have fabricated GaMnAs/AlAs/GaMnAs ferromagnetic tunnel junctions, and have demonstrated large tunneling magnetoresistance (TMR). The feasibility of preparing such magnetic quantum heterostructures based on (GaMn)As, we believe, will open up unique possibility of coupling spinrelated phenomena with the well-established band engineering in III-V semiconductors. @FootnoteText@ @footnote 1@ T. Hayashi, M. Tanaka, T. Nishinaga, H. Shimada, H. Tsuchiya, Y. Ootuka, 8th Int. Conf. on Molecular Beam Epitaxy, Malibu, August 1996, J. Cryst. Growth 175/176, 1063 (1997). @footnote 2@ T. Hayashi, M. Tanaka, K. Seto, T. Nishinaga, H. Shimada, K. Ando, Appl. Phys. Lett. 71, 1825 (1997). @footnote 3@ M. Tanaka, J. Vac. Sci. & Technol. B16, 2267(1998).

10:20am **MI-MoM7 Epitaxial Ferromagnetic Ni@sub 2@MnGa Film Grown on GaAs (001) by Molecular Beam Epitaxy**, ***J.W. Dong***, *L.C. Chen, D.M. Carr, C.J. Palmstrom,* University of Minnesota

In the bulk, stoichiometric Ni@sub 2@MnGa is ferromagnetic with a Curie temperature 376°K. Above 202°K, the stable austenitic phase has the cubic L2@sub 1@ Heusler structure with a lattice parameter 3% larger than GaAs. This structure can be considered as a NaCl crystal structure of Mn and Ga with Ni in the tetrahedral sites. It may also be considered as an 'ordered' CsCl structure with a simple cubic lattice of Ni with every other interstitial site filled with Mn and Ga, respectively. The similarity in crystal structures suggests that metallic compounds with either the NaCl or CsCl structures should act as excellent templates for Ni@sub 2@MnGa growth. The growth of Ni@sub 2@MnGa on GaAs with a 6 ML-thick Sc@sub 0.3@Er@sub 0.7@As (NaCl structure) lattice matched to GaAs interlayer resulted in single crystal growth. In-situ reflection high energy electron diffraction patterns were streaky, indicative of high crystalline quality. Ex-situ X-ray diffraction and plan-view TEM selected area electron diffraction patterns confirmed single crystal growth and showed that a 300Å thick Ni@sub 2@MnGa grew pseudomorphically on GaAs. Considering the lattice mismatch, this seems surprising. However, we speculate that the epitaxy is stabilizing a new tetragonal phase of Ni@sub 2@MnGa with a = b = 5.65 Å, c = 6.12 Å and will present a model to explain this. Magnetic measurements using vibrating sample and superconducting quantum interference device magnetometers revealed the Ni@sub 2@MnGa to have in-plane magnetization and a Curie temperature ~320°K. The growth and properties of Ni@sub 2@MnGa films grown with a NiGa (CsCl structure) interlayer and directly on GaAs will be compared with ones grown on Sc@sub 0.3@Er@sub 0.7@As interlayers. The effect of the interlayer on the interfacial properties will also be discussed.

10:40am **MI-MoM8 MBE Growth and Characterization of bcc Fe@sub X@Co@sub 1-X@/GaAs(001) Heterostructures**, ***L.C. Chen***, *B.D. Schultz, J.Q. Xie, C.J. Palmstrom,* University of Minnesota

We have successfully grown bcc Fe@sub X@Co@sub 1-X@ on GaAs(001) at 175°C by Molecular Beam Epitaxy. In-situ reflection high energy diffraction indicates a two dimensional growth mode of epitaxial bcc Fe@sub X@Co@sub 1-X@ on GaAs(001). A 40Å thick Al protective layer was deposited in-situ at a substrate temperature <0°C prior to removal from the MBE system. Ex-situ atom force microscopy studies show atomic steps indicative of a step-flow growth mode. X-ray diffraction data reveal an epitaxial orientation of bcc Fe@sub X@Co@sub 1-X@(001)||GaAs(001). A Rutherford backscattering spectrometry channeling minimum yield of @chi@=11% suggests good crystalline quality epitaxial bcc Fe@sub X@Co@sub 1-X@. Vibrating sample magnetometry measurements revealed in-plane magnetization and square hysteresis loops. In order to minimize interfacial reactions and diffusion during the Fe@sub X@Co@sub 1-X@ growth, we investigated the use of an epitaxial Sc@sub X@Er@sub 1-X@As diffusion barrier interlayer. Sc@sub X@Er@sub 1-X@As is thermodynamically stable on, and is lattice matched to, GaAs. Reflection high energy diffraction indicates a two-dimensional growth mode of epitaxial single crystal Fe@sub X@Co@sub 1-X@ film growth on the Sc@sub X@Er@sub 1-X@As surface at both 175°C and 470°C. Both ex-situ Rutherford backscattering spectrometry and in-situ Auger electron spectroscopy did not detect arsenic in Fe@sub X@Co@sub 1-X@ films. The effect of Sc@sub X@Er@sub 1-X@As thickness and Fe@sub X@Co@sub 1-X@ growth temperature on the growth mode and magnetic properties will be discussed. Further studies of interfacial transportation properties will also be reported.

11:00am **MI-MoM9 Low-temperature Gaseous Nitriding and Subsequent Oxidation of Epitaxial Ni/Fe Bilayers**, ***A.V. Mijiritskii***, *M.A. James, D.O. Boerma,* University of Groningen, The Netherlands

Fe-nitrides are of interest due to their anti-corrosive, mechanical and magnetic properties. From a technological point of view, one of the most attractive ways to form Fe-nitrides is gaseous nitriding of Fe in a NH@sub 3@+H@sub 2@ mixture. The disadvantage of this method is the necessity to apply relatively high temperatures upon the nitriding. Lately, a method has been discovered allowing fabrication of pore-free Fe-N phases in a mixture of NH@sub 3@+H@sub 2@ at relatively low temperatures (550-625 K) by using a Ni cap-layer as a catalyst. In the present work we study the behaviour of epitaxial Ni/Fe bilayers upon low-temperature gaseous nitriding as well as the subsequent oxidation of the Ni/Fe-N systems formed. A number of experimental techniques was employed including XRD, RBS, XPS, and CEMS. Epitaxial Ni/Fe bilayers were grown on MgO(100) in-situ by molecular beam epitaxy (MBE) or ex-situ by laser ablation deposition (LAD). Nitriding was done in a dedicated N-oven at 575 K at different nitriding potentials of the NH@sub 3@+H@sub 2@ mixture depending on the nitride phase to be produced. Oxidation of the Ni/Fe-N systems obtained was performed in an O-oven at 525 K in P(O@sub 2@)=1x10@sup -6@ mbar. Upon nitriding in NH@sub 3@+H@sub 2@, oxidation of Fe was observed due to small fraction of H@sub 2@O present in the N-oven. On the basis of the RBS measurements it was concluded that to prevent the oxidation, the thickness of the capping Ni layer should exceed 200 Å. XRD measurements performed on as-nitrided samples revealed that Fe-nitride phases form at higher nitriding potential values in the case of epitaxial Ni/Fe bilayers compared to policrystalline Ni/Fe bilayers. This is probably due to the absence of nucleation sites in the epitaxial layers. The epitaxial relationships of the phases produced and the details of the nitriding and oxidation kinetics are being discussed.

11:20am **MI-MoM10 Epitaxial Growth of La-Ca-Mn-O Thin Film on Out-of-Plane Twinned LaAlO@sub 3@**, ***J.-H. Song***, Korea Institute of Science and Technology, Korea*; K.K. Kim,* Korea Institute of Science and Technology, Seoul*; J.H. Song,* Korea Institute of Science and Technology*; D.-K. Choi,* Hanyang University, Korea*; Y.J. Oh, H.-J. Jung, W.K. Choi,* Korea Institute of Science and Technology, Seoul

LCMO thin film with 145 nm thickness was epitaxially grown on LaAlO@sub 3@ (100) substrate using RF magnetron sputtering. The crystalline structure of LCMO thin film on LaAlO@sub 3@ was characterized using backscattering (BS)/channeling and 4-circle X-ray diffractometer. Thin film grown at 600@sup o@C and 100 W shows the minimum channeling yield of 4.98%. XRD @theta@-rocking also showed the FWHM of 0.311@sup o@ for LCMO (200) peak, which is quite small compared to the previous reported values of 0.4@sup o@-0.5@sup o@. But the @theta@-rocking curve seemed to be composed of 2 peaks which was known due to strained-layer and relaxed-layer. In the RBS and BS/channeling study, only direction showed difference by 1.12@sup o@. In addition, we observed the substrate has the out-of-plane twinned structure from hight resolution XRD @theta@-rokcing on LaAlO@sub 3@ (200) peak. From above results, we confirmed the film with only strained layer was epitaxially grown on the out-of-plane twinned substrate. The full width at half maximum value of XRD @theta@-rocking on LCMO film (200) peak was 0.147@sup o@ after BS/channeling analysis. This value is smaller value than any other reported values of LCMO on LaAlO@sub 3@.

Magnetic Interfaces and Nanostructures Technical Group
Room 618/619 - Session MI+VM+AS-MoA

Magnetic Recording: Media and Heads

Moderator: D.E. Fowler, Maxtor Corporation

2:00pm **MI+VM+AS-MoA1 Spectro-Microscopy of Magnetic Materials Using Polarized Soft X-Rays**, ***J. Stohr***, IBM Almaden Research Center **INVITED**

The talk discusses the motivation for and challenges of obtaining magnetic information for ferromagnetic and antiferromagnetic systems on a length scale below 100nm. It reviews the principles of linear and circular x-ray magnetic dichroism spectro-microscopy and presents state-of-the-art results (20nm resolution) obtained with a dedicated soft x-ray photoelectron emission microscope (PEEM) installed on the Advanced Light Source (ALS) at Lawrence Berkeley National Laboratory. Results include studies of the antiferromagnetic domain structure at the surface of LaFeO3(100), NiO(100) and polycrystalline NiO and the ferromagnetic domain structure in hard/soft magnetic tunnel junctions. Future plans to reach a spatial resolution below 10nm will also be discussed.

2:40pm **MI+VM+AS-MoA3 Micromagnetic Properties and Recording Performance in High Density Magnetic Recording Media**, ***T. Suzuki***, *G. Lauhoff,* Toyota Technological Institute, Japan **INVITED**

In order to increase areal recording density, much effort has been made to improve magnetic charactreristics and microstructure in magnetic recording media. In order for decreasing noise and for realizing a sharp transition between written bits, an inter-granular exchange coupling must be lowered, which enhances a thermal instability of magnetization. Given this conditions, it is vitally important to understand the role of magnetic activation volume or magnetic coupled region in conjunction with micromagnetics, which plays a key role in noise mechanisms. The present study is to discuss activation volume in longitudinal magnetic recording media of various types including CoCrPtTa thin-films and granular-type recording media. The activation volume is evaluated based on the time decay of magnetization at a certain field. A novel method to define the activation volume is proposed. The Barkhausen volume is estimated through the field-sweep-rate dependence of coercivity. It is found that the activation volume, which is of the order of 10@super -18@ cm@super -3@, decreases with applied field, then levels off, and starts increases at fields beyond coercivity. This trend is found for all the high density recording media of CoCrPtTa and granular-type media under consideration. The recording noise is found to be closely related to activation volume. Measurments of @delta@M curves suggest that lesser the granular-exchange-coupling is, the smaller the activation volume becomes.

3:20pm **MI+VM+AS-MoA5 Sub 50 nm Planar Magnetic Nanostructures Fabricated by Ion Irradiation**, *T. Devolder,* ***C. Chappert***, IEF/Université Paris Sud, France*; Y. Chen,* L2M Bagneux/CNRS, France*; H. Bernas,* CSNSM/Université Paris Sud, France*; J.-P. Jamet, J. Ferré,* LPS/Université Paris Sud, France*; E. Cambril,* L2M Bagneux/CNRS, France **INVITED**

Areal density enhancement is a major challenge in magnetic recording. Near field magneto-optical techniques are one fast-developing attempt to respond. At bit density values above 65 Gbits/in@super 2@, a most drastic requirement will be to write stable bits with nanometer wall jaggedness, at very precise locations on the disk. Patterned media could be a promising response to this problem.@footnote 1@ However, surface roughness, and polarization dependent effects due to abrupt changes in optical index, will likely deteriorate the signal to noise ratio. Through interface mixing, light ion (He+) irradiation can modify in a precisely controlled way the magnetic properties of multilayers, with negligible change of surface roughness and optical indices. In (Co/Pt) multilayers with perpendicular easy magnetization axis, the anisotropy decreases with irradiation, which first reduces the coercive force, then induces in-plane magnetization. Patterning only the magnetic properties can then be obtained by irradiation through a lithographic PMMA resist mask.@footnote 2@ Using SiO@sub 2@ masks, we have fabricated regular arrays of such irradiation-patterned nanostructures with sizes down to 30 nm. Different configurations such as hard (resp. soft) nanostructures in soft (resp. hard) media have been obtained and characterized using far field magneto-optical microscopy. Special attention has been devoted to the study of the transition zone between irradiated and protected areas, and its effect on magnetization reversal. The technique may be a powerful tool for ultrahigh density magnetic recording applications. @FootnoteText@ @footnote 1@ S. Chou et al., Data Storage 35 (1995). @footnote 2@ C.Chappert et al., Science 280, 1919 (1998).

4:00pm **MI+VM+AS-MoA7 Crystallographic Texture and Stress in Co-Based Magnetic Recording Media and Underlayers**, ***B.M. Clemens***, *G. Khanna,* Stanford University **INVITED**

The magnetic and recording properties of Co-based media are a strong function of crystallographic texture and stress in the media layers, which are in turn strongly influenced by the texture and stress of the Cr underlayer. The anisotropy in strain and the distribution of c-axes in the hcp Co alloy media can determine the magnetic hysteresis anisotropy through magnetostrictive and magnetocrystalline effects. The processing conditions and mechanical texture grooves in the NiP/Al substrate strongly influence the microstructural and mechanical properties of the Cr and Co films. We report x-ray studies of the texture and strain in Cr and Co-based films sputter deposited over a range of temperatures and substrate biases on smooth and mechanically textured substrates. All films showed an in-plane compressive stress. The magnitude of the stress in Cr and Co films grown without a substrate bias decreases with decreasing growth temperature, consistent with thermal mismatch stress. The stress in the Cr films grown with a -300V bias was greater than that of unbiased films, and independent of growth temperature. This suggests that the bias-induced stress is close to the yield stress of the film. However, the biased Co films show a decrease in compressive stress with decreasing temperature. For mechanically textured substrates, the stress measured in the direction perpendicular to the texture grooves was less compressive relative to the parallel direction in both Cr and Co. However, the stress anisotropy vanishes in smooth substrates. A simple strain relaxation model is used to explain the observed Cr stress values in the textured disks. The anisotropic strain in the Cr may also account for the observed preferential alignment of Co c-axes along the grooves. Calculation of the magnetoelastic and magnetocrystalline energies predicts that Co stress anisotropy and the preferential alignment of Co c-axes along the grooves both contribute to the observed hysteresis anisotropy.

4:40pm **MI+VM+AS-MoA9 Noise in GMR Recording Heads**, ***H.T. Hardner***, *M.B. Hurben,* Seagate Technology **INVITED**

Magnetoresistive sensors exploit a close coupling between magnetization and resistance to convert changes in magnetic field to an electrical signal. Thus, the enhanced sensitivity of the giant magnetoresistive (GMR) materials to magnetic field is accompanied by larger electrical noise due to magnetization noise. A magnetic contribution to 1/f noise originates in thermal fluctuations in magnetization. This is a concern for sensors intended for low frequency applications rather than for magnetic recording heads due to the very high frequencies at which the heads operate. However, discrete steps in the resistance can also appear due to large discrete changes in domain structure. When these steps occur as a continuous magnetic signal is applied to the device they are called Barkhausen noise. In small enough devices discrete magnetoresistive steps can be observed even at fixed magnetic field. While the sensitivity of the resistance to changes in magnetization is proportional to the magnetoresistance, the propensity for complex domain structure with fluctuations between multiple metastable states varies by material, processing, and design. The suppression of these fluctuations to create a device with a single stable magnetization state is a key goal in the design and manufacture of magnetoresistive recording heads. This talk will provide some brief background on how recording heads are stabilized as well as an overview of resistance noise data from GMR devices including comparisons of different materials and the use of resistance noise measurements to study domain structure. Recent results on resistance noise in spin-valve recording heads both at the finished stage and during wafer processing will be presented along with discussion of how a detailed study of electrical noise can help identify stability problems. Analysis of both time and frequency domain data will be considered.

Magnetic Interfaces and Nanostructures Technical Group
Room 618/619 - Session MI+VM+AS-TuM

Magnetic Recording: Media

Moderator: H.T. Hardner, Seagate Technology

8:20am **MI+VM+AS-TuM1 Perpendicular Patterned Media: Fabrication and Demonstration of Data Storage**, ***J. Wong***[1], *A. Scherer,* California Institute of Technology*; M. Todorovic, S. Schultz,* University of California, San Diego

Patterned media has been proposed as one of the solutions to extending data storage densities beyond 100Gbits/in@super 2@. We have fabricated perpendicular patterned media using a combination of high resolution electron beam lithography, dry etching, and electroplating. Futhermore, we have successfully demonstrated data storage in such structures. We first use vector scanned electron beam lithography to define the dot array pattern on the PMMA coated Al@sub 0.9@Ga@sub 0.1@As/GaAs substrate. After development, this pattern is transferred into the substrate using Chemically Assisted Ion Beam Etching (CAIBE). Immediately following CAIBE, we convert the Al@sub 0.9@Ga@sub 0.1@As layer into (Al@sub 0.9@Ga@sub 0.1@)@sub 2@O@sub 3@ using wet thermal oxidation. We take advantage of the highly selective etching properties of GaAs and the durable masking properties of (Al@sub 0.9@Ga@sub 0.1@)@sub 2@O@sub 3@ to create high aspect ratio Ni columns. After the dot arrays are defined in the substrate, we use electroplating to fill the etched holes with Ni, followed by polishing.@footnote 1@ Using Magnetic Force Microscopy, we find that the Ni columns are stable single domain magnets. We demonstrate data storage in these structures by controllably orienting the magnetization of individual 170nm diameter Ni columns using conventional thin film write poles. We subsequently read back the stored information using current MR or GMR read heads.@footnote 2@ This demonstration bridges the gap between the fabrication of such structures and their use in actual magnetic storage systems. Work is in progress to characterize higher density arrays (~1.3, 2.6, and 5.2Gbits/in@super 2@) in the form of data tracks (1µm in the x-direction and 0.5, 0.25, and 0.125µm apart respectively in the y-direction). @FootnoteText@ @footnote 1@ J. Wong et al., J. Appl. Phys. 85, 5489, 1999. @footnote 2@ M. Todorovic et al., Appl. Phys. Lett. 74, 2516, 1999.

8:40am **MI+VM+AS-TuM2 Ion Beam Patterning of Magnetic Recording Media With a Stencil Mask**, ***B.D. Terris***, *L. Folks, D. Weller, J.E.E. Baglin, A.J. Kellock,* IBM Almaden Research Center*; H. Rothuizen,* IBM Zurich Research Lab*; P. Vettiger,* IBM Zurich Research Lab, Switzerland

In conventional scaling of magnetic recording media, the grain size is reduced as the bit density is increased, while the number of grains per bit is held approximately constant to maintain signal to noise levels. This scaling approach, however, will reach a fundamental limit when the grain sizes become so small that they are subject to reversal due to thermal excitation on time scales of less than the required data retention time. One approach to circumventing this thermal limit is to create magnetic bits that behave as single magnetic entities, e.g. either single domains or a collection of strongly coupled grains, rather than the hundreds of weakly coupled grains per bit found in conventional granular recording media. In one approach to patterned media, ion beam irradiation is used to locally alter the magnetic properties of thin Co/Pt multilayer films.@footnote 1@ With sufficient ion dose, the easy axis of magnetization is rotated from out-of-plane to in-plane. We have used this process in conjunction with a silicon stencil mask having 1 micrometer diameter holes to pattern regularly spaced micrometer-sized regions of magnetically altered material over areas of a square millimeter. The nature of these magnetic structures has been investigated by magnetic force microscopy. The technique is demonstrated with mask-sample spacing as large as 0.5 mm. In addition, smaller regions of magnetic contrast, down to 100 nm, were created by using two masks with partially overlapping micrometer holes. Unlike other patterning techniques, this approach is non-contact and does not require post-processing to clean the disk, both potential manufacturing advantages. @FootnoteText@ @footnote 1@ C. Chappert et al., Science 280,1919(1998).

9:00am **MI+VM+AS-TuM3 Ion Induced Magnetization Reorientation in Co/Pt Multilayers for Patterned Media**, ***D. Weller***, *J.E.E. Baglin, K.A. Hannibal, M.F. Toney, L. Folks, A.J. Kellock, M.E. Best, B.D. Terris,* IBM Almaden Research Center

Ion beam patterning of magnetic thin films using stencil masks is a prospective path towards ultrahigh-density magnetic recording media. Co/Pt multilayers are ideally suited for this application, since they undergo a spin-reorientation transition from easy axis out-of-plane to easy axis in-plane upon irradiation with ions of suitable energy and dose.@footnote 1@ The mechanism, leading to the observed modulation in magnetic properties is of great fundamental and technological interest and will be discussed in this paper. Electron beam deposited Co/Pt multilayers with representative structure [Si-substrate/SiNx/20 nm Pt buffer/10x(0.3nm Co/1 nm Pt)/2 nm Pt cap layer] were used. These structures have high coercivity (H@sub C@ = 5000- 8500 Oe) and exhibit square perpendicular hysteresis. The high coercivity is attributed to the the large perpendicular anisotropy (K@sub u@ = 4.3 10@super 7@ erg/cm@super 3@) and granularity of these films as indicated in AFM surface topography measurements. The structures were subjected to various doses and currents of 700 keV N@super +@ ions and investigated after each irradiation step using grazing incidence X-ray reflectivity and Kerr hysteresis loop measurements. Direct evidence for ion beam mixing at the Co/Pt interface is found from the XRD data. In particular, we find an almost linear decrease of the integrated intensity of the first grazing incidence Bragg peak with ion dose. This correlates with the measured remanence ratio and anisotropy, however, not with the coercivity, which drops off much faster. @FootnoteText@ @footnote 1@ C. Chappert et al., Science 280, 1919 (1998).

9:20am **MI+VM+AS-TuM4 Texture and Strain in Cr/NiAl Films Grown on Glass Substrates**, ***G. Khanna***[2], *B.M. Clemens,* Stanford University

Glass has recently emerged as a promising candidate to replace NiP/Al in magnetic recording media due to its smooth surface and high shock resistance. A NiAl seed layer may be employed to produce the desired (112) orientation in the Cr underlayer and a (1010) orientation in the Co-alloy magnetic layer. Since NiAl forms the template for subsequent growth of Cr and Co, determining its growth texture and strain is critical to understanding the microstructure and magnetic properties of the media. We report on synchrotron radiation experiments on Cr/NiAl films of various thicknesses grown on glass substrates at elevated temperatures. Our results demonstrate that the growth of the NiAl (and consequently the Cr) on glass substrates is markedly different from Cr growth on traditional Al/NiP substrates. While a strong (002) out-of-plane texture develops at elevated temperatures in the latter case, no particular growth orientation dominates in the NiAl. Both (110) and (112) reflections appear out-of-plane in Cr films grown on thin seed layers. This result indicates that both growth orientations are present in the NiAl since the Cr grows epitaxially on the NiAl surface. Furthermore, several out-of-plane reflections appear in thick NiAl films which implies that, initially, there is simultaneous growth of NiAl grains having several different orientations. Integrated intensities of (110) reflections suggest that NiAl (110) grains are overgrown as the film thickness increases. A comparison of pole figures shows that the NiAl (110) peak is shifted to @Delta@ @psi@ = 30 from the out-of-plane direction for thicker films. The evolution of the texture with depth may be quantified using grazing incidence geometry and varying the incident angle. Intensity ratios from GIXS in-plane reflections corresponding to particular out-of-plane orientations are used to depth profile the texture. The in-plane reflections may also be used to determine the inhomogeneous strain in both layers.

9:40am **MI+VM+AS-TuM5 Ultrafast Magnetization Dynamics in Magnetic Thin Films**, ***T.M. Crawford***, Seagate Research **INVITED**

If one extrapolates the current growth trends for disc drive data rates, the data rate expected by the year 2005 is 2.4 Gbits/sec, requiring magnetization reversal frequencies in the GHz range. However, Permalloy (NiFe), a standard material used for inductive write heads, exhibits ferromagnetic resonance (FMR) at ~ 630 MHz, which is a 10%-90%, precession-limited switching time of 550 ps. While increasing the saturation magnetization and/or anisotropy shifts this resonance to higher frequencies, the gain in switching speed is proportional to only the square root of such increases. As a result, operating magnetic recording heads at or near the FMR frequency may be a necessity to achieve the desired data rates in future storage devices. This rapid increase in data rate toward the

[1] **Falicov Student Award Finalist**

[2] **Falicov Student Award Finalist**

fundamental switching speed limit has generated renewed interest in the field of high speed magnetic switching and magnetodynamics, originally studied extensively in the 1950's and 1960's. This renewal has been assisted by the availability of faster electronic and optical techniques with improved signal-to-noise for characterizing magnetic materials and devices at times well below 1 ns. Recent contributions to this field in the form of time-domain switching measurements, where the film magnetization is driven far from equilibrium, will be reviewed. Subtle material-dependent phenomena which have been observed by these techniques, including possible differences in bulk and surface magnetic properties, will be discussed, as will the possibility of actively controlling the magnetodynamics to achieve a desired behavior. Finally, the extension of these techniques to more complicated materials systems and nanoscale device structures will be addressed.

10:20am **MI+VM+AS-TuM7 Temperature Dependent Characterization of Thermal Stability of Longitudinal Magnetic Recording Media**, ***A. Moser***, *D. Weller, E. Fullerton, K. Takano,* IBM Almaden Research Center

Temperature dependent characterization of thermal stability was performed on a series of magnetic recording media at temperatures between 300 K and 420 K using a static write/read tester.@footnote 1@ The investigated samples are CoPtCr alloys with thicknesses in the range between 5.5 nm to 13 nm. First, the thermal stability of a recorded bit track was studied by measuring the time-dependence of the read-back amplitude between 0.8 s and 70000 s. Second, the time-dependent coercivity was measured by applying a magnetic field pulse of 5 ns to > 60 s width opposite to the sample's initial magnetization. Finally, the samples were characterized by SQUID magnetometry yielding temperature dependent coercivities, viscosity parameters and irreversible susceptibilities. The measurements are discussed with a quasi-independent particle model. The measured stability ratios (ratio between energy barrier for magnetization reversal to thermal energy) and signal decay rates are found to decrease faster than simple scaling with temperature would predict. @FootnoteText@ @footnote 1@ A. Moser, D. Weller and M.E. Best, J. Appl. Phys. 85, 5018 (1999)

10:40am **MI+VM+AS-TuM8 High Resolution FE-Auger Electron Spectroscopy: Applications in Magnetic Recording, Heads and Media**, ***C.A. Fenno***, Seagate Technology - Colorado Design Center

As the Disk Drive Industry pushes toward higher capacity, smaller form factors, and better performance, head and disc design has changed considerably. Technological advances have resulted in decreased dimensions; thinner layers on the disc and within the head reader element, and lower flight heights. As a result the tools used in material characterization requires improved spatial resolution, increased depth resolution and increased spectral resolution. One answer to the challenge of evaluation and characterization of smaller disc and head features is FE-Auger Electron Spectroscopy. FE-Auger provides elemental analysis with excellent spatial resolution. In the best case the electron spot size can achieve 20nm although in the practical case on disc and head features an electron spot size of 60-100nm is more typical. Features of sub-micron dimensions are routinely analyzed with FE-Auger. In some cases high spectral resolution FE-Auger data can reveal chemistry as in the case of titanium-, silicon-, and aluminum-based particles as well as in the case of some oxides and carbides. This chemical data is obtained from particular energy shifts or peak shape change from the respective materials. This presentation will show several examples where the high spatial and spectral resolution available with FE-Auger was instrumental in diagnoses in drive failure analysis.

11:00am **MI+VM+AS-TuM9 Characterization of Co/CN@sub x@ Granular Media Prepared by Nanolamination**, *C. Ruby, J. Du, R. Zhou,* ***S.C. Street***, *J. Barnard,* The University of Alabama

Cobalt-carbon thin films proposed for use as granular magnetic media are generally prepared by co-deposition sputtering. An alternative method is nanolamination of the component layers (media and matrix) followed by annealing. The potential advantages of this approach include precise control over component volume fractions and ease in fabricating large, uniform samples. We have produced and characterized thin film granular structures prepared from nanolaminate layers of Co and CN@sub x@. TEM studies of the microstructure indicate that for certain samples discrete domains are generated, with mean grain sizes of around 20 nm, with near lognormal distribution. These films have coercivities above 1200 Oe. Surface characterization by XPS depth profiling indicates that the annealed films have oxidized cobalt in the very near surface region, although initial study did not show any magnetic hysterisis loop shift. AFM measurements show that the surface of the film roughens significantly upon annealing, with the RMS roughness increasing from 0.2 nm to 1.0 nm. Thus, it appears that the mixing involved in the annealing process, which gives rise to grain formation, also degrades the smooth surface of the CN@sub x@ capping layer and exposes some of the cobalt to ambient. The implications of this process on tribological issues is explored.

11:20am **MI+VM+AS-TuM10 Characterization of Hard Disk Drives by Time-of-Flight Secondary Ion Mass Spectrometry (TOF-SIMS)**, ***B. Hagenhoff***, *R. Kersting,* TASCON GmbH, Germany*; D. Rading, S. Kayser, E. Niehuis,* ION-TOF GmbH, Germany

Hard disks used in hard disk drives consist of a complex inorganic and organic layer structure. Whereas substrate near layers are inorganic of origin and can be comparatively thick, layers closer to the surface become very thin and are finally covered by an organic F containing lubricant. Defective production processes as well as normal use can change the original layer structure and composition. For an analytical characterization of these changes a technique is required which gives detailed information on the chemical composition in lateral as well in depth directions. Time-of-flight secondary ion mass spectrometry (TOF-SIMS) is ideally suited to perform this task because it offers elemental as well as molecular information with high sensitivity. A 3-D representation of the sample can be obtained by combining sputter depth profiling and imaging. With modern TOF-SIMS instruments meanwhile a lateral resolution of less than 200 nm and a depth resolution of only a few nm can be obtained. We therefore applied TOF-SIMS to the characterization of commercially available hard disks. We concentrated on the identification of the lubricant present in the uppermost monolayer, screening for corrosion spots and layer structure elucidation. Special emphasis was laid on the automation of measurement and data evaluation routines in order to enhance sample throughput for industrial applications. Examples for spectroscopy, imaging and depth profiling will be presented.

Magnetic Interfaces and Nanostructures Technical Group
Room 618/619 - Session MI-TuA

Magnetic Spectroscopies

Moderator: S.D. Bader, Argonne National Laboratory

2:00pm **MI-TuA1 Electronic Structure of Single Crystal CrO@sub 2@, *C.B. Stagarescu,*** *X. Su, D.E. Eastman,* University of Chicago*; K.N. Altmann, F.J. Himpsel,* University of Wisconsin, Madison*; A. Gupta,* IBM T.J. Watson Research Center

CrO@sub 2@ was predicted to exhibit half-metallic behavior with 100% spin polarization for electrons at the Fermi level, making it an ideal spin-injector for spin-polarized tunnelling junctions. Recently, a spin polarization of 90% at the Fermi level has been measured with a superconducting point contact.@footnote 1@ We have determined the relevant electronic states using polarization-dependent X-ray absorption (XAS) from the Cr 2p and O 1s core levels into the Cr 3d and O 2p states near the Fermi level, by X-ray magnetic dichroism (XMCD) at these edges, and by spin-polarized photoemission measurements. A clear picture emerges from the O 1s absorption edge, where a sharp peak is observed at 529.2 eV, followed by two peaks at energies of 2.1 and 3.5 eV higher. The first peak is excited only by the electric field vector (E) in the a-b plane, implying O 2p orbitals lying in that plane. It also exhibits a positive XMCD signal, which demonstrates significant hybridization of these (O 2p@sub x@, 2p@sub y@) states with the magnetic Cr 3d states of t@sub 2g@ character that produce the expected 100% majority spin polarization at the Fermi level. The two upper peaks have the opposite polarization dependence, implying an orientation of their O 2p orbitals mainly along the c axis (2X increase in magnitude from E parallel to the a axis to E perpendicular to the a axis, compared to a 10X decrease for the first peak). XMCD spectra obtained with magnetization along the easy (c) and hard (a) axis are compared. The consequences of these results for current models of the electronic structure are discussed. @FootnoteText@ @footnote 1@ R. J. Soulen et al, Science, 282, 85 (1998).

2:20pm **MI-TuA2 Underlying Simplicity of Magnetic Dichroism in the Photoelectron Spectroscopy of Gd*, J.G. Tobin,*** *S.R. Mishra,* Lawrence Livermore National Laboratory*; T.R. Cummins, G.D. Waddill,* University of Missouri, Rolla*; G. van der Laan,* Daresbury Laboratory, UK

Despite severe complexity in the 'raw' spectra of the Gd 5p's, the linear dichroic differences from remanently magnetized Gd/Y exhibit a startling underlying simplicity and consistency. The Gd 5p peaks display a strong cross sectional increase due to 'resonant photoemission' in the photon energy range of 135 to 150 eV. To properly model the pairs of 'raw' spectra acquired in linear dichroism experiments, an atomic model including multielectronic effects such as orbital momentum coupling is required. [1] However, the difference spectra obtained from the pairs are remarkably simple and consistent, in both experiment and atomic simulations. The development of a simplified one-electron picture to analyze the dichroic differences will also be discussed. S.R. Mishra, T.R. Cummins, G. D. Waddill, W.J. Gammon, G. van der Laan, K.W. Goodman, and J.G. Tobin, 'On the Nature of Resonant Photoemission in Gd,' Phys. Rev. Lett., 81, 1306 (1998).

2:40pm **MI-TuA3 Element-Resolved Magnetism Using Core-Resonant Magneto-Optical Techniques*, J.B. Kortright,*** *S.-K. Kim,* Lawrence Berkeley National Laboratory **INVITED**

Most magnetic films of current interest involve multiple magnetic species either homogeneously or heterogeneously distributed in single or multiple layers; examples include alloy or compound thin films, exchange-coupled layers or phases, and interfacial magnetism. A variety of soft x-ray magneto-optical techniques can resolve the aggregate magnetic response of such materials into that of the individual magnetic constituents, thereby offering opportunities to obtain a more detailed microscopic understanding of the macroscopic properties of interest. We have been extending traditional photon-based magneto-optical techniques, embodied in the complex Faraday and Kerr effects, from the near-visible regions into the soft x-ray range containing core levels of the 3d transition metals with associated large resonances in magneto-optical properties. Measuring the polarization of transmitted and reflected beams, in addition to their intensity, provides information that can, e.g., determine elemental moments both longitudinal and transverse to the propagation direction. In addition to field-dependent element-resolved information (hysteresis loops), spatial information both laterally and in depth on the nanometer scale and up is available from scattering and microscopy. Examples of the application of these techniques to better understand questions in exchange-coupled layers and alloy films will be given. @FootnoteText@ This work was supported by the Director, Office of Energy Research, Office of Science, Materials Sciences Division, of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

3:20pm **MI-TuA5 Interatomic Effects in Resonant Photoemission in Fe/Cr Alloys and Bilayers*, E. Arenholz,*** Lawrence Berkeley National Laboratory*; A.W. Kay, C.S. Fadley,* Lawrence Berkeley National Laboratory and Univ. of California, Davis

Recently, first measurements and theoretical calculations of an interatomic multi-atom resonant photoemission effect (MARPE) have been reported by our group in measurements on several magnetic metal oxides (Science 281, 679 (1998)). MARPE occurs when the photon energy is tuned to a core-level absorption edge of an atom neighboring the emitting atom, with the photoemitting level having a lower binding energy than the resonant level; the resonant excitation is then found to significantly increase the photoemission intensity. We have now observed such effects in Fe/Cr alloys and bilayers. E.g. in Fe@sub 0.5@Cr@sub 0.5@, the Cr 2p intensity is enhanced by 20% when the photon energy is tuned to the Fe L@sub 3@ edge. Since MARPE is an interatomic effect the resonant enhancement of the Cr intensity in Fe/Cr alloys is expected to scale linearly with the number of Fe near neighbors. Although a monotonic decrease in the MARPE effect in Cr with decreasing Fe concentration is indeed found, deviations from the linear relationship expected from random mixing of Fe and Cr are observed. These findings will be discussed in terms of possible compositional clustering in Fe/Cr alloys, including additional data from Fe/Cr bilayers that were used to estimate the sensing length of the MARPE effect in this system. First observations of magnetic circular dichroism in the effect will also be presented.

3:40pm **MI-TuA6 Dispersions of Metallic Quantum Well States in the Cu/fccM(100) [M = Ni, Co, Fe] Systems*, A.G. Danese,*** *R.A. Bartynski,* Rutgers University

The study of the electronic properties of nonmagnetic/ferromagnetic bi-layers is essential to understanding the phenomenon of oscillatory magnetic coupling that is seen in magnetic multilayers. Using a phase accumulation model, we have calculated the dispersions of metallic quantum well (MQW) electronic states along @GAMMA@-barX-bar in the systems Cu/fccM(100) where M = Ni, Co, Fe. The model predicts that MQW states disperse with a high effective mass in regions of the 2-dimensional Brillouin zone where projected band gaps occur in the ferromagnetic material. Such regions occur near the belly and neck of the Cu Fermi surface. Near the belly, the regions of high effective mass will be observed below the Fermi energy (E@sub F@) for all three systems. Flat dispersions near the neck will occur about 1eV below the Fermi energy for Ni, about 1eV above E@sub F@ for Fe, and will pass through E@sub F@ for Co. These calculations give a good account of direct and inverse photoemission measurements from Cu/fccCo(100). We have recently performed inverse photoemission on Cu/fccFe(100) and Cu/fccNi(100) and the dispersions of the MQW states in these systems will be discussed and compared with the predictions of the phase accumulation model. Furthermore, there is evidence of parallel, flat MQW bands both below and above the Fermi level in the hybrid Cu/Fe/Cu/Ni system which indicate a possible optical resonance. This work was funded by the NSF, grant no. DMR98-01681 and the Petroleum Research Fund, grant no. ACS-PRF-33750-AC6,5.

4:00pm **MI-TuA7 Photoemission Study of Pseudomorphic Fe@sub x@Ni@sub 1-x@ and Co@sub x@Ni@sub 1-x@ Films on Cu(100)*, M. Hochstrasser,*** The Pennsylvania State University, U.S.*; N. Gilman, R.F. Willis,* The Pennsylvania State University*; F.O. Schumann, J.G. Tobin,* Lawrence Livermore National Laboratory*; E. Rotenberg,* Lawrence Berkeley National Laboratory (Advanced Light Source)

The k-space electronic structure of Fe@sub x@Ni@sub 1-x@ and Co@sub x@Ni@sub 1-x@ alloy films epitaxially grown on Cu(100) has been investigated with changing stoichiometry in angle-resolved photoemission and is compared to the electronic structure of fcc films of Co and Ni, as well as of Cu. We have monitored changes in the Fermi surface with changing stoichiometry and changing magnetic behavior. In the bulk, the magnetic moment deviates strongly from the Slater-Pauling curve at an Fe concentration of 65%, dropping quickly to zero as does the Curie temperature, at which point a structural phase transition from fcc to bcc is observed. Recently, it has been shown that Fe@sub x@Ni@sub 1-x@ films can establish in the fcc phase when grown as ultrathin films on Cu(100).@footnote 1@ The fcc to bcc structural transformation is quenched, but the magnetic instability persists. Furthermore, we

investigated with spin-resolved photoemission spectroscopy the regions relevant for the magnetic coupling with changing composition in Fe@sub x@Ni@sub 1-x@ films on Cu(100). We adress the questions: 1. Is there a relationship between the electronic structure and the sudden change in magnetization at a critical composition? 2. How does the Fermi surface evolve in these pseudomorphic alloy films? 3. What is the polarization of the states thought to be responsible for the oscillatory exchange coupling? The measurements show that the sp-band is a prominent feature of the Fermi surface throughout k-space for all of these alloys. A band structure calculation of Ni allows us to identify d-hole pockets arising from holes in the d-band(s) increasing with changing stoichiometry. The states thought to be responsible for the oscillatory exchange coupling, giving rise to giant magentoresistance (GMR) effects, are identified. @FootnoteText@ @footnote 1@ F. Schumann et. al., Phys. Rev. B, 56, 2668 (1997).

4:20pm **MI-TuA8 Magnetic Properties of Fe-based Alloys***, **F.O. Schumann**, J.G. Tobin,* Lawrence Livermore National Laboratory

The magnetic properties of fcc Fe@sub x@Ni@sub 1-x@ and Fe@sub x@Co@sub 1-x@ alloys grown on Cu(100)were investigated in an element-specific fashion.The technique employed was linear dichoism in photoemission (MLDAD), which by varying the chirality can also determine the magnetization axis. We observed a different behavior for the two alloys at Fe concentrations above 60%. At this concentration the Fe@sub x@Ni@sub 1-x@ alloy shows a strong reduction of the Fe dichroism associated with the invar instability.@footnote 1@ This is in contrast to the Fe@sub x@Co@sub 1-x@ alloy, where the Fe dichroism stays essentially constant across the concentration.This would indicate that a volume-moment instability is absent, which disagrees with a recent theoretical study.@footnote 2@ Despite these differences both systems show a change of the easy axis at roughly the same electron count.For small Fe concentrations the easy axis is in-plane along the [110] direction. This changes into the [100] direction at Fe@sub 60@Ni@sub 40@, which is at 0.8 excess electrons per atom when compared with Fe.This is different to the bulk, where a change occurs at Fe@sub 35@Ni@sub 65@. We find the easy axis change for Fe@sub x@Co@sub 1-x@ to occur at 35% Fe. This would be equivalent to 0.65 excess electrons when compared with Fe. @FootnoteText@ @footnote 1@ F.O. Schumann et al., Phys. Rev. Lett 79,5166 (1997). @footnote 2@ P.James et al., Phys. Rev. B 59,419 (1999).

Vacuum Metallurgy Division
Room 620 - Session VM+MI+AS-TuA

Magnetic Recording: Head/Disk Interface and Overcoats

Moderator: Y.W. Chung, Northwestern University

2:00pm **VM+MI+AS-TuA1 Ultra Thin DLC Film as Magnetic Disks Overcoat***, **X. Chu**, B. Zhang, K.. Johnson,* MMC Tech.

Sputtered DLC film of 100 to 200 A has been used for protective coating on thin film magnetic recording disk for years. DLC overcoat material of choice is hydrogen and/or nitrogen doped amorphous carbon deposited by magnetron sputtering. Increasing areal density in magnetic hard drives requires thinner overcoat to reduce signal loss between magnetic film and read head. Functional overcoat with thickness of 50A will be needed for next generation recording medium. Tribological performance of sputtered carbon films suffers at values below 100 A because of a degradation in physical properties. Alternative deposition techniques, such as ion-beam deposition process, create denser and harder films with the improved physical and tribological properties. In this paper we will present data on the deposition and characterization of 50 A to 30 A DLC films deposited both by sputter and IBD process. Process parameter effect on structure and mechanical properties of sputtered CNx, CHx film, and ion beam deposited CHx was studied. XPS and Raman were used to characterize film microstructure and showed the sputtered CNx film was mostly sp2 bonded. Tribology of the films were tested by Contact Start Stop (CSS) testers and the result of carbon wear can be correlated to AFM nano-wear test. 30A ion-beam deposited CHx film showed good CSS tribological performance comparable to 100 A sputtered films.

2:20pm **VM+MI+AS-TuA2 Tribological Properties of Protective Carbon Coatings Used in Magnetic Storage Devices Investigated on a Sub-Nanometer Scale***, **A. Wienss,*** University of Saarbrücken, Germany*; G. Persch-Schuy,* IBM Germany Storage Systems Division, Germany*; U. Hartmann,* University of Saarbrücken, Germany

Ultrathin carbon coatings are used in the magnetic storage industry to protect sensitive sensor heads and magnetic media against mechanical damage. Such a damage can be modelled by artificially generated scratches using Scanning Force Microscope (SFM) techniques. Loading forces in the µN range are applied, resulting in scratches with residual depths of only a few Å. A special image subtraction technique is presented which allows careful analysis of tiny grooves even on rough surfaces. This technique compensates for drift effects during scanning. The scratching resistance of various a-C:H and CN@sub x@ films is determined. For a-C:H, an increasing amount of hydrogen results in a decreasing scratching resistance, which is a well-known behavior. Beyond a certain hydrogen content, a further increased hydrogenation causes a reproducible, slight increase of the scratching resistance. In order to explain this, the role of the friction coefficient will be discussed.

2:40pm **VM+MI+AS-TuA3 Ultrathin Overcoats For Magnetic Media: Is Hardness What We Are Looking For ?***, **B. Marchon,*** IBM Almaden Research Center **INVITED**

As areal recording densities approach 20 Gigabit per square inch, the demand for ultrathin media overcoat (<5 nm) becomes more pressing. This talk will attempt to identify the various properties that are required to achieve good performance under increasingly severe mechanical and environmental conditions. In an attempt to bridge the process-performance gap, we will review the details of the head/disk interface system, and how the mechanical and chemical structure/properties can be optimized to achieve the required reliability. In particular, issues related to tribochemistry and interactions with the lubricant will be addressed, as well as a general discussion on what specific mechanical properties are important.

3:20pm **VM+MI+AS-TuA5 Air Bearing Collision Dynamics***, **S.E. Stupp**, R.J. Blanco, T. Riener, B.D. Strom,* Quantum Corporation **INVITED**

A few years ago, a disk drive program encountered an unusual problem: drives built with one vendor's heads (vendor A) suffered from an excessive number of thermal asperity events (TAs); drives built with head's from another vendor (vendor B) did not have as many TAs, but they did have a number of crashes. Spinstand experiments confirmed that there was a significant difference in the response of the two vendor's air bearings to collision with the 100 nm high asperities found in these drives. For example, the fly height of vendor A's heads was essentially unchanged on contact with an asperity, while vendor B's heads exhibited a fly height change (these differences may explain the drive results). The underlying problem in the drive program was ultimately traced to particulate contamination and was corrected. However, the experiments raise an interesting question: Why is there a difference in the dynamic response of the two vendor's heads? In this work we present a systematic study of this problem, which we christen Air Bearing Collision Dynamics (ABCD). The asperity collision responses of several different air bearing designs (including full rail and island type) were studied by measuring the TA signal, the change in flying height, acoustic emission (AE), and laser Doppler vibrometry, in controlled experiments on a spinstand. Since a large enough asperity can cause any head to crash, the asperity size was modest (approximately equal to the fly height). In agreement with our earlier experiments, differences in the response of the different air bearings were found. In addition, the AE signals indicate that certain island type air bearing designs can undergo multiple head-disk contacts after the asperity has passed. These results are potentially concerning, because many head vendors are moving towards this type of air bearing design. Finally, in an attempt to understand the origin of the differences in the dynamic response of different air bearing designs, we report the results of numerical modeling of the asperity and air bearing designs.

4:00pm **VM+MI+AS-TuA7 Interaction of Fluoroalcohols and Fluoroethers with Various Types of Carbon Overcoats***, **N. Shukla**, A.J. Gellman,* Carnegie Mellon University

This work is focussed on understanding the fundamentals of head-disk interface tribology at very low flying heights and higher spin rates. Since there will be room for only a single molecular monolayer of the lubricant on the disk surface at low flying heights we have studied the molecular level interaction of lubricants with carbon overcoats that protect the disk surface. We have modeled a most commonly used PFPE lubricant (Fomblin Zdol) using short chain model compounds and measured the desorption energy of these compounds on carbon films. The short chain model compounds used are 2,2,2 trifluoroethanol (CF@sub3@CH@sub2@OH) and perfluorodiethyl ether (CF@sub3@CF@sub2@OCF@sub2@CF@sub3@) which are representative of both the end group and the main chain of Fomblin Zdol. Temperature programmed desorption spectroscopy is used to measure the desorption

energy of model compounds and also to understand the nature of the interaction of these short chain compounds with carbon overcoats. Initial results show that ethers interact with carbon overcoats through electron donation from the oxygen lone pair electron and the alcohols interact with carbon overcoats through hydrogen bonding. In addition we have studied the effect of various film compositions on the interaction of the lubricants in order to understand if the film composition has any effect on the nature of the bonding of the lubricant. The different types of overcoats used are hydrogenated, nitrogenated, diamond-like carbon and Ion beam sputtered overcoats. We have observed that by varying the percentage of hydrogen or nitrogen content in the film composition or by changing the carbon overcoat deposition conditions as in diamond like carbon overcoats or in an ion beam sputtered overcoat there is no significant change in the interaction of the lubricant with carbon overcoat. The alcohols however bond stronger than ethers on all overcoats, which is consistent with the structures, proposed by diffusion measurements.

4:20pm **VM+MI+AS-TuA8 Angle Resolved ESCA Methods: Molecular Conformation of Fluorocarbon Lubricant**, ***M.A. Karplus***, *D.J. Pocker,* IBM-SSD

Simple but useful methods for interpreting angle-resolved ESCA data from real-world samples are presented. First is a model allowing thinly-covered and thickly-covered substrate. It can be usefully applied, even in a manual fashion, with common office spreadsheets. Next, a simple slab model, with the help of canned minimization routines, can bring out subtleties in overlayer structures. Even a deeply buried monatomic layer can be isolated. The following are presented as examples. Perfluoropolyether (Zdol) lubricant on hard disk carbon overcoat shows coexisting monolayer and multilayer regions, consistent with structures identified by surface energy@footnote 1@ and ellipsometric surface diffusion@footnote 2@ measurements. Next, layering within the lubricant shows significant perfluoropolyether backbone adjacent to the overcoat surface accompanied by a discernible excess of ether oxygen. The latter facts indicate that the inverted-U conformation sometimes sketched for bonded lubricants is an exaggeration, certainly for the system studied. @FootnoteText@ @footnote 1@ G. W. Tyndall, R. J. Waltman, and D. J. Pocker, Langmuir 14, 7527 (1998). @footnote 2@ X. Ma, J. Gui, L. Smoliar, K. Grannen, B. Marchon, M. S. Jhon, C. L. Bauer, J. Chem. Phys. 110, 3129 (1999).

4:40pm **VM+MI+AS-TuA9 Airbearing Designs for High Density Recording**, **INVITED**

Magnetic Interfaces and Nanostructures Technical Group
Room 618/619 - Session MI+EM-WeM

Spin-Dependent Tunneling and Transport

Moderator: K. Bussmann, Naval Research Laboratory

8:20am **MI+EM-WeM1 Models of Spin-dependent Tunneling**, ***S. Zhang***, University of Missouri, Rolla **INVITED**

There are a number of theoretical models of spin-dependent tunneling. Some are based on toy models and others are built on electronic structures of ideal tunnel junctions obtained from ab-initio methods. The question is whether these models are relevant to the experimental realization of the magnetotransport of magnetic tunnel junctions. We analyze these model predictions by taking into account non-ideal nature of the magnetic tunnel junctions studied to date. It is shown that most of the theoretical conclusions are not reliable in interpreting experimental data. There are at least three intrinsic mechanisms on the voltage dependence of magnetoresistance: the effect of electronic structure, inelastic tunnel channels, and spin-dependence of electric field penetrations. The last effect comes from spin-polarized electron screening. When a voltage is applied across a magnetic tunnel junction, charges and spins are accumulated at the interfaces. The conduction electrons tend to screen these charges and spins via Coulomb and exchange interactions; this leads to a spin-dependent voltage absorption by the electrodes. We calculate the voltage dependence of magnetoresistance by including this field penetration effect. When one considers magnetic tunnel junctions beyond simple trilayer structures, e.g., double barrier junctions, a number of additional complications arise. Among them, the energy and spin relaxation of tunnel electrons becomes important. We examine these processes in detail, and present the I-V characteristics and junction magnetoresistance for both two-terminal and three-terminal geometries.

9:00am **MI+EM-WeM3 High Performance Demonstration of Magnetic Tunnel Junction Random Access Memory***, ***W.J. Gallagher***, *S.L. Brown, Y. Lu, E.J. O'Sullivan, P.L. Trouilloud, D.A. Abraham, J. Bucchignano, R.H. Koch, Y.H. Lee, R. Robbertazzi, M. Rooks, J. Yoon, R.A. Wanner, S.S.P. Parkin, D. Pearson, K.P. Roche, M.G. Samant, P.M. Rice, A. Lee, R.E. Scheuerlein,* IBM **INVITED**

We describe a magnetic tunnel junction (MTJ) RAM demonstration involving the integration of 0.25 µm CMOS technology with a special research-scale magnetic tunnel junction "back end." The magnetic back end is based upon state of the art mutilayer magnetic growth technology available on a research scale. For the demonstration, the wafers were cut into one-inch squares for depositions of bottom-pinned exchange biased magnetic tunnel junctions. The samples were then processed through four additional lithographic levels to complete the circuits. Special care was required to achieve fine lithography on the one-inch pieces aligned to the underlying circuits. Both deep uv stepper lithography and e-beam lithography were utilized. Patterning of the magnetic layers involved physical removal of the magnetic material by means of ion beam milling, an etching process not commonly used in semiconductor technology. Redeposition, which accompanies ion milling and is exacerbated in dense arrays, had to be carefully controlled with combinations of angled mills in order to minimize the occurrence of junction shorts and maximize the yield of working bits. Key performance aspects demonstrated in 1 K bit arrays included reads and writes in less than 10 ns and nonvolatility. These results suggest that MTJ MRAM might simultaneously provide much of the functionality now provided separately by SRAM, DRAM, and NVRAM. . @FootnoteText@ @footnote *@ Work supported in part by DARPA contract MDA972-96-C-0014.

9:40am **MI+EM-WeM5 Pinhole Decoration in Magnetic Tunnel Junctions**, ***D. Allen***[1], *R. Schad, G. Zangari, I. Zana, D. Yang,* University of Alabama*; M.C. Tondra, D. Wang,* Nonvolatile Electronics

Magnetic tunnel junctions are of interest for their possible applications in magnetic sensors and nonvolatile memory devices. The possibility of local shortcuts in the insulating layers of magnetic tunnel junctions, known as pinholes, can cause malfunctions in these devices. The reduction of insulator thicknesses will make this problem more severe. The ability to image pinholes could lead to further development of magnetic tunnel junctions. The imaging of structures that are not directly observable with imaging is traditionally done by decoration. This can be achieved by exploiting the conductivity of the pinholes. We decorated pinholes in a 1.8nm thick Al@sub2@O@sub3@ layer by electrodeposition of copper. These copper cauliflower-like structures can be imaged by conventional microscopies. Dielectric breakdown could be a source of pinhole creation. Applying 0.5 V for electrodeposition (as used here) would exceed the breakdown threshold for weak points in the insulator. This would create pinholes at points with insulator thickness less than 0.5 nm. This is an opportunity of the method. Upon application of increasing voltage pulses prior to deposition it will allow discrimination of potential breakdown spots as a function of their thickness. The chemical conditions were tailored to avoid damaging the insulator layer or creating new pinholes. This was verified by studying surface roughness (Atomic Force Microscopy), chemical composition (X-ray Photoelectron Spectroscopy) and layering quality (X-ray Diffraction).

10:00am **MI+EM-WeM6 Novel Hybrid Magnetoelectronic Device for Magnetic Field Sensing**, ***D.M. Schaadt***, *E.T. Yu, S. Sankar, A.E. Berkowitz,* University of California, San Diego

Structures in which magnetic and electronic materials are combined offer a variety of possibilities for realization of devices with dramatically improved functionality or performance as compared to conventional devices. We have designed, characterized, and analyzed a novel hybrid magnetoelectronic device: a monolithic field-effect-transistor-amplified magnetic field sensor in which a granular Co-SiO@sub2@ tunnel magnetoresistive (TMR) thin film is incorporated into the gate of a p-channel Si metal-oxide-semiconductor field-effect transistor (MOSFET). In this structure, current flow through the TMR film leads to a buildup of electronic charge within the gate, and consequently to a transistor threshold voltage shift. For a fixed voltage applied across the TMR layer, an external magnetic field changes the TMR film resistance, and consequently the current and charge within the gate. The resulting threshold voltage shift leads to a pronounced response to the external magnetic field in the transistor current-voltage characteristics. The relative current change induced by application of a 6 kOe external magnetic field at room temperature was amplified from 5% for the current through the TMR film to 21% for the transistor subthreshold current. The absolute current response in the saturation regime increased by a factor of about 500 compared to that of the TMR film alone. These results were achieved in a non-optimized device structure; substantially better performance should be achievable with relatively straightforward improvements in device design and processing. A detailed analysis of the operation of this device and of methods for optimization of performance will be presented.

10:20am **MI+EM-WeM7 Andreev and Conduction Electron Spectroscopy of Interfacial Spin Transport**, ***R.A. Buhrman***, Cornell University **INVITED**

The enhanced interfacial conductance of an N-S contact, due to the Andreev reflection of electrons with energy below the superconducting energy gap, provides a powerful means of measuring interfacial transmission rates, as well as any net spin polarization in the non-superconducting electrode. Thus very small F-S nanocontacts can be used to quantitatively measure the interfacial transmission probability for each spin orientation. This technique can also be extended to the determination of the spin-dependent transmission rates through thin magnetic layers. We have produced F-S and N-F-S nanocontacts lithographically, and have determined the net spin-polarization of the direct current emerging from several bulk ferromagnetic films, and the spin filtering behavior of ultra-thin ferromagnetic layers. Measurements with different N electrodes illustrate the importance of the band structure mismatch in determining the degree of the spin-filtering. The bias dependence of the nanocontact interface resistance in the normal state can also be used to examine the degree to which the interface results in inelastic, spin-flip scattering processes. For certain N electrodes, very strong inelastic scattering is observed at relatively low energies. I will compare these single interface measurements with the current-perpendicular-to-the-plane magnetoresistance results that we have obtained with spin-valve and GMR nanopillar devices less than 100 nm in diameter. The low energy spin filtering measurements will also be compared with higher energy, ~ 1eV, spin filtering measurements that our group has been conducting with an STM-based magnetic microscope.

11:00am **MI+EM-WeM9 Spin-Polarization of La@sub 2/3@Sr@sub 1/3@MnO@sub 3@**, ***D.C. Worledge***, *T.H. Geballe,* Stanford University

Spin-polarized tunneling measurements using La@sub 2/3@Sr@sub 1/3@MnO@sub 3@/SrTiO@sub 3@/Al tunnel junctions are reported. The deposition technique and efforts to control the interface quality will be discussed. At sufficiently low temperatures the application of an applied

[1] **Falicov Student Award Finalist**

magnetic field splits the peaks in the dI/dV curve, allowing a measurement of the spin polarization to be made.

11:20am **MI+EM-WeM10 Electrical Spin Injection into LED Heterostructures**, ***B.T. Jonker***, *B.R. Bennett,* Naval Research Laboratory*; G. Kioseoglou, A. Petrou,* State University of New York, Buffalo

Optical excitation has routinely been used to create spin polarized carrier populations in semiconductor heterostructures. Surprisingly long spin lifetimes and diffusion lengths have been reported in optically pumped GaAs in studies which have addressed both semi-classical@footnote 1@ and quantum coherent regimes.@footnote 2,3@ It is very desirable to electrically inject spin polarized carriers via a ferromagnetic contact to increase the potential for practical applications. This has been an elusive goal, however, and only modest effects (@<=@ 1%) have been obtained.@footnote 4@ In an effort to investigate the efficiency of electrical spin injection into semiconductors, we have fabricated light emitting diode structures with ferromagnetic contacts. The radiative recombination of spin polarized carriers in quantum wells results in the emission of circularly polarized light, with the degree of optical polarization directly proportional to the carrier spin polarization. The samples consist of FM / InAs / AlSb / GaSb / AlSb heterostructures grown by MBE on p-GaAs(001) substrates in which the GaSb quantum well serves as the active region for radiative recombination. Standard optical lithography and chemical etch procedures were used to define mesa structures with transparent surface contacts. Measurements are performed as a function of injection current, magnetic field, and temperature. We compare results from ex situ contacts with those obtained from samples for which the ferromagnetic films are deposited in situ via MBE. @FootnoteText@ @footnote *@ This work was supported by the Office of Naval Research. @footnote 1@ D. Hagele, M. Oestreich, W.W. Ruhle, N. Nestle and K. Eberl, APL 73, 1580 (1998). @footnote 2@ A.P. Heberle, W.W. Ruhle and K. Ploog, PRL 72, 3887 (1994). @footnote 3@ J.M. Kikkawa and D.D. Awschalom, PRL 80, 4313 (1998); Nature 397, 139 (1999). @footnote 4@ Y.Q. Jia, R.C. Shi and S.Y. Chou, IEEE Trans. Magnetics 32, 4707 (1996).

11:40am **MI+EM-WeM11 Electron Spin Interferometry**, ***C.H. Back***, *S. Egger,* ETH Zürich, Switzerland*; J. Krewer,* Blaupunkt-Werke GmbH, Germany*; D. Pescia,* ETH Zürich, Switzerland

Quantum interference of electron waves in Fabry-Perot type solid-state resonators has been observed in a number of experiments. The applications of this phenomenon include quantum-well based semiconductor devices,@footnote 1@ accurate mapping of the band structure of solids and surfaces@footnote 2,3,4,5@ and visualizing the spatial dependence of quantum mechanical wave functions by means of Scanning Tunnelling Spectroscopy (STS).@footnote 5@ Here we use quantum interference to switch the spin state of the electrons. The spin quantum resonator consists of a Cu-film of variable thickness sandwiched between vacuum and a magnetic Co-film. Electrons are injected into the resonator from the vacuum side. The Co-film provides a spin dependent reflector. Varying the resonator thickness results in periodic switching of the spin state of the specularly reflected electrons. We apply spin interferometry to study oscillatory interlayer exchange coupling and find a divergence of the coupling period predicted by theory.@footnote 6@ We discuss the implications of spin interferometry as spin polarimeter or spin polarized source and propose that interferometric spin selection should be observable in Spin Polarized STS. @FootnoteText@@footnote 1@Corcoran, E., Diminishing Dimensions, Sci.Am. 263, p.74-83, November Issue, (1990). @footnote 2@Paggel, J.J., Miller, T., Chiang, T.-C., Quasiparticle Lifetime in Macroscopically Uniform Ag/Fe(100) quantum Wells, Phys.Rev.Lett.81, 5632-5635, (1998). @footnote 3@Ortega, J.E., Himpsel, F.J., Mankey G.J., Willis, R.F., Quantum-well states and magnetic coupling between ferromagnets through a noble-metal layer, Phys.Rev.B 47, 1540-1552 (1993). @footnote 4@Kawakami, R.K. et al., Quantum-well states in copper thin films, Nature 398, 132-134 (1999). @footnote 5@Crommie, M.F., Lutz, C.P., Eigler, D.M., Imaging standing waves in a two-dimensional electron gas, Nature 363, 524-527 (1993). @footnote 6@Edwards,D.M., Mathon, J., Oscillations in exchange coupling across a nonmagnetic metallic layer, J.Magn.Magn.Mat. 93, 85-88 (1991).

Magnetic Interfaces and Nanostructures Technical Group
Room 618/619 - Session MI-WeA

Giant Magnetoresistance

Moderator: B.A. Everitt, Seagate Technology

2:00pm **MI-WeA1 Hot Electron Attenuation Lengths in Magnetic Multilayers**, ***R. Lu***, *K.L. Kavanagh,* University of California, San Diego*; C.J. Powell, P.J. Chen, F.G. Serpa, W.F. Egelhoff, Jr.,* National Institute of Standards and Technology

We are using ballistic electron emission microscopy (BEEM) to measure electron transport across magnetic metal multilayers. Room temperature measurements in air have been carried out on Au/M/Si(100) or Au/M/Au/Si(100) diodes, sputter deposited at 175 or 300K, where M is Co, Fe, Ni, or NiFe(81:19). STM images of the 5nm thick Au surfaces show 10-20nm diameter crystallites, with a typical roughness of 3-6nm, depending on the deposition temperature. Corresponding BEEM images show grain dependent BEEM currents, with uniform contrast across each grain, independent of surface morphology, presumeably a function of the Au or magnetic-metal grain orientation. Averaged BEEM spectra for the Au/M/Si diodes, as a function of magnetic metal thickness (0 - 2nm) show decreasing (Ni or NiFe) or increasing (Co and Fe) BEEM thresholds with increasing metal thickness, indicative of changing magnetic metal/semiconductor interface coverage and/or reactions. Plots of log BEEM current versus M thickness are linear giving hot electron (1-1.5eV) attenuation lengths for Co, Fe, NiFe, and Ni of 2, 5, 8 and 13±2Å, respectively. Magnetic metal sandwich diodes, (Au/M/Au/Si) show comparable attenuation lengths but with smaller BEEM currents, likely the result of greater interface scattering. We are in the process of carrying out BEEM magnetotransport measurements on GMR layers and will report these results at the meeting.

2:20pm **MI-WeA2 Exchange Bias in Fe/Cr Double Superlattices**, ***J.S. Jiang***, *G.P. Felcher, A. Inomata, R. Goyette, C. Nelson, S.D. Bader,* Argonne National Laboratory

The exchange bias effect is a magnetic pinning phenomenon at the interface between a ferromagnet (F) and an antiferromagnet (AF). It is characterized by a field-offset, or "biased", hysteresis loop. Research on the exchange bias effect has been limited by difficulties in identifying the interfacial magnetic structure and in assessing the role of interfacial roughness. The strength of exchange bias typically observed experimentally is more than an order of magnitude smaller than that predicted by theory. We demonstrate the exchange-bias effect in sputter-deposited epitaxial Fe/Cr "double superlattice" structures that consist of ferromagnetically and antiferromagnetically coupled Fe/Cr superlattices. The AF/F interface in our novel double superlattices is coherent compared to conventional exchange bias systems consisting of dissimilar AF and F phases. The double superlattices offer flexibility in configuration and tunablity of the magnetic coupling and anisotropy. Magnetization results show that AF/F exchange coupling affects the nucleation of reverse magnetic domains, and that the magnitude of the exchange bias field is given directly by the classic formula for collinear spin structures. The collinear spin distribution is confirmed by polarized neutron reflectivity. Work supported by US-DOE BES-MS Contract No. W-31-109-ENG-38.

2:40pm **MI-WeA3 Surface Diffusion Mechanism for the Exchange Coupling between a Ferromagnetic Layer and an Antiferromagnetic Layer**, ***C. Hou***[1], *K. Zhang, T. Zhao, H. Fujiwara,* The University of Alabama

It is the surface net spin that is considered to be responsible for the exchange coupling between a ferromagnetic (F) layer and an antiferromagnetic (AF) layer. For an AF surface with roughness, statistics shows that an AF grain with a total number of spins n = n@super +@ + n@super -@, has an average net number of spins pointing in one direction of n@sub net@ = absolute value of (n@super +@ - n@super -@) = n@super 1/2@ with n@super +@ and n@super -@ denoting the number of spins in "+" and "-" directions within one AF grain, respectively. For an AF layer with total grains N = N@super +@ + N@super -@, it is expected N@super +@ /N@super -@ = 1 as deposited without the F layer, where N@super +@ and N@super -@ denote the number of grains with net spin in the "+" and "-" directions, respectively. Therefore the surface spins of all the AF grains still cancel each other. When a F layer is deposited on top of the AF layer under a field in "+" direction, the balance of N@super +@ and N@super -@ is broken, resulting in N@super +@ / N@super -@ > 1. Thus, the overall net moments are obtained without changing n@sub net@ of each grain. It is generally accepted that this is the cause of the exchange coupling. A NiFe/FeMn/NiFe sample shows reasonable amount of exchange bias field H@sub eb@ and coercivity H@sub c@ for both of the NiFe layers as deposited in a field. With post annealing with a field in the pinned direction, it is found that both H@sub eb@ and H@sub c@ of the two NiFe layers are increased. The results can't be explained by the increase of only the ratio N@super +@ /N@super -@. It is concluded that it is the increase of the individual n@sub net@ that cauess the above phenomenon. The increase of n@sub net@ is thought to occur through surface spin diffusions.

3:00pm **MI-WeA4 Magnetic Stability of Exchange Coupled Magnetic Systems**, ***A. Inomata***, *J.S. Jiang, C.-Y. You, J.E. Pearson, S.D. Bader,* Argonne National Laboratory

The growing demand for higher density magnetic recording and the development of magnetoelectronic devices require controllable magnetic properties on the nanometer scale.@footnote 1@ The application of interfacial exchange coupling is attractive for this purpose. The exchange bias effect occurring at the interface between a ferromagnet(F) and an antiferromagnet(AF) has been used for GMR heads in high density magnetic recording, and exchange-spring magnets consisting of exchange coupled hard and soft ferromagnetic phases are candidates for the next generation of permanent magnet materials. We present a comparison of the magnetic stability in exchange bias and exchange spring systems. The exchange bias system used is the Fe/Cr "double superlattice" structures constructed as [Fe/Cr]@super AF@/Cr/[Fe/Cr]@super F@ with appropriate Cr thickness representing the F and AF.@footnote 2@ And for the exchange spring system we used SmCo/Fe bilayer structures grown epitaxially on different templates to give uniaxial, biaxial and random in-plane anisotropy.@footnote 3@ The switching field and remanent magnetization of both systems were measured by the magneto-optic Kerr effect during repeated reversal of the soft layer magnetization by field cycling. All samples are stable after 10@super +6@ cycles. The effects of the pinning layer and the interfacial spin configuration will be discussed. Work supported by US-DOE BES-MS Contract No. W-31-109-ENG-38. @FootnoteText@ @footnote 1@ S.Gider et al. Science, 281, 797, 1998. @footnote 2@ J.S.Jiang et al. Submitted to Phys.Rev.Lett. @footnote 3@ E.E.Fullerton et al. Phys.Rev.B.58, 12193, 1998.

3:20pm **MI-WeA5 CPP-GMR for Magnetoelectronic Memory**, ***K. Bussmann***, *G. Prinz, B. Bass, S.-F. Cheng,* Naval Research Laboratory*; D. Wang, J. Daughton,* Nonvolatile Electronics, Inc. **INVITED**

Current perpendicular-to-plane giant magnetoresistance (CPP-GMR) has been demonstrated to provide enhanced GMR relative to that measured using the current-in-plane (CIP) geometry with similar multilayer architectures. We have been pursuing this advantage in work performed at the Naval Research Laboratory in developing a new non-volatile magnetic memory compatible with existing Si-CMOS technology. The functionality of this approach improves as the device dimension is reduced to sub-micrometer levels. At these dimensions the micromagnetic switching processes are strongly influenced by edge effects and it is important to include these terms, along with intrinsic magnetic materials properties, to obtain stable '0' and '1' configurations. We will show our results on circular disk devices that stabilize the magnetization in right or left-handed helicity. The devices are constructed as magnetic layers separated by non-magnetic spacer layers. Magnetic layers are alternately rendered 'hard' and 'soft' by varying the thickness of the layers as 'thick' or 'thin', respectively. The residual magnetic pole density at the device edge is minimized by the nature of the parallel alignment of the magnetization to the circumference of the disk, an effect driven by the exchange coupling intrinsic to each layer. Parallel and antiparallel helicity orientations of the magnetization are obtained by flowing current through the device, allowing programmability to '0' (parallel) and '1' (antiparallel) states. We show and interpret switching data on devices ranging from 0.25 - 0.6 micrometers in diameter and present an analysis of utility of these structures in CPP-GMR magnetoelectronic memory.

4:00pm **MI-WeA7 High-Speed Dynamics of Submicrometer GMR Devices**, ***S.E. Russek***, *National Institute of Standards and Technology* **INVITED**

Most of the applications of GMR and spin-dependent tunneling devices require them to be very small (line widths of ~300 nm) and very fast (operation frequencies > 1 GHz). The simplest devices typically consist of 4 to 10 layers of magnetic, nonmagnetic, insulator, and conducting materials with thicknesses of 0.6 nm to 10 nm. In this talk I will present high-speed

[1] **Falicov Student Award Finalist**

measurements of sub-micrometer spin valves being driven by magnetic field impulses and step excitations with peak widths and ristimes of less than 300 ps. We have observed sub- 300 ps rotations and switching (180 degree rotation) of these devices and free induction decay (damped precessional motion) with characteristic frequencies of 2 - 6 GHz. The response of the devices have been compared to Landau-Lifshitz-Gilbert (LLG) micromagnetic simulations and high-speed measurements of magnetization rotation in sheet films using second-harmonic MOKE. The value of the dynamical parameters of the small devices, such as the damping constant, have been compared to those measured using more traditional methods on larger samples, with a smaller range of motion of the magnetization, and a less complex layer structure. The effect of disorder due to edge roughness, surface roughness, and variable interlayer coupling have been studied using LLG simulations and the results have been compared to the dynamical response of real devices to assess the importance of disorder in real systems. Both the damping constant and the degree of disorder are shown to be important in high-speed operation of these devices.

4:40pm **MI-WeA9 RF Diode Sputter Deposition of GMR Multilayers**, ***W. Zou***, *H.N.G. Wadley,* University of Virginia*; D. Wang, D. Brownell,* Nonvolatile Electronics, Inc.

Radio frequency (RF) diode sputtering has been used for the growth of giant magnetoresistive (GMR) metal multilayers. A systematic series of experiments have been conducted to evaluate the dependence of magnetic properties and magnetoresistance upon growth conditions (i.e. background pressure, input power) for NiFeCo/CoFe/CuAgAu multilayers with different CuAgAu thickness during RF diode sputter deposition using an argon plasma. Atomic force microscopy results have shown that the background pressure and plasma power have large effects upon column width and surface morphology that eventually affect GMR properties. A multiscale modeling study has been used to investigate the origin of these phenomena and to identify the origin of the relationships between the experimental observations and growth conditions. Novel deposition strategies for morphology control have been identified.

5:00pm **MI-WeA10 Effects of UV Illumination on Dry Etch Rates of NiFe-based Magnetic Multilayers**, ***H. Cho***, *K.P. Lee, K.B. Jung, S.J. Pearton,* University of Florida*; R.J. Shul,* Sandia National Laboratories

Dry etch patterning of magnetic multilayer stacks (eg. NiFeCo/CoFe/Cu/CoFe/NiFeCo) is possible under high density plasma (HDP) conditions using chemistries such as Cl@sub 2@/Ar or CO/NH@sub 3@. The etch mechanism is ion-assisted desorption of metal chloride or metal carbonyl products. Much higher (@>=@ factor of 3) etch rates are achieved with the Cl@sub 2@-based plasma chemistries, but the rates are still limited by desorption of the FeCl@sub x@ or Cu@sub 3@Cl@sub 3@ etch products. Simultaneous UV irradiation of the sample surface during HDP Cl@sub 2@ etching has been found to convert Cu@sub 3@Cl@sub 3@ into more volatile CuCl@sub 2@ and Cu@sub 2@Cl@sub 3@ species, lowering the activation energy for desorption and enhancing the Cu etch rate.@super (1)@ We have studied the effects of UV illumination on the etch rates of NiFe and NiFeCo in Cl@sub 2@/Ar and CO/NH@sub 3@ discharges, and on the etch selectivity of these materials over a variety of different mask materials (SiO@sub 2@, photoresist, photo-definable polymers) as a function of illumination flux, process pressure and HDP source power. For prevention of post etch corrosion it is still necessary to use H@sub 2@O rinsing or in-situ H@sub 2@ or SF@sub 6@ plasma removal of chlorinated etch residues.

Magnetic Interfaces and Nanostructures Technical Group
Room 618/619 - Session MI+NS-ThM

Patterned or Self-Assembled Magnetic Nanostructures

Moderator: Z.Q. Qiu, University of California, Berkeley

8:20am **MI+NS-ThM1 1-D Propagation of a Magnetic Domain Wall in Submicron Magnetic Wire**, ***T. Ono***, *H. Miyajima,* Keio University, Japan; *K. Shigeto, K. Mibu, N. Hosoito, T. Shinjo,* Kyoto University, Japan **INVITED**

A novel method to detect single domain wall motion in a submicron magnetic wire by utilizing the giant magnetoresistance (GMR) effect is presented.@footnote 1@ Recent developments of nanolithography techniques make it possible to prepare submicron dots or wires with well-defined shape, leading to the current attention on the quantum phenomena in mesoscopic magnetic materials, such as macroscopic quantum tunneling and macroscopic quantum coherence. However, the direct magnetization measurements of mesoscopic magnetic materials are practically difficult because of their small volume, and have been performed using samples consisting of a huge number of presumably identical particles. As a result, the essential magnetic properties of a single particle or wire were masked by the inevitable distribution of size or shape. Up to now, quantitative measurements on dynamical properties of a domain wall in a submicron magnetic wire, such as velocity estimation were almost impossible. The method described in this paper has a great advantage to detect a single magnetic domain wall motion, since the GMR change is directly proportional to the magnitude of the switching layer magnetization in a magnetic wire. It should be noticed that the domain wall position can be determined by this method as a function of time, and, thus, we can measure the velocity of a single domain. The wall velocity linearly depends on the applied magnetic field H and is described as v = μ(H - H@sub 0@), where v is the wall velocity, μ so-called wall mobility. In case of NiFe wire 40 nm in thickness and 500 nm in width, it was obtained that μ = 2.6 (m/sOe), and H@sub 0@ = 38 (Oe) at 100 K. @FootnoteText@ @footnote 1@ T. Ono, H. Miyajima, K. Shigeto, K. Mibu, N. Hosoito and T. Shinjo, Science, 284 (1999) 468-470.

9:00am **MI+NS-ThM3 Magnetism of Interconnected Co Nanodots Grown on the N-modified Cu(001) Surface**, ***K.D. Lee***, *T. Iimori, F. Komori,* University of Tokyo, Japan

Square arrays of ultrathin Co nano-size dots interconnected by 1 monolayer-height Co nanostripes are grown on the N-modifed Cu(001)c(2x2) substrate. Scanning tunneling microscopy shows the Co atoms are nucleated at the naked Cu(001) substrate exposed between ordered arrays of c(2x2) square patches forming such a novel Co nanostructure. The sizes of Co dots and interconnecting nanostripes are controlled by the amount of Co deposition at room temperature. Magnetic properties of these nanostructures have been investigated by using magento-optical Kerr effect between 100 K and 450 K. Analysis of hysteresis loops as a funtion of temperature as well as thickness reveals that these Co dot arrays have remarkably different magnetic properties from ultrathin fcc Co films grown on clean Cu(001) surface with the same average thickness, such as two-step increase of the saturation magnetization and coercivity with decreasing temperature. We attribute these novel magnetic properties to the magnetic interaction among Co dots mediated by the interconnecting Co stripes.

9:20am **MI+NS-ThM4 Periodic Magnetic Microstructures using Glancing Angle Deposition**, ***B. Dick***[1], *M.J. Brett, M. Malac, R.F. Egerton,* University of Alberta, Canada

Arrays of magnetic pillars have been proposed as a potential high-density data storage medium.@footnote 1@ The advanced deposition technique known as GLancing Angle Deposition (GLAD)@footnote 2@ has been used to fabricate Ni and Co posts. Because of the nature of initial film nucleation, these posts were distributed randomly on the substrate surface with a large-scale periodicity of around 350nm and individual post diameters of 100 to 150nm. We have grown arrays of posts by suppressing the randomness inherent within the initial nucletion stage of film growth. Shadowing sites were fabricated by pre-patterning a thin Cr or Ti layer on silicon substrates into a square array using electron beam lithography. These sites shadow regions of the substrate from incident flux during film deposition and act as preferred nucleation sites for the Ni and Co pillars. Using this process, we have obtained a regular post period of 500nm, with post diameters and heights of 300nm and 375nm respectively. This presentation will describe the GLAD deposition process, report on the film's periodic structure, and characterise the film's domain structure (MFM) and hysteresis response curve. Further development on decreasing the period between individual posts is continuing, and we exptect that 200nm spacing should be attainable using this simple, single-step evaporation process. @FootnoteText@ @footnote 1@S.Y. Chou. Proceedings of the IEEE. 85(4), 1997. @footnote 2@K. Robbie, J.C. Sit, M.J. Brett. J. Vac. Sci. Technol. B. 16(3), 1998.

9:40am **MI+NS-ThM5 Magnetic Quantum Cellular Automata**, ***R.P. Cowburn***, University of Cambridge, UK, United Kingdom; *D.K. Koltsov, A.O. Adeyeye, M.E. Welland,* University of Cambridge, UK **INVITED**

Nanometre scale magnetic particles (nanomagnets) are promising candidates for implementing Magnetic Quantum Cellular Automata (MQCA) architectures. In order to use nanomagnets in this way their magnetic properties must be fully understood. In particular, the conditions required to obtain a single domain state (and hence the ability to signal a 1 or a 0) must be established. Furthermore, in order to achieve room temperature operation of MQCA, magnetostatic coupling between nanomagnets must be understood and controlled. We have performed a detailed experimental and theoretical investigation into these aspects of nanomagnetism. We have used high resolution electron beam lithography to fabricate nanomagnets in the size range 40-500nm with elliptical or circular geometries. We find that the shape anisotropy introduced by the elliptical form greatly stabilises the single domain state; in the absence of any ellipticity, all of the nanomagnets greater than approximately 100nm in diameter collapse into a flux closing vortex state. We have then fabricated chains of sub-100nm nanomagnets with gaps as small as 15nm between neighbouring edges. We find experimental evidence for strong magnetostatic coupling. We have thus achieved the conditions necessary for a MQCA implementation, i.e. a well defined digital state even at room temperature which can be switched by interactions from neighbouring cells. We have used the finding described above to make a working room temperature MQCA gate. CMOS electronic signals are interfaced directly to the magnetic system by passing a small current through a gold track underneath part of the gate; outputs are currently read by focusing a laser beam onto a magnetic test point and using the magneto-optic Kerr effect to monitor its magnetic state. The gate achieves an overall power gain (and hence the ability to work at room temperature and to fan out) by an applied oscillating magnetic field.

10:20am **MI+NS-ThM7 Growth, Magnetization, and Magnetoresistance of Self-Assembled Lateral Multilayers**, *E.D. Tober,* Lawrence Berkeley National Laboratory; ***R.F. Marks***, *D.D. Chambliss, R.F.C. Farrow,* IBM Almaden Research Center

The angular dependent magnetoresistance, magnetization, and growth of epitaxial Fe@sub eta@Ag@sub 1 - eta@ self-assembled lateral multilayers@footnote 1@ (SALMs)have been examined via MOKE, 4-point resistance probes, STM, LEED, X-ray MCD, and TEM. SALMs consist of epitaxial thin film alloys of immiscible metals grown on Mo(110)/Al@sub 2@O@sub 3@(11-20) template layers and display a unique form of compositional ordering not observed in the bulk. These systems are observed to form a compositionally ordered alloy of alternating, contiguous stripes of Fe and Ag with the long axis of the stripe coinciding with the Mo[001] direction in the plane of the substrate. The average stripe periodicities are on the order of 1.8 to 2.3 nm along the Mo[-110] (perpendicular to the stripes) direction depending on film stoichiometry. These films are found to contain a high degree of magnetic anisotropy with the easy direction lying in-plane parallel to the Mo[001] direction. The low temperature anisotropic magnetoresistance (AMR) and low field magnetoresistance (MR) are examined as a function of field angle for two nearly orthogonal current directions. The SALM structures are observed to display a significant AMR (roughly 10% maximum for the entire structure). Furthermore, a pronounced MR is observed with a maximum @Delta@R/R of 0.88% (~29% in the active layer) at 2.7 K. @FootnoteText@ @footnote 1@ "Self-assembled lateral multilayers from thin film alloys of immiscible metals", E. D. Tober, R. Farrow, R. Marks, K. Kalki, G. Witte, and D. D. Chambliss, Phys. Rev. Lett. 81 N9, 1897.

10:40am **MI+NS-ThM8 Stripe Domains in Ultraflat Fe/Cu(001) Particles**, ***C. Stamm***, *A. Vaterlaus, U. Maier, D. Pescia,* ETH Zuerich, Switzerland

Atomically thin particles of Fe on Cu(001), grown at room temperature, are investigated using a Scanning Electron Microscope with Polarization Analysis (SEMPA): a Mott detector is used to analyze the perpendicular as well as one of the in-plane spin components of the secondary electrons.

[1] **Falicov Student Award Finalist**

The magnetic particles with thickness of a few atomic layers are produced by Molecular Beam Epitaxy through a mask placed in front of the Cu substrate. As in laterally extended thin films of Fe/Cu(001), particles whose lateral size exceed 1 μm contain stripe domains with magnetization perpendicular to the film plane. The width of the stripes is independent of the lateral size of the particles and their shape. Sizing down the Fe particle leads to a single-domain configuration. In contrast, in-plane magnetized ultrathin Co/Cu(001) particles are found in a single domain state, irrespective of their lateral size.@footnote 1@ @FootnoteText@ @footnote 1@C. Stamm, F. Marty, A. Vaterlaus, V. Weich, S. Egger, U. Maier, U. Ramsperger, H. Fuhrmann and D. Pescia, Science 282, 449 (1998).

11:00am **MI+NS-ThM9 Magnetic Properties of Iron Clusters Deposited on Graphite**, ***A. Rosén,*** *M. Andersson,* Göteborg University, Sweden*; M. Hansson,* Chalmers University of Technology, Sweden*; R. Wäppling, B. Kalska,* Uppsala University, Sweden*; N. Tarras-Wahlberg,* Göteborg University, Sweden*; C. Johansson,* Chalmers University of Technology, Sweden

Magnetic properties of iron clusters deposited on graphite Iron clusters with a wide size distribution were produced in a laser vaporisation source and deposited on a graphite substrate. The magnetic relaxation of the clusters was studied with Mössbauer spectroscopy. At 300 K the sample was dominated by fast superparamagnetic behaviour, whereas the relaxation slowed down at lower temperature and six-peak components, representative for static or near-static spinconfigurations, dominated the Mössbauer spectra at 5 K. This indicates that the sample consists of mono-domain particles having an average size between 5 and 10 nm. From the hysteresis loops we obtained that the saturation magnetization was in the range of bulk a -iron and that the coercivity and the remanence increase with decreasing temperature in the whole temperature range. This behaviour is typical for a system of mono-domain particles with a wide size distribution.

11:20am **MI+NS-ThM10 Magnetic Properties of Co and Fe Particles on Sapphire Single Crystal Surfaces**, ***T. Risse,*** *T. Hill, M. Mozaffari-Afshar, H.-J. Freund,* Fritz-Haber-Institut der Max-Planck-Gesellschaft, Germany

We have used in situ Ferromagnetic Resonance (FMR) to investigate the magnetic properties of small Co and Fe particles deposited on sapphire single crystal surfaces. Co and Fe grow as 3-dimensional particles, as deduced from the angular dependence of the FMR spectra. This result was confirmed by STM studies on an Al@sub 2@O@sub 3@ model surface grown on top of a NiAl(110) single crystal. The FMR spectra of Co or Fe particles deposited at 298 K reveal a uniaxial out-of-plane magnetization with the magnetization lying in the surface plane. A comparison of the measured angular dependence of the resonance position with 2-dimensional films show that experimental results are consistent with a 3-dimensional growth of the particles determined by the STM measurements. A closer examination of the FMR spectra indicates that these small particles exhibit superparamagnetism. With increasing amount of deposited metal the anisotropy of the systems increases indicating a more ferromagnetic behavior of the system. Annealing the samples to elevated temperatures (900K) leads to structural changes of the particles namely an increase of the particle size as deduced from FMR and Auger spectroscopy. Whereas the qualitative behavior of the magnetic anisotropy for Co deposits remains unchanged, the behavior of the iron particles changes drastically. The particles do not show a uniaxial anisotropy of a single resonance line but a complex pattern of several resonance lines. A discussion of this aspects in terms of shape as well as magnetocrystalline anisotropy will be given. Temperature dependent measurements of the Fe particles reveal a reduced Curie temperature compared to the bulk. The strong changes of the line shape with increasing temperature will be discussed in terms of a thermal fluctuations of the magnetization.

11:40am **MI+NS-ThM11 Magnetic Behavior of Nanosize Cobalt Particles in (SiO@sub 2@, MgO, CoO) Matrix**, ***J.Y. Yi,*** *M.L. Rudee,* University of California at San Diego

Magnetic granular composite films composed of nanosize metal particles separated by a non-magnetic matrix, have interesting magnetic properties due to the finite size of the metal particles. Recently we found that ferromagnetic (FM) and antiferromagnetic (AFM) composite films such as Co-CoO films had much larger coercivity (~1 kOe at 300 K) than conventional granular Co-SiO@sub 2@ films (superparamagnetic at 300 K) in the same composition range. The increased coercivity was believed to be due to the exchange coupling between FM Co and AFM CoO, and the microstructure of the Co particles. These results indicated that the overall properties of the metal phase were affected by not only the intrinsic properties of them but also the characteristics of the matrix phase. To examine the matrix effects, Co-SiO@sub 2@, Co-MgO and Co-CoO granular composite films were prepared by co-sputtering from separate Co and each oxide target. Each film had 30~40 volume % of Co. The estimated Co particle size from x-ray peak broadening effect was about 7 nm. Magnetic hysteresis loops showed that the superparamagnetic behavior of Co at room temperature in the Co-SiO@sub 2@ and the Co-MgO systems whereas 500 ~ 1000 Oe of coercivities were observed in the Co-CoO films. AT 10 K the coercivity of the Co-SiO@sub 2@ film increased to 760 Oe while the coercivity of the Co-MgO and Co-CoO films increased to 6 kOe and 10 kOe, respectively. Unlike the Co-SiO@sub 2@ system, a small M-H loop shift was observed in the Co-MgO system at 10 K and disappeared above 50 K. This results indicated that there would be a small amounts of Co oxide phase existed in Co-MgO films and this may be the reason for the high coercivity at low temperature. In the Co-CoO system, the loop shifts were observed up to 250 K. In this presentation the magnetic properties of each film will be discussed based on the microstructural and magnetic effects from the different matrix.

The Science of Micro-Electro-Mechanical Systems Topical Conference

Room 620 - Session MM+MI-ThM

Processing and Integration Technology

Moderator: L.M. Miller, Jet Propulsion Laboratory

9:00am **MM+MI-ThM3 Magnetic Micromachining Technology: From Materials to Components to Actuators**, ***M.G. Allen,*** Georgia Institute of Technology **INVITED**

The fabrication of micromachined structures based on magnetic elements requires the development of both magnetically soft and hard materials, as well as suitable processes that allow the incorporation of these materials into microelectromechanial systems (MEMS). This presentation summarizes approaches to materials and fabrication techniques for magnetic MEMS, and illustrates their use through several examples, including: flux concentrators to improve the sensitivity of magnetotransistors; integrated inductive components for electronic packages; and fully-integrated, magnetically-actuated microrelays.

10:20am **MM+MI-ThM7 Fabrication and Characterization of Polycrystalline Silicon Thin Films with Hydrofluoric Acid Permeability for Sacrificial Etching of Underlying Oxide Layers**, ***Y. Kageyama,*** *T. Tsuchiya, H. Funabashi, J. Sakata,* Toyota Central R&D Labs., Inc., Japan

Polycrystalline silicon (poly-Si) thin films with permeability to a concentrated hydrofluoric acid solution were fabricated for use in in-situ vacuum encapsulation of micro sensor devices on silicon wafers, and porous microstructures of the films related to the permeability were elucidated. A partial cavitation of grain boundaries, which was induced by heavy doping of phosphorus and consequent segregation of soluble precipitates, was designed for passage of fluid which resolves underlying borophosphosilicate glass (BPSG) or non-doped silica glass (NSG) layer. Poly-Si films of 0.1μm in thickness were made by solid phase crystallization of amorphous films deposited by low-pressure chemical vapor deposition, and were converted to be permeable by doping. Three types of the doping methods were tried, and only a phosphorus oxichloride decomposition method proved to be effective to obtain permeability. The permeability was evaluated by measuring selective removal rates of underlying sacrificial oxide layers, and lateral BPSG removal of more than 50μm was observed within 90 sec at a room temperature through the permeable poly-Si thin films. The removal rates of BPSG layers were about ten times faster than those of NSG layers, which can be attributed to phosphorus concentration in oxide, and were dependent on post-annealing temperatures, whereas those of NSG layers did not depend on the annealing temperatures. The microstructures of these permeable poly-Si thin films were first observed by secondary electron microscope and field emission secondary electron microscope, which revealed submicron pores between silicon grains that acted as the fluid paths.

10:40am **MM+MI-ThM8 A New Chemistry for Rapid Etching of SiO@sub2@**, ***C.I.H. Ashby,*** *C.M. Matzke, L. Griego,* Sandia National Laboratories

Plasma etching of SiO@sub2@ has traditionally been achieved using a fluorocarbon-based plasma. Very fast SiO@sub2@ etch rates (> 1 μm/min) are obtained using high-density plasmas and CH@subx@F@suby@ source gases. Although these plasmas provide fast preferential etching of

SiO@sub2@ vs. Si by controlled deposition of a polymer, that same polymer deposition makes CH@subx@F@suby@ processes unsuitable for applications where the surface chemical properties of the SiO@sub2@ are important. Fabrication of deep trenches in fused SiO@sub2@ without chemical alteration of the SiO@sub2@ surface by a fluoropolymer deposit is essential for applications such as electrophoretic and electro-osmotic separations using microfabricated channels ("chemlab on a chip"). Rapid (0.4 µm/min) etching of fused silica has been achieved without the use of polymerizing fluorocarbon gases by the addition of N@sub2@ to SF@sub6@/Ar mixtures in an electron-cyclotron-resonance (ECR) reactor. Addition of N@sub2@ to SF@sub6@ increases the etch rate of SiO@sub2@ by up to 30%. After deep (10 µm) trench etching, the smoothness of the etched surface is comparable to that of unetched SiO@sub2@. Nitrogen might play two roles in enhancing SiO@sub2@ etching: 1) increasing the F atom concentration and/or 2) facilitating the etching of the SiO@sub2@ matrix through the formation of volatile NO@subx@ products. Optical emission studies using Ar actinometry suggest the second mechanism dominates under our plasma conditions. Process characteristics under a variety of plasma conditions will be presented. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under Contract DE-AC04-94AL85000.

11:00am **MM+MI-ThM9 Residual Stress Characterization of Thick PECVD Oxide Films for MEMS Applications**, ***R. Ghodssi***, *X. Zhang, K.-S. Chen, K.A. Lohner, M. Spearing, M.A. Schmidt,* Massachusetts Institute of Technology

Vapor deposited films are of vital importance in many sensors and actuators where they are used to form electrical or mechanical elements. In order to achieve higher electrical and mechanical power levels, thicker films are often desired. However, the deleterious effects of residual stress tend to increase with film thickness. In particular, excessive wafer bow and even cracking may prohibit integration within a micro-device. This paper presents residual stress characterization for PECVD Novellus@super TM@ oxide films with thicknesses in the range of 10 - 40 µm. These films are deposited at 400°C and densified at 1100°C in a nitrogen environment. Wafer curvature measurements were performed to investigate the residual stress in the thick PECVD oxide films as a function of temperature. These results show that the residual stress in thick PECVD oxide films is a combination of both thermal expansion mismatch stress and an intrinsic stress due to the deposition process and resulting microstructure. Furthermore, the densification step plays an important role in determining the residual stress state. For instance, a 10 µm thick PECVD oxide film exhibits a wafer bow of 50 µm and 250 µm before and after densification, respectively. Additional high temperature experiments indicated that cracks formed at temperatures between deposition and densification. The tendency to form cracks is a strong function of film thickness. For films thicker than 15 µm, cracks formed in the film at temperature below 1100°C. Laminated plate theory has been applied to extract residual stress data for the curvature measurements. This data is then correlated with the deposition and densification conditions to guide process development so as to reduce wafer curvature and to eliminate cracking.

11:20am **MM+MI-ThM10 Process and Fabrication of a Thin Film PZT Pressure Sensor**, ***E. Zakar***, *M. Dubey, B. Piekarski, J. Conrad, R. Piekarz, R. Widuta,* Army Research Lab

Piezoelectric crystals or ceramics are very attractive for static and dynamic pressure sensors. One of the very promising piezoelectric materials is PZT (Lead Zirconate Titinate - 52/48). MEMS technology was applied to fabricate several static PZT pressure sensors and capacitance method was used to characterize it. Sol-gel derived PZT thin films (250 - 500 nm) were deposited on platinized (SiO@sub 2@- 1000/ Ti - 20/ Pt - 170 nm) Si substrates. Top Pt electrode was sputtered deposited on PZT films and was patterned using ion milling. The PZT films were etched using Reactive Ion Etching (RIE) and ion milling. Comparative studies (etched surface, sidewalls and electrical properties) of ion milling and RIE of PZT and oxide were also completed. The RI etch rate of PZT was studied using different electrode shield (graphite, alumina, ardel) materials with power (100 to 500 W) and pressure of HC@sub 2@ClF@sub 4@ gas plasma. The measured RI etch rate of PZT varied from 10-100 nm/min. The ion-milling rate of Pt was 33nm/min, PZT-23nm/min and Oxide-31nm/min. A unique technique of soft and hard bake of photo resists along with change in incidence angles of ion beam were used to eliminate fencing problem during ion milling. Desired slope of the etched walls was also produced using above technique. The etched surface and side walls were smooth and clean up to 2µm feature size. Four level photo-mask process was used to fabricate the pressure sensors. A low stress PECVD oxide film was deposited (at 200°C) to isolate the top and bottom electrodes. The Pt electrodes further bonded with Ti/Au leads which were patterned using wet etching (KOH + I@sub 2@). Several pressure sensors with different dimensions (300x300 and 200x200 µm@super 2@) were fabricated. The average values of measured capacitance, 1023 and 453 pF, are in excellent agreement with calculated values.

11:40am **MM+MI-ThM11 Microfabricated Low-Power Broad-Band Light Source Utilizing Tungsten Filaments**, ***E.W. Jones***, *T. George,* JPL-California Institute of Technology*; M.L. Tuma,* NASA-Glenn Research Center*; R. Hansler,* Lighting Innovations-John Carroll University

A miniature,Si chip-based, incandescent light source utilizing tungsten filaments is being developed for integration into fiber optic systems to wavelength multiplex a suite of fiber-optic sensors operating in harsh environments from -50 C to 600 C. The requirements for the light source are that it operate at 2800 K, with an output power >100 mW in the 500-900 nm spectral band with spectral power variance of no more than 4% over the spectral band. In addition, it should be rugged, long-lived, with an output stabilization time of about 1 second, and have a "footprint" comparable to LED devices. Other uses for these filaments are automobile headlights, and systems for vehicle navigation, in remote applications such as monitoring bridges for stress, and industial plant monitoring. To date, several filament fabrication approaches are being attempted. The first uses sputtered tungsten films (1-2 microns thick) patterned in various filament geometries. These filaments have been operated at < 2200 C) is the mounting of coiled-coil wire filaments on microfabricated Si chips. Lastly, 25-micron-thick W sheet stock is being patterned to produce planar spiral filaments. Filaments satisfying the above criteria will be packaged into a hermetically sealed three-chip stack consisting of a bottom reflector chip, a middle filament chip, and a top 5 mm x 5 mm SiN membrane optical window chip, integrated with an optical fiber. The fabrication procedures as well as the optical and electrical characterization results will be discussed in detail.

Magnetic Interfaces and Nanostructures Technical Group
Room 618/619 - Session MI+NS-ThA

Magnetic Imaging

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

2:00pm **MI+NS-ThA1 Cryogenic Magnetic Force Microscopy Instrumentation**, ***M. Roseman***, *P. Grutter,* McGill University, Canada

We describe our cryogenic magnetic force microscope, operating between 4 and 300 Kelvin. The instrument is designed to fit within a 3" diameter bore of an 8 Tesla magnet. Cooling is achieved through the use of He exchange gas, which is pumped out prior to imaging in order to provide a vacuum of better than 10@super -5@ mbar during operation. The instrument uses a fibre optic interferometer to measure cantilever deflections. Through the use of a phase lock loop, this interferometric signal allows for the tracking of the cantilever resonant frequency with a resolution of 0.25 Hz in a 100 Hz measurement bandwidth. Our cantilevers are commercially available, made of single crystal silicon coated with a magnetic film, and routinely exhibit Q-factors of greater than 100,000 at 4 Kelvin. Piezoelectric-based clamping linear positioners, with step sizes of 50 nm (at 77 Kelvin) and capable of operation in high magnetic fields, perform in-situ tip and fibre approaches. As an effective means of vibration isolation, we suspend the microscope from a soft bellows. Comprised of 70 convolutions, the bellows damps out vibrations by more than an order of magnitude, effectively isolating the microscope from the surrounding environment, including pump vibrations and liquid helium boil-off. Particular attention has been paid to optimizing the signal to noise ratio through a systematic study of various noise sources, with the intent of achieving a thermally limited sensitivity.

2:20pm **MI+NS-ThA2 Modified Tips for High Resolution In-plane Magnetic Force Microscopy**, ***L. Folks***, IBM Almaden Research Center*; J.N. Chapman,* University of Glasgow, UK*; M.E. Best, P.M. Rice,* IBM Almaden Research Center*; B.D. Terris,* IBM Almaden Research center*; D. Weller,* IBM Almaden Research Center

Commercial batch-fabricated coated MFM tips have been modified to allow high resolution imaging of the in-plane components of stray field above a sample. A hole of diameter ~ 20nm was milled through the magnetic coating layer to the underlying silicon at the apex of each tip with a focussed gallium ion beam. The tips were then magnetized in the direction parallel to the sample plane. The hole at the apex forms a small pole gap and it is the interaction of the stray field from this gap with the sample stray field which produces the MFM signal. Accordingly, the resolution achievable is determined by the diameter of the hole milled at the apex. Note that such a controlled modification of the magnetic tip coating was suggested by Hill.@footnote 1@ High and low density data tracks, with transition spacings ranging from 1 micrometer to 50 nanometers, written in longitudinal granular recording media have been used to demonstrate the utility of the tips. By comparison of experimental results with simple theoretical models it is shown that the tips are strongly sensitive to the in-plane components of stray field. Furthermore, the modified tips exhibit better resolution than the unmodified tips, as may be seen from a side-by-side comparison of data collected from high density written transitions. The modified tips offer an inexpensive route to high resolution imaging of stray fields associated with in-plane domain structures. Hence they are of particular value for high density magnetic recording media investigations since the in-plane component of stray field is closely related to the signal detected by the recording head. @FootnoteText@ @footnote 1@ E. W. Hill, IEEE Trans. Magn. 31, 3355 (1995).

2:40pm **MI+NS-ThA3 Progress Toward Achieving Single-Spin Force Detection**, ***B.C. Stipe***, *D. Rugar, H.J. Mamin, C.S. Yannoni,* IBM Almaden Research Center*; T.D. Stowe, T.W. Kenny,* Stanford University

Magnetic resonance force microscopy was originally proposed@footnote 1@ as a method for imaging individual electron or nuclear spins. This talk will focus on recent progress toward achieving the necessary force sensitivity, tip field gradient, and spin lifetime to detect a single electron spin under real experimental conditions (i.e., with a sharp, submicron-size magnet mounted on an ultrasensitive cantilever within 100 Å of a sample surface). Characterization of the magnetic tip is especially important since the field gradient from the tip determines of the force from the spin. In addition, the spin relaxation rate can increase in the presence of magnetic field fluctuations from the tip. We have characterized the magnetic fluctuations of the tip at the cantilever frequency based on field dependent dissipation measurements on both Co thin film and NdFeB particle tips. NdFeB tips showed greatly reduced dissipation/fluctuations due, in part, to their high crystalline anisotropy. These tips should generate field gradients greater than 3 G/Å at the target spin, resulting in a force of more than 30 aN. Using custom fabricated single crystal silicon cantilevers at 2.5 K, we have achieved a force resolution of 2.8 aNHz@super -1/2@ far from the sample surface. However, within 500 Å of the sample, tip-surface interactions can significantly increase the force noise and cantilever frequency jitter. The origin of these effects and methods for reducing them will be discussed. This work is supported, in part, by the Office of Naval Research. @FootnoteText@ @footnote 1@ J.A. Sidles, Phys. Rev. Lett. 68, 1124 (1992).

3:00pm **MI+NS-ThA4 Magnetic Imaging by Spin-polarized Scanning Tunneling Microscopy**, ***W. Wulfhekel***, *J. Kirschner,* MPI fur Mikrostrukturphysik Halle, Germany

A new approach to spin-polarized scanning tunneling microscopy based on the magneto tunnel effect between a ferromagnetic tip and a ferromagnetic sample is demonstrated. By periodically changing the magnetization of the tip in combination with a lock-in technique, topographic and spin-dependent parts of the tunnel current are separated. This allows to simultaneously record the topography and the magnetic structure of the sample. First results are given for polycrystalline Ni and single crystalline Co(0001) surfaces, revealing a high spin contrast of up to 20% of the tunneling current, low data acquisition times of few ms/pixel and a resolution down to 10nm. The magnetic origin of the observed signal is proven rigorously by recording the domain wall motion due to an applied magnetic field during scanning. Potentials and limitations of this new technique are discussed.

3:20pm **MI+NS-ThA5 Spin-Polarized Scanning Tunneling Spectroscopy: Magnetic Domain Imaging and Beyond**, ***R. Wiesendanger***, *M. Bode, M. Getzlaff,* University of Hamburg, Germany **INVITED**

Spin-polarized vacuum tunneling from ferromagnetic thin film probe tips into exchange-split surface states of rare-earth thin films is demonstrated and applied to magnetic domain imaging with a spatial resolution below 20 nm. The bias dependence of the spin polarization extracted from tunneling spectroscopy data is found to be in surprisingly good agreement with results from spin-resolved (inverse) photoemission indicating that spin-dependent density-of-states effects dominate over matrix element effects. It is also shown that spin-polarized electronic states can yield high tunneling magnetoresistance. On the other hand, surface contamination leads to a strong decrease of the measured spin-polarisation by impurity-assisted scattering which influences strongly the vacuum-TMR effect as well as the contrast in spatially resolved magnetic imaging applications.

4:00pm **MI+NS-ThA7 Scanning-aperture Photo-emission Microscope for Magnetic Imaging**, ***G.M. McClelland***, *C.T. Rettner,* IBM Almaden Research Center

We have demonstrated a new technique for magnetic imaging that is ultimately capable of spatial resolution better than 5 nm. In our instrument, photoemission is excited by a laser focused to a 10-micron spot. A scanning aperture above the magnetic surface allows only electrons from a small selected region to reach the electron detector. The magnetization in this region is determined from the dependence of photoemission on the circular polarization of the laser. Images of 10-nm-thick Co-Pt multilayer thin films on sapphire have been obtained. From a cesiated film, a high quantum efficiency of 0.002 was observed from 458 nm laser light. Circular dichroism of +/- 2 % is recorded by alternating the circular polarization of the light while scanning. The tip distance above the surface is maintained by advancing the tip until 1-nA tunneling to a positive sample is observed, then withdrawing 15 nm and switching polarity to detect photoemission through the tip. The resolution we observe agrees well with the 35-nm-sized aperture in the gold tip. From the observed noise, we project that there is enough signal to image at 5 nm resolution if a small enough aperture can be fabricated. Recent calculations show that image forces on the electron from the aperture walls act to make the effective aperture even smaller than the physical diameter. The insensitivity of the instrument to varying magnetic fields should make it ideal for time dependent magnetization measurements in an applied field.

4:20pm **MI+NS-ThA8 Magnetic and Chemical Microanalysis Using SEMPA and SAM**, ***G. Steierl,*** *W. Lutzke, H.P. Oepen, J. Kirschner,* Max-Planck-Institut für Mikrostrukturphysik, Germany

Industrial demands led to an enormous interest in micromagnetic analysis tools that can be applied to a wide range of samples including lithographically produced samples with complex chemical compositions. To meet these requirements a new instrument was designed that combines Scanning Auger Microscopy (SAM) and Scanning Electron Microscopy with Polarization Analysis (SEMPA). The core elements are a Schottky thermal field emitter electron gun with coaxial cylindrical mirror analyzer (PHI-SAN 670), a retractable electron-lens system and a spin detector based on Spin Polarized Low Energy Electron Diffraction (SPLEED). The characteristics of these core elements are described and the performance of the entire system is demonstrated by high-resolution chemical and magnetic analysis of Ni@sub 80@Fe@sub 20@- and Co elements. The microstructures of 50nm thickness were produced by using electron beam lithography and lift-off. Oxidized Si(111)-wafers were used as substrate material with an oxide layer thickness ranging from about 10nm (natural oxide layer) to 1200nm (thermally oxidized). It is demonstrated that the electrical insulation of the microstructures due to the oxide-layer does not impede high resolution domain microscopy, if suitable surface preparation techniques are used. Several details of the domain patterns encountered in microstructures of different geometry (squares, rectangles, disks) and of lateral length ranging from 500nm to 10 µm are reported.

4:40pm **MI+NS-ThA9 Low Temperature Magnetic Domain Imaging with Spin Polarized Low Energy Electron Microscopy**, ***E.D. Tober,*** NCEM, Lawrence Berkeley National Laboratory*; G. Witte,* Ruhr-Universität Bochum, Germany*; H. Poppa,* NCEM, Lawrence Berkeley National Laboratory

Spin Polarized Low Energy Microscopy (SPLEEM) has for the first time been employed to examine magnetic surfaces below room temperature. With the recent addition of a liquid nitrogen based cooling stage for our instrument, we have the ability to achieve sample temperatures in the range of 110 - 2200 K. SPLEEM has the advantages of high spatial resolution (~10.0 nm) and atomic height resolution combined with image acquisition at near video rates. A full description of the system design as well as its application in exploring the magnetic domain formation in thin films of Co grown in situ on Pt(111) and Au(111) surfaces will be presented.

5:00pm **MI+NS-ThA10 Ballistic Electron Magnetic Microscopy: Imaging Magnetic Domains with Nanometer Resolution**, ***W.H. Rippard***[1], *R.A. Buhrman,* Cornell University

A new magnetic imaging technique with nanometer resolution, ballistic electron magnetic microscopy (BEMM), is introduced and used to image magnetic structure in copper-cobalt multilayer films. Magnetic domains are clearly observed and are found to give more than 300% contrast in the resulting BEMM images. Domain wall motion is also studied as a function of applied magnetic field. Magnetic contrast is observed on length scales of less than 100 nm and fluctuations of the ballistic transport in the system are observed on scales of less than 10 nm. The magnetic contrast is found to be strongly dependent on magnetic layer thickness while only weakly dependent on the number of layers in the multilayer stack. An energy dependent difference in the electron transport as a function of the relative alignment between the magnetic layers is also reported, revealing the effects of the Co band structure on the ballistic current transport. Strong magnetic contrast is observed at energies as high as 4 eV, demonstrating a large asymmetry in the effective spin-dependent mean free paths in this system. The local nature of the technique also allows the direct imaging of the effects of interfacial dopants on the ballistic transport in the multilayer films. Results from such dusting studies are also presented.

[1] **Falicov Student Award Finalist**

Magnetic Interfaces and Nanostructures Technical Group
Room 618/619 - Session MI-FrM

Magnetic Thin Films

Moderator: C.J. Palmstrom, University of Minnesota

8:20am **MI-FrM1 New Phenomena in Laterally Modulated Magnetic Thin Films**, ***Z.Q. Qiu,*** University of California, Berkeley **INVITED**

Ultrathin magnetic films grown on atomically stepped surfaces exhibit many interesting properties due to the lateral modulation at the nanometer scale. To systematically control the atomic steps curved substrates are utilized to provide a continuous range of step density. Fe and Co films grown on curved Ag(001), W(001) and Cu(001) have been investigated by means of the surface magneto-optic Kerr effect. The atomic steps induce an in-plane, uniaxial magnetic anisotropy with the easy axis either parallel or perpendicular to the step edges. The strength of the step-induced anisotropy is linearly roportional to step density for fcc magnetic films, but scales quadratically for bcc magnetic films. The Neel pair-bonding model provides a possible explanation for these observations. Even more intriguing results occur when substrate magnetism is induced at the stepped interface, as for the Fe/Pd(001) system. The ferromagnetic nature of the interfacial fcc Pd dominates the anisotropy to result in a linear dependence of the step-induced anisotropy on step density even though the Fe overlayer is bcc. The step-induced moment in this system is also shown to enhance the Curie temperature. Finally, for the Fe/Cr(001) system, the compensated, stepped Cr(001) surface is found to produce a 90-degree coupling between the Fe and Cr moments. When this effect competes with the step-induced anisotropy, the Fe magnetization undergoes an in-plane spin-reorientation transition from perpendicular to parallel to the step edges with increasing step density.

9:00am **MI-FrM3 Interrelation of Morphology and Structure in Ultrathin Magnetic fcc FeCo Alloy Films on Cu(001)**, ***W. Kuch,*** *A. Dittschar,* Max-Planck-Institut für Mikrostrukturphysik, Germany*; M. Zharnikov,* Universität Heidelberg, Germany*; C.M. Schneider,* Institut für Festkörper- und Werkstofforschung Dresden, Germany

Chemically random epitaxial ultrathin alloy films allow the study of correlation between morphology, structure, and magnetism for continuously varying structural parameters. This can be achieved if variation of the film composition leads to a continuous alteration of film properties such as the lattice constant and the average magnetic moment. We present a multi-technique investigation of structure, morphology, and magnetism of epitaxial Fe@sub x@Co@sub 1-x@ alloy ultrathin films grown on Cu(001) over the whole composition range up to thicknesses of 9 ML. The films grow at room temperature in a distorted fcc structure with random chemical order. The amount and sign of the distortion depend on thickness and composition. Below 60-70% Fe content the alloy films are smooth and tetragonally compressed in the vertical direction in the interior of the films, with tetragonally expanded layers at the surface. The strain is continuously reduced with increasing Fe concentration, and at 60-70% Fe content the interior of the films reaches the unstrained fcc structure. For higher Fe concentrations the occurrence of several superstructures is observed, which are attributed to regular structural rearrangements. At the same time the roughness of films with more than 4-6 ML is significantly enhanced. This is discussed in terms of the vertical strain at Fe concentrations above 70%, the sign of which is reversed with respect to lower Fe concentrations, leading to tetragonally expanded layers. No indications for the presence of low-moment fcc Fe were found in any of the films.

9:20am **MI-FrM4 Structure and Magnetic Properties of Cu/Co/Cu/H-Si(110) Films**, ***S. Maat,*** *M.T. Umlor, G.J. Mankey,* University of Alabama

We report the results of a study of the structural and magnetic properties of Co films deposited on Cu/H-Si(110). A Cu(111) buffer layer is formed by evaporation or UHV sputter deposition on the H-terminated Si(110) surface. From consideration of bulk lattice constants, the Cu films undergo a 6% expansion along the [1, -1, 0] direction and a 13% compression along the [1, 1, -2] direction. The structure as a function of buffer layer thickness from 1 nm to 100 nm is determined with a combination of LEED, Auger electron spectroscopy and RHEED. The optimum sputtering conditions for producing well-ordered fcc(111) films were determined. The buffer layer crystallography was found to be strongly dependent on the sputtering conditions, with a transition from polycrystalline to single-crystal as the sputtering power is increased. Evaporated films were found to grow as single crystals. Co films grown on single-crystal buffer layers exhibit a six-fold LEED pattern with diffuse spots. The Co films were capped with a protective Cu layer and the magnetic properties were measured ex-situ with MOKE and MFM. MOKE data perpendicular to the Cu [1, -1, 0] direction reveals a stepped hysteresis loop shape characteristic of a combination of triaxial and uniaxial in-plane anisotropy. This loop shape is attributed to a combination of uniaxial strain incorporated in the films and the three-fold crystalline anisotropy of the hcp structure. @FootnoteText@ Supported by DOD grant DAAH04-96-1-0316 and shared equipment through NSF grant DMR-9809423.

9:40am **MI-FrM5 Magnetization Reversal in Ultrashort Magnetic Field Pulses**, ***H.C. Siegmann,*** *C.H. Back,* Swiss Federal Institute of Technology, Switzerland*; R. Allenspach,* IBM Zurich Research Laboratory, Switzerland **INVITED**

Ultrashort magnetic field pulses with amplitudes of up to 20 Tesla at picosecond duration are generated in the final focus test beam facility of the Stanford Linear Accelerator. These unique magnetic field pulses have been used to study magnetization reversal in a variety of thin ferromagnetic films. High resolution magnetic contrast images reveal the magnetization patterns generated by one or several field pulses from which we deduce the elementary processes responsible for the magnetization reversal. For perpendicular magnetized samples we observe ring domains which are reminiscent of the field contour lines during exposure. Their radii represent switching fields which are in quantitative agreement with the coherent rotation model. The broadening of the transition region between oppositely magnetized domains is due to static and dynamic fluctuations of the magnetic anisotropy. For films with uniaxial anisotropy in the plane of the film we observe "figure 8" magnetic patterns due to the necessity to conserve angular momentum while generally much smaller fields compared to the perpendicular samples are sufficient for the ultrafast reversal. We show that the demagnetizing field produced by the precession of the magnetization out of the plane of the film completes the reversal after the external field ceases to exist. The material property of primary importance in ultrafast reversal is the damping of the precession of the magnetization around the direction of the external field. We show that it is strongly influenced by the degree of crystallinity of the sample.

10:20am **MI-FrM7 Ginzburg-Landau Theory of Perpendicular Magnetized Ultrathin Films**, ***A. Berger,*** Argonne National Laboratory

Ultrathin ferromagnetic films have been found to exhibit a strongly enhanced magnetocrystalline anisotropy, which can even be sufficient to overcome the demagnetizing effect and stabilize a perpendicular magnetized state in the entire ferromagnetic temperature range. Such perpendicular magnetized systems have been particularly interesting with respect their thermodynamic properties and were reported to confirm predictions for the two-dimensional Ising model. However, recent experiments on perpendicular magnetized Ni/Cu(100)-films have shown indications for domain formation near the Curie temperature that seems to occur without weakening of the effective anisotropy (crystalline + dipolar).@footnote 1@ Therefore, this observation seems to be fundamentally different from earlier results reported for a number of ultrathin film systems where domain formation is found in the immediate vicinity of the reorientation phase transition, which is associated with the vanishing of the effective anisotropy. To understand the above phenomena we have evaluated the free energy of a perpendicular magnetized material using the Ginzburg-Landau theory. In accordance with previous results, we find that for sufficiently large anisotropy values no conventional domain structure is formed at any temperature. However, we find that a domain structure based on the formation of linear domain walls (LDW-phase) lowers the energy in a substantial region around the critical point. In addition, the domain size is estimated to be microscopically small so that this domain structure should be formed for any realistic sample size. We will discuss the details of the calculated phase diagram with particular emphasis on the implication that the LDW-phase prohibits a direct ferromagnetic, paramagnetic phase transition. Work supported by the U. S. Department of Energy, Basic Energy Sciences, Materials Science under Contract W-31-109-ENG-38. @FootnoteText@ @footnote 1@P. Poulopoulos et al., Phys. Rev. B 55, 11961 (1997).

10:40am **MI-FrM8 Dimensional Crossover in Ultrathin Ni Films on Cu**, ***R. Zhang,*** The Pennsylvania State University*; M. Hochstrasser,* The Pennsylvania State University, U.S.*; N. Gilman, R.F. Willis,* The Pennsylvania State University

Theory predicts that in a magnetic system the long-range order parameter, the magnetization, as a function of the temperature disappears at the Curie

temperature according to M=M@sub 0@(1-T/T@sub C@)^@beta@. For 3D Heisenberg and Ising systems @beta@ are 0.365 and 0.325 respectively. For 2D Ising system @beta@ is 0.125. In our experiments, we have studied the finite-size-effect shift of the T@sub C@(n) of a thin film of n layers, as phenomenologically described by the shift exponent @lambda@. There are two ways of defining this exponent. Traditionally, one measures the shift of T@sub C@(n) with respect to the bulk critical temperature T@sub C@(bulk). Alternatively, one may also define: @Delta@T:=[T@sub C@(bulk)-T@sub C@(n)]/T@sub C@(n) ~ n^(-@lambda@'), which defines @lambda@'. We studied with the surface magneto-optical Kerr effect (SMOKE) the behavior of @beta@ and @lambda@ of Ni films on Cu(100), Cu(110) and Cu(111) in a wide temperature range and with changing thickness. We observe a different behavior for films on Cu(100) and Cu(110) compared to films on Cu(111). Ni films on Cu(100) and Cu(110) show a sharp transition from a 3D Heisenberg @beta@ value to a 2D exponent of ~0.21, whereas for Ni films on Cu(111) no such sharp transition can be observed. This behavior is a strong indication of the role of quantum size effects on the behavior of electronic states, i.e., the sharp transition is a manifestation of quantum-well states existing in a gap in the bulk continuum of sp states, and the absence of such a gap along the direction (E.D. Hansen et al. J.Phys, 9, L435 (1997)). The transition is indicative of a cross-over from 3D to 2D. The finite-size scaling exponents reflect the magnetic behavior of the bulk phase with corrections, as recently argued theoretically by Henkel et al.(PRL, 80, 4783 (1998)). What this work shows is that field theoretic corrections are sensitive to the symmetries of the epitaxial lattices.

11:00am **MI-FrM9 Enhancement of Perpendicular Magnetic Anisotropy and Surface Alloy of Co/Pt(111) Ultrathin Films***, C.S. Shern, H.Y. Her,* ***Y.E. Wu,*** National Taiwan Normal University, ROC

The magnetic anisotropy of Co/Pt(111) was studied by surface magneto-optic Kerr effect (SMOKE). The perpendicular magnetic anisotropy appears for Co deposited on a flat Pt(111) surface with a thickness between 0.8 and 3.7 ML. The perpendicular uniaxial magnetic anisotropy disappears for Co deposited on a sputtered Pt(111) surface because the magnetocrystalline anisotropy has diminished due to the absence of crystalline structure in the films. During surface alloy formation in 1 ML Co on the flat Pt(111) surface, we quantitatively demonstrate an enhancement in the magneto-optic Kerr signal. The maximum enhancement in MO signal is as large as 200 % after alloy formation at 710 K. The formation of Co-Pt alloy was confirmed by AES and LEED. The perpendicular magnetic anisotropy persists in the annealing process until the ultrathin film is annealed at temperatures above 850 K. The enhancement is also observed in thicker films when the formation of Co-Pt alloy has been developed, but both the out-of-plane and the in-plane anisotropy appear at a higher annealing temperature.

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