# SYMPOSIUM T

## Materials for Magnetic Devices–Magneto-Electronics and Recording

April 16 – 19, 2001

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* Invited paper

## TUTORIAL

### ST T: THE SPINTRONICS REVOLUTION
**Monday, April 16, 2001**
**1:00 p.m. - 5:00 p.m.**
**Nob Hill C/D (Marriott)**

New material structures having new mechanisms for spin dependent transport are being applied to a wide range of electronic functions, including magnetic field sensors, read heads for hard drives, nonvolatile memory, and galvanic isolators. The evolution the material properties of giant magnetoresistive (GMR) materials from multilayers to sandwiches and spin valves, and of magnetic tunnel junctions (MTJs) is described. Materials trade-offs in magnetic sensors and isolators are described in some detail. Opportunities for further material improvements will be described. Integration of these new magnetic structures with integrated circuits is necessary in some applications and desirable in others, and leads to other materials challenges. The integration of magnetic materials with semiconductors has evolved considerably in the last several decades, and the trend suggests that some new forms of integrated semiconductor and magnetic materials are likely. The new DARPA program on Spins In Semiconductors (SPINS) may be one platform on which such devices are conceived.

**Instructor:**
**Dr. James Daughton**, Nonvolatile Electronics, Inc.

SESSION T1: NEW DIRECTIONS IN MATERIALS
Chairs: Bethanie J.H. Stadler and Luis J. Cruz
Tuesday Morning, April 17, 2001
Golden Gate C3 (Marriott)

**8:30 AM *T1.1**
MATERIALS PROPERTIES OF SPIN VALVE STACKS FOR 100GBIT/IN$^2$ HEAD APPLICATIONS. Sining Mao, Advanced Head Concept, Seagate Recording Heads, Minneapolis, MN.

Ultra high density magnetic recording technology needs a solid understanding about the thin film magnetic materials such as spin valve or spin tunneling junctions. In this talk, a systematic study will be presented to evaluate the technical challenges of spin valve head in the data storage product for 100Gbit/in$^2$ [1]. The spin valve process–microstructure–performances relationship was emphasized with a variety of examples including NiMn, PtMn, CrMnPt, and IrMn spin valve heads. A comparison between Top, bottom, and Dual spin valve heads will be given. Transport properties at cryogenic temperatures provide information on the interface and imparity scattering. Thermal stability is a very key issue for HDD head application and will be emphasized [2]. Sensitivity and stability shall be compromised in the ultra high density head designs. The evaluation of spin valve head from 5G to 50G was used to predict the 100G spin valve head performance and the feasibility of a real application. The possible path for the 100Gbit/in$^2$ recording head is also evaluated.
[1] Ed Murdock et. al., "Practical issues for magnetic recording heads at 100Gbit/in$^2$ and more", Invited talk at Intermag 1999, paper BA-02.
[2] Sining Mao et. al, "Thermally stable spin valve films with synthetic antiferromagnet pinned by NiMn for recording heads beyond 20 Gbit/in$^2$", J. Appl. Phys. 87, 5720 (2000). In collaboration with Zheng Gao, Chunhong Hou, Jian Chen, Eric Linville, P.R Chen, Song Xue, Hong Wang, and Ed Murdock.

**9:00 AM *T1.2**
PINHOLES AND NANO-OXIDE SPECULAR LAYERS IN SPIN VALVES. W.F. Egelhoff, Jr., R.D. McMichael, P.J. Chen, R.A. Fry and C.J. Powell, NIST, Gaithersburg, MD; G. Beach, D. Martien and A.E. Berkowitz, UCSD, La Jolla, CA.

Recently, nano-oxide layers (NOL) grown in giant magnetoresistance (GMR) spin valves have attracted much interest as a method of achieving the increased GMR associated with specular reflection at Co/oxide interfaces while still permitting the use of Mn-based antiferromagnets (AF) to pin the hard layer and Permalloy (Py) to make the free layer soft. A typical structure would be IrMn/Co/NOL/Co/Cu/Co/NOL/Co/Py. In order for the switching characteristics of the spin valve to benefit from the AF and Py the NOL must be thin enough so that strong magnetic coupling across the NOL exists. Otherwise, the magnetic films separated by the NOL could switch separately. We have investigated pinholes in the NOL in the structure 10 nm IrMn /2.5 nm Co/Ru/2.5 nm Co/4 nm Cu/2.5 nm Co/NOL/2.5 nm Co/Ru/2.5 nm Co/NiO. Without a NOL the center Co film is 5 nm thick, and the GMR loop obtained by switching it is shifted ~300 Oe from zero field by synthetic AF Co/Ru/Co and the exchange bias of the IrMn. Using CoO as a NOL we find that as its thickness reaches ~1 nm, there is a sudden drop from ~ 300 Oe to single digits. It appears that for CoO<1 nm, pinhole coupling across the CoO forces the two Co films to switch together, but as the last of the pinholes in the CoO close up at ~1 nm the center Co film can switch separately. In contrast, when $Al_2O_3$ is the NOL there is no sudden drop in the coupling with thickness, instead it resembles a 1/t decay. Such observations constitute a new approach to the study of pinholes, and we have used it to investigate a variety of oxides and metal spacer layers to clarify the behavior of pinholes.

**10:00 AM T1.3**
MAGNETISM OF COBALT BASE ARTIFICIAL LATTICE FILM. Masataka Masuda, Shun Matsumoto, Yasunori Hayashi, Kyushu Univ, Dept of Engineering, Fukuoka, JAPAN.

The Co base artificial lattice films have attracted much interest by their special magnetization properties. We discussed the effect of the Pt layer thickness on the magnetic anisotropy, and we showed the effect of the hydrogen ion implantation on the magnetic properties of Pt/Co multi-layered films. The Pt/Co multi-layered films are formed on Si(111) substrates with molecular beam epitaxy. We did structure analysis, magnetic domain analysis and magnetic characteristics evaluation with XRD, MFM and VSM, respectively. Among the series of films of 0.5nm Co layer, XRD showed that the film of 1.0nm Pt layer had a highest periodicity and that they had complete (111) plane orientation. The magnetic domains of these films showed typical stripe structure. The magnetic domain size reduced with the increase of the thickness of the Pt layer. We found out the coercivity increased linearly as a function of the length of magnetic domain wall of the unit area. By a result of VSM, the multi-layered films of Pt thickness of less than 2.8nm had perpendicular magnetic anisotropy. The value of perpendicular anisotropy energy changed by the Pt layer thickness and showed a maximum value with 1.0nm Pt / 0.5nm Co multi-layered film. After hydrogen implantation to the films, XRD showed that the lattice distance was elongated with the hydrogen dose. Also, MFM observed that the magnetic domain size reduced with the increase of the hydrogen dose. The easy axis of magnetization changed from perpendicular to parallel in the plane with the increase of the hydrogen dose. After evacuation of hydrogen at 373K, the perpendicular anisotropy was recovered. This phenomenon suggested that the origin of magnetic anisotropy was mainly the lattice mismatch and distortion in the layer interface. We would mention also about Pd/Co multi-layered films.

**10:15 AM T1.4**
TEMPERATURE DEPENDENCE OF THE MAGNETO-RESISTANCE OF Co/Re SUPERLATTICES. Timothy Charlton, David Lederman, Dept of Physics, West Virginia University, Morgantown, WV.

Hcp $(10\bar{1}0)$ Co/Re superlattices were grown by dc magnetron sputtering on sapphire $(11\bar{2}0)$ substrates with the [001] direction of the superlattice in the film plane. The temperature dependent magnetoresistance (MR) was measured on samples patterned by photolithography from 10K to 300K in a 5.5T superconducting magnet. The pattern allows the measurement of the MR with the current (I) and the magnetic field (H) parallel or perpendicular to the magnetic easy axis (C, [001] direction) more precisely than using the standard Van der Pauw technique. Measurements at 5K on an antiferromagnetically-coupled sample shows dips in the MR near $H = 0$ when $H \parallel C$ and $H \perp I$ and, dips below the saturation value at $H \sim 2.5$ kOe for the $H \parallel C$ and $H \parallel I$ configuration due to the competition between the anisotropic magnetoresistance (AMR) and the giant magnetoresistance (GMR). We will present the effect of temperature on this competition between AMR and GMR.

**10:30 AM T1.5**
COMPOSITION-MORPHOLOGY-PROPERTY RELATIONS FOR GMR MULTILAYERS GROWN BY RF DIODE SPUTTERING. W. Zou, H.N.G. Wadley, X.W. Zhou, R.A. Johnson, Department of MS&E, University of Virginia, Charlottesville, VA. D. Brownell, Nonvolatile Electronics, Inc. Eden Prairie, MN.

The magnetotransport properties of giant magnetoresistance (GMR) multilayers are significantly affected by the atomicscale structure of the interfaces between the conducting and ferromagnetic (FM) metal layers. The interfacial roughness and the extent of intermixing at these interfaces are both thought to be important. A combination of experimental and modeling studies have been used to investigate control of interface structure can be achieved during the growth of GMR multilayers by RF diode deposition and the consequences of such control for magnetotrans-port. The dependence of magnetotransport properties upon the composition of the conducting layer were examined. The study revealed that multilayers using CuAgAu as the conducting layer achieve better giant magnetoresistance properties, but film grown with pure Cu as the conducting layer exhibit no GMR effect. To provide insight into this phenomenon, three different thicknesses of Cu and CuAgAu films have also been deposited and their surface morphology and roughness have been experimentally obtained. Atomic force microscopy (AFM) results reveals when CuAgAu is used (instead of pure Cu), the RMS roughness and grain size are reduced and prevent formation of pin holes. By using a newly developed embedded atom method (EAM) alloy potential, a Molecu-lar Dynamics study has been used to investigate the layer by layer growth phenomena and to iden-tify the origin of the relationships between the experimental observations and layer compositions. Consequently, The MD analysis show the CuAgAu is found to promote smoother interfaces because silver acts as a surfactant and helps to achieve a pin hole free film at lower film thickness.

**10:45 AM T1.6**
OSCILLATORY ANGULAR DEPENDENCE OF EXCHANGE BIAS FOR EPITAXIAL NiO-Co (001) BILAYERS. S. Dubourg, J.F. Bobo, LPMC-CNRS-INSA, Toulouse , FRANCE; B. Warot, J.C. Ousset and E. Snoeck, CEMES-CNRS, Toulouse, FRANCE.

We have sputter-deposited NiO-Co bilayers on MgO (001) substrates. NiO grows epitaxially on MgO at 900°C and subsequently the room deposited 80 Å thick Co films have a fcc crystal structure in epitaxy with the oxide underlayer. These samples were warmed up to 300°C and then zero-field or field cooled through the NiO Neel temperature (a 300 Oe magnetic field was applied along the [100] or the [110] MgO axis). Magnetic hysteresis loops were obtained by magneto-optical Kerr effect, the magnetic field being oriented in the plane of the substrate for various angles $\alpha$ with respect to the [100] direction. The usually expected behavior for such experiments is a very smooth angular $\alpha$ dependence of the exchange bias $H_E$ close to a cosine with only one sign change over 180°. Consequently data can be fitted using a Stoner-Wohlfhart model including an unidirectional term due to exchange coupling and an extra uniaxial term for polycrystalline samples. The high crystallographic coherence of our NiO/Co bilayers induces a very unusual oscillatory $H_E$ ($\alpha$) dependence with several sign changes according to the NiO axis field application. Despite of the Co magnetization switching is not a pure coherent rotation, we propose a Stoner-Wohlfhart model including four fold anisotropy and unidirectional exchange anisotropy which explains these typical magnetic properties.

**11:00 AM T1.7**
MAGNETIC CHARACTERIZATION OF (001) AND (111) Ni FILMS EPITAXIALLY GROWN ON MGO. Rosa A. Lukaszew, Vladimir Stoica and Roy Clarke, Physics Department, University of Michigan, Ann Arbor, MI.

One interesting application of epitaxial magnetic thin films is to use them as one of the electrodes in a spin-dependent tunneling junction, in order to use the magnetocrystalline anisotropy to define the required two states of the magnetization. [1] In our preliminary work, we prepared epitaxial magnetic films on Cu buffer layers grown on Si substrates. [2] The single crystalline quality of the films was particularly evident in the magnetization hysteresis loops, shown by a sharp reversal at fairly high fields ( 120 Oe), when the samples were magnetized along the crystallographic easy axis. In order to explore the possibility of epitaxial magnetic films on less reactive substrates, we studied the growth on MgO substrates. This type of metal ceramic interfaces is also important in applications as diverse as magnetic storage media and supported catalysts. We have shown that it is possible to obtain epitaxial (001) and (111) Ni films grown on MgO substrates. [3] In particular we observed that the crystalline quality of the films improves considerably after 10 nm of film growth. We will now present our studies on the magnetic properties on these films, particularly the azimuthal dependence of the magnetization reversal using MOKE, correlating our findings with the structural characterization obtained with RHEED, STM and XRD.
[1]. "Use of magnetocrystalline anisotropy in spin-dependent tunneling", Lukaszew, R.A., Sheng, Y., Uher, C. and Clarke, R., Appl. Phys. Lett. 75 (1999) 1941.
[2]. "Smoothening of Cu films grown on Si(001)", Lukaszew, R.A., Sheng, Y., Uher, C. and Clarke, R., Appl. Phys. Lett. 76 (2000) 724.
[3]. "Epitaxial growth of (001) and (111) Ni films on MgO substrates", Lukaszew. R.A., Stoica, V. A., Uher, C. and Clarke, R. MRS Fall 2000 Meeting, Boston, MA.

**11:15 AM T1.8**
EXCHANGE-BIASED NiO-Co NANOFACETED BILAYERS GROWN ON MgO (110). S. Dubourg, J.F. Bobo, LPMC-CNRS-INSA, Toulouse, FRANCE; B. Warot, J.C. Ousset and E. Snoeck, CEMES-CNRS, Toulouse, FRANCE.

We have sputter-grown self-organized faceted NiO-Co epitaxial bilayers on MgO(110). Due to very close lattice parameters, NiO adopts the same NaCl crystallographic structure as the substrate but it minimizes its surface energy growing in a stripe-shaped morphology elongated along [001] MgO direction. The Co layers then deposited on NiO adopt a fcc structure. It consists of a set of connected nanowires whose height is about 50 Å, length is near to 1$\mu$m and lateral periodicity 100 ÅMagnetic properties of the Co layers were investigated by magneto-optical Kerr effect from 10K to room temperature. They are dominated by strong shape-induced uniaxial anisotropy and exchange coupling with the antiferromagnetic underlayer. Magnetization loops recorded along the easy axis exhibit a perfect squareness and switch in less than 10 Oe. Transverse measurements indicate that switching occurs by domain nucleation and/or domain wall propagation. On the contrary, close to the [$\bar{1}$10] hard axis, magnetic switching occurs by coherent rotation that we fitted using a Stoner-Wohlfhart model including strong uniaxial anisotropy and exchange coupling terms. The bi-stable Co magnetization state along its easy axis has been used for ordering the NiO spins configuration from room temperature to 10K. Sign and value of exchange bias induced by such a thermal treatment can be modulated thanks to a wide magnetocrystalline or local path energies distributions.

**11:30 AM T1.9**
Abstract Withdrawn.

**11:45 AM T1.10**
EXCHANGE COUPLING AND SPIN-FLIP TRANSITION OF $CoFe_2O_4/\alpha$-$Fe_2O_3$ BILAYERED FILMS. Tatsuo Fujii, Takuya Yano, Makoto Nakanishi and Jun Takada, Dept of Applied Chemistry, Okayama Univ, Okayama, JAPAN.

(102)-oriented $\alpha$-$Fe_2O_3$ epitaxial films deposited on $\alpha$-$Al_2O_3$(102) are known to have an unique spin-flip transition at about 400 K [1]. The spin axis lying within the (102) plane above 400 K changes almost normal the plane at room temperature. We will report the magnetic properties of $CoFe_2O_4/\alpha$-$Fe_2O_3$ bilayered films. The spin-flip transition of $\alpha$-$Fe_2O_3$ could influence the magnetic properties of $CoFe_2O_4$, and vice versa. $CoFe_2O_4/\alpha$-$Fe_2O_3$ (ferrimagnetic / antiferromagnetic) bilayered films on $\alpha$-$Al_2O_3$(102) were prepared by helicon plasma sputtering method. The $CoFe_2O_4$ layer grown on $\alpha$-$Fe_2O_3$(102) had an (100)-preferred orientation. Magnetization and Mössbauer measurements of bilayered films suggested that the $CoFe_2O_4$ layer had an in-plane magnetic anisotropy while the $\alpha$-$Fe_2O_3$(102) had the spins aligned perpendicular to the film plane. The bilayered films did not show the spin-flip transition. The ferrimagnetic spins of the $CoFe_2O_4$ layer were coupled perpendicularly to the antiferromagnetic spins of the $\alpha$-$Fe_2O_3$ layer, due to the exchange coupling between $CoFe_2O_4$ and $\alpha$-$Fe_2O_3$. The large in-plane anisotropy of the $CoFe_2O_4$ layer could suppress the spin-flip transition of the $\alpha$-$Fe_2O_3$ layer.
[1] T.Fujii, M. Takano, R. Katano, Y. Isozumi and Y. Bando, J. Magn. Magn. Mat, 135(1994) 231.

SESSION T2: MICROMAGNETICS TO NANOMAGNETICS – THE NEXT STEP
Chairs: Edward S. Murdock and Olle Heinonen
Tuesday Afternoon, April 17, 2001
Golden Gate C3 (Marriott)

**1:30 PM *T2.1**
MAGNETIC AND MAGNETORESISTIVE PROPERTIES OF NANOPATTERNED ELEMENTS. C.A. Ross, Y. Hao,. F. Castano, S. Haratani, Dept. of MS&E, Massachusetts Institute of Technology, Cambridge, MA; Henry I. Smith, B. Vogeli, M. Walsh, Dept. Electrical Engineering and Computer Science, Massachusetts Institute of Technology, Cambridge, MA.

Many magnetoelectronic devices, such as read heads and magnetic random access memories, are based on small magnetoresistive elements whose resistance is a function of their magnetization state. These elements usually consist of a multilayer stack which includes magnetic films, non-magnetic spacers, and pinning layers such as antiferromagnets. As the elements become smaller, magnetostatic coupling between the magnetic layers dominates the behavior, leading to antiparallel alignment of the magnetic layers and raising their switching fields. In this work, we have used nanolithography techniques to pattern magnetoresistive elements with diameters of 50 nm and lengths of 100 nm and above, to examine how the magnetic and magnetoresistive behavior scales with element size. Films such as Co/Cu/NiFe pseudo-spin valves are sputtered then patterned into arrays of elements using interference lithography combined with ion milling. The magnetic hysteresis of the arrays is measured using magnetometry and magnetic force microscopy, and the magnetoresistance is measured by connecting the arrays with conductor lines in a self-aligned lithography process. As an example, in an unpatterned Co 4 nm/Cu 3 nm/NiFe 6 nm film the magnetic layers are magnetized parallel at remanence and the two layers switch at 40 Oe and 10 Oe respectively. After patterning into an array of 80 nm x 140 nm elements, the hysteresis loop of about $10^9$ elements was measured. The magnetic layers in each element are now magnetized antiparallel at remanence, and the particles are single-domain. Distinct switching of the two layers can still be observed, and occurs at 600 Oe and -180 Oe for the Co and NiFe respectively. We will discuss the magnetic behavior of such elements as a function of size, characterize the distribution of switching fields and its origin in the film microstructure, and discuss methods for controlling the switching fields of nanoscale elements.

**2:00 PM *T2.2**

HIGH RESOLUTION MFM FOR MICROMAGNETICS. George D. Skidmore, Andrew Kunz, C E. Campbell, and E. Dan Dahlberg, School of Physics and Astronomy, Minneapolis, MN.

We have previously developed electron beam deposited spikes for use in magnetic force microscopy [1] with a spatial resolution of on the order of 30 nm [2]. These high resolution tips have been used to determine the micromagnetic structure of nanofabricated cylindrical nickel dots or cylinders with a perpendicular anisotropy. The dots have diameters in the range from 68 to 1000 nm, and thicknesses range between 48 and 140 nm. Also, the micromagnetic structure has been determined by Landau-Lifshitz-Gilbert (LLG) micromagnetic simulations. There is excellent agreement between the experiments and the simulations with no adjustable parameters in the simulations [3]. It is found the ratio of the dot diameter to the stripe period of an unpatterned nickel film of the same thickness predicts which magnetic states are energetically favorable. The smallest particles (ratio equal to or less than 3/2) have a simple magnetic structure consisting of one to three domains which can be characterized as either a stripe or a bulls-eye domain pattern. At larger diameters there emerge many different metastable states characterized by a stripe structure with somewhat random patterns, but with a stripe period the same as in nickel films of the same thickness.

[1] "Improved Spatial Resolution in Magnetic Force Microscopy," George D. Skidmore, Sheryl Foss, and E. Dan Dahlberg, Appl. Phys. Lett.. 71, 3293-3295 (1997).
[2] "Microscopic Magnetization Reversal in Perpendicular Anisotropy CoCr Thin Films," Gottfried Wastlbauer, George D. Skidmore, Chris Merton, Jake Schmidt, E. Dan Dahlberg, and Joseph Skorjanec, Appl. Phys. Lett. 76, 619-21 (2000).
[3] "Evolution of the Complexity of Magnetic Domain Structure in Nanoscale Nickel Dots," George D. Skidmore, Andrew Kunz, C.E. Campbell, and E. Dan Dahlberg, to be published.

**2:30 PM T2.3**

OBSERVATION OF MAGNETIC STATES AND NUCLEATION FREE SWITCHING IN MESOSCOPIC RING MAGNETS.
Mathias Kläui, Johan Rothman, Luis Lopez-Diaz, Carlos A.F. Vaz, J.A.C. Bland, University of Cambridge, Cavendish Laboratory, Cambridge, UNITED KINGDOM; Zheng Cui, Rutherford Appleton Laboratory, Chilton, UNITED KINGDOM.

Pre-patterned Si(100) substrates have been used to grow free-standing epitaxial ring magnets of Cu(100)/Co(100)/Cu(100)/Si(100). TEM and EELS investigations into the growth profile have confirmed that the magnetic material on the structures is physically disconnected from the magnetic material in the trenches thus preventing any exchange interaction between the structures and the trenches. Since the magnetic material is deposited not only on the ring structures but over the entire sample, magneto-optical measurements are difficult. Accordingly, the samples were magnetically characterised using specially adapted magneto-optic Kerr effect and Magnetic Force Microscopy techniques. Magnetic measurements and micromagnetic simulations of the rings with diameters between 0,7$\mu$m and 1,8$\mu$m show that a two step switching process occurs at high fields, indicating the existence of two different stable states. In addition to the vortex state, which occurs at intermediate fields, we have identified a second state which is also stable at remanence and undergoes a simple and well characterised nucleation free domain wall propagation switching process. Micromagnetic simulations predict that one of the consequences of the proposed switching process is the fact that rings reverse by falling into vortex states with different circulation when the field is applied in opposite directions. Scanning Kerr Microscopy measurements confirm this prediction. This means a particular vortex state (clockwise or counter-clockwise) can be prepared using a uniform field only, which can be important for technological applications.

**2:45 PM T2.4**

COMPUTATIONAL MODELING FOR MAGNETIC-SENSOR-BASED THREE-DIMENSIONAL VISUALIZATION OF MICROCRACKS. Leonid Muratov, David Lederman, and Bernard R. Cooper, Dept. of Physics, West Virginia University, Morgantown, WV.

We have made substantial progress in developing a magnetic-scanning-based volume visualization capability for visualizing microcracks and other faults within metallic components of aircraft and other objects. Development of the technology involves parallel design of the hardware, needed software, and computational modeling. This report is directed to the computational aspects. The presence of cracks, phase segregation, or even submicron-sized grain boundaries creates a disruption of the magnetic field response to an externally applied electrical current running through the material. These effects can be detected through the magnetic field leakage in the external near-surface region. Using a computer model of an array of magnetic tunnel junction detectors, magnetic 'signatures' of various faults and/or material borders and domains have been calculated using finite element analysis and portrayed by icons. We have considered a number of typical cracks and flaws, of different dimensions and orientations, within the bulk of the component. The database of signatures thus generated allows fast recognition of faults and generation of their images in real time. Significant efforts have been made to provide an adequate three-dimensional visualization of the shape and distribution of microcracks, the magnetic field lines (visually indicating the distribution of the magnetic field intensity), and delineation of the surface of the faults in relationship to the component surface. Volume imaging in three dimensions is the key element in the utility of our approach. We have adopted a multilayer hierarchy of volume visualization capability. Relatively simple problems are addressed at any location by using the Internet connection and inexpensive stereo-ready graphics cards and corresponding eyeware available for PC's. Viewing images at an ImmersaDesk, as available at the WVU Virtual Environment Laboratory, and/or at a portable CAVE-like system driven by NT or Linux PC provides a significant increase of viewing quality.

**3:30 PM T2.5**

HIGH FREQUENCY BEHAVIOR OF Fe-Co-N THIN FILMS.
N.X. Sun and S.X. Wang, Center of Research on Information Storage Materials, Stanford University, Stanford, CA; T.J. Silva, National Institute of Standards and Technology, Boulder, CO.

High frequency behaviors of soft magnetic Fe-Co-N films with different dispersion angles and a Permalloy film were studied with a pulsed inductive microwave magnetometer at different bias fields along both hard axis and easy axis. The inductive time-domain data were analyzed to obtain the Landau-Lifshitz damping parameter. Frequency domain analysis was used to obtain the permeability spectrum. Ferromagnetic resonance (FMR) frequencies were determined as both the zero-crossing frequency of the real permeability spectrum, $f_0$, and the peak frequency of the imaginary permeability spectrum $f_p$. The Fe-Co-N films with low dispersion angle show a peak in the damping parameter when the transverse bias field is close to the anisotropy field $H_k$. In addition $f_0$ is enhanced relative to $f_p$. The Fe-Co-N films with larger dispersion angle, however, do not exhibit enhanced damping or $f_0$. As a control study, we found that $f_0$ and $f_p$ are virtually identical for the Permalloy film. Careful spectral analysis of the low dispersion Fe-Co-N films shows that the permeability spectra of the Fe-Co-N films exhibits a clear superposition of two peaks in the imaginary part of the spectra when the transverse bias field is within 4 Oe to $H_k$ ($\sim$18 Oe). The 2$^{nd}$ peak has a peak frequency about twice of the 1$^{st}$ peak, and has a maximum area of about 30% of the first peak when the transverse bias field is close to $H_k$. The appearance of the 2$^{nd}$ peak in the imaginary spectra of the Fe-Co-N films results in enhanced damping and $f_0$ for transverse bias fields close to $H_k$.

**3:45 PM T2.6**

SUBMICRON-SCALE PERIODIC MAGNETIC ARRAYS.
V. Metlushko, Department of Electrical Engineering and Computer Science, University of Illinois at Chicago, Chicago, IL; B. Ilic, School of Applied and Engineering Physics, Cornell University, Ithaca, NY; M. Grimsditch, N. Zaluzec, J. Johnson, Materials Science Division, Argonne National Laboratory, Argonne, IL; H. Koo, R.D. Gomez, University of Maryland, MD; P. Neuzil, R. Kumar, Institute of Microelectronics, SINGAPORE.

The magnetic behavior of nano-magnetic arrays is determined by the magnetic properties of the individual elements, their spacing and symmetry of array. The properties of individual magnetic nano-dot are governed by the interplay between the crystalline anisotropy and shape anisotropy. For polycrystalline dots of Co, Ni, Fe and permalloy containing a large number of grains of different orientation, the net magnetocrystalline anisotropy is expected to be small compared to the shape anisotropy. The shape anisotropy will therefore dominate the dot anisotropy. Using the Magnetic Force Microscopy (MFM) we investigated the magnetic properties of periodic arrays of polycrystalline submicron magnetic dots and anti-dots of Co, Fe (in plane magnetization), and [Co4/Pt10]n (out of plane anisotropy) with characteristic sizes $\sim$100-400 nm and periods of $d = 0.5 - 1\mu$m defined by e-beam or laser interferometric lithography on a Si wafer and patterned using lift-off or etching. To avoid complications due to changes in growth-induced anisotropy and or thickness, elliptical elements of various sizes and shapes were deposited simultaneously on a single substrate. The magnetization pattern inside the dots changed drastically when the axis-aspect ratio were reduced. In addition, we demonstrated that not only the shape of the dot but the array period and symmetry controlled the remanet state of closely spaced arrays. The example of the domain wall engineering in negative arrays will be shown.

**4:00 PM T2.7**
SHAPE TUNING OF MAGNETIC STABILITY IN NANO-PARTICLES: THE ROLE OF DIPOLAR INSTABILITY POCKETS.
M. Grimsdtich, A. Berger, J. Johnson, Materials Science Division, Argonne National Laboratory, Argonne, IL; V. Metlushko, Electrical Engineering Dept., University of Illinois at Chicago, Chicago, IL; B. Ilic, School of Applied Phys., Cornell Univ., Ithaca, NY; P. Neuzil and R. Kumar, Inst. of Microelctronics, Singapore, SINGAPORE.

Magnetization reversal onset fields have been measured in a series of nano-arrays of 30 nm thick Co and 20 and 30 nm thick permalloy elements. Elliptical elements with differing aspect ratios and with rounded or pointed ends have been investigated. The experimental results are compared with theoretical calculations, which are based on the concept of spin wave softening. These calculations enable us to identify regions near the particle ends, in which the tendency toward dipolar driven instability is substantially enhanced. These dipolar instability pockets are found to be responsible for the onset of magnetization reversal and allow for a calculation of the switching onset field without the need for full micromagnetic calculations. The calculated values, which depend only on the exchange constant, saturation moment and the shape of the elements, produce excellent agreement with the measured switching fields as a function of shape (rounded or pointed), material (Co or permalloy), and aspect ratio (1.2 to 7). The model even reproduces the actual switching fields to within less than 100 Oe, confirming the fact that the concept of dipolar instability pockets describes the essential physics of the magnetization reversal onset in nano-particles. Due to the tremendous technological significance of magnetic stability in nano-particles, the concept of dipolar instability pocket should also prove to be an indispensable tool for materials design.
Work at ANL supported by US Department of Energy.

**4:15 PM T2.8**
MICROMAGNETIC INVESTIGATIONS OF THE EXCHANGE PINNING IN NiFe/Cu/NiO TRILAYERS.
O. de Haas, R. Schäfer, C.M. Schneider, L. Schultz, Inst. f. Festkörper- und Werkstofforschung (IFW) Dresden, Dresden, GERMANY; Y.M. Chang, C.H. Ho, W. Pan, M.-T. Lin, Dept. of Physics, Taiwan National University, Taipei, TAIWAN.

The phenomenon of exchange biasing, i.e., a unidirectional anisotropy arising from a ferromagnet (FM) being in close contact to an antiferromagnet (AFM), is often used to define a reference magnetization direction in spin valve systems. The fundamental physical mechanisms associated with this unidirectional anisotropy are not yet fully understood. Of particular technological relevance is the temperature behavior of the exchange biasing which determines the limits of application. The case in which the strength of the coupling between AFM and FM is varied by a nonmagnetic interlayer is of fundamental interest. We therefore investigated $Ni_{80}Fe_{20}$/Cu/NiO trilayers as a model system. The magnetic domain structures in the Permalloy layer were imaged for various Cu layer thicknesses and temperatures by means of Kerr microscopy. The temperature-dependent studies show that a domain pattern formed above the blocking temperature $T_B$ of the NiO film is completely frozen in after the system has been cooled down below $T_B$. Close to $T_B$, however, the system passes through various states of stability against magnetization reversal. In the most stable state ("strong pinning") at low temperature and large Cu spacer thickness the initial domain state is always restored even after applying magnetic fields up to 0.5 T in various directions. For higher temperatures (below $T_B$) and intermediate spacer thicknesses the pinning appears to be weakened. As a consequence, the frozen-in domain state is only preserved, if the external field is applied along the hard magnetic axis. Applying the field along any other direction causes the domain pattern to change irreversibly. In this case the change of the magnetization distribution takes place by domain wall motion. The new domain pattern is again restored after applying the field along the hard axis. These results are discussed with respect to the application of exchange-biasing layers in magnetic sensors.

**4:30 PM T2.9**
MAGNETO-RESISTANCE AND INDUCED DOMAIN STRUCTURE IN TUNNEL JUNCTIONS.
M. Hehn, O. Lenoble, D. Lacour, A. Schuhl, Laboratoire de Physique des Matériaux, Nancy, FRANCE; D. Hrabovsky, J.F. Bobo, A.R. Fert, Laboratoire de Physique de la Matière Condensée, Toulouse, FRANCE.

Magnetization reversals in sputtered Co layers used in a magnetic tunnel junction are studied using transport measurements, magneto-optic Kerr magnetometry and microscopy. The magnetization reversals of the hard and the soft Co layer have been studied separately and their ferromagnetic coupling is shown when combined in the tunnel junction. Using the tunnel magneto-resistive effect as a probe for micromagnetic studies, we first evidence the existence of an unexpected domain structure in the soft Co layer. This domain structure originates from the duplication of the domain structure of the hard Co layer template into the soft layer via ferromagnetic inter-electrode coupling. Then a detailed analysis of the kerr microscopy images shows that all features appearing in the variation of tunnel resistance as a function of applied field are associated to the domain phase evolution of each electrode. By tailoring the magnetic properties of the hard Co layer, we have demonstrated that the appearance of the domain duplication is driven by the magnetic anisotropy of the hard layer. Reducing this anisotropy leads to domain duplication but with effects non discernible in the tunnel magnetoresistance signal. Indeed, the duplication of low density 360° domain walls are then only observed on the TMR signal. Finally, a brief theoretical description of the domain duplication process allows us to extract the main parameters governing the effect. With this, we shed light on the parameters to adjust in order to get or avoid this phenomenon.

**4:45 PM T2.10**
CONTROL OF MAGNETIC ANISOTROPY FIELD IN FeTaN FOR ULTA-HIGH-FREQUENCY APPLICATION.
Sung-Ryong Ryu, Seok Bae, Jong-Han Jeong, Choong-Sik Kim, Seoung-Eui Nam, Hyoung-June Kim, HongIk Univ, Dept of Metallurgical Eng. & Materials Sci., Seoul, KOREA.

Recently, FeTaN films for high frequency electromagnetic devices have been widely investigated due to their high saturation magnetization, high anisotropy, and low coercivity. It is reported that Yamguchi's (Tohoku University) paper included the result for the patterned magnetic thin films followed by the fabrication of thin film inductor. However, FeTaN thin films have an advantage in the higher initial permeability because of higher saturation magnetization than that of conventional soft magnetic materials. Anisotropy field of soft magnetic thin films such as FeTaN is an important factor for the thin film inductor in 1~2GHz-drive mobile communication handset application. In this paper, the effect of shape anisotropy on the ultra-high-frequency magnetic characteristics of FeTaN films was investigated. Patterned FeTaN films which were to research the effect of shape anisotropy were prepared by lift-off process and $SiO_2$ was used for insulating materials which were to reduce eddy current losses between stripe lines. Patterned FeTaN films with stripe lines exhibited high Hk about 40Oe. Ferromagnetic resonance frequency was also enhanced. It resulted from the increased anisotropy field of patterned FeTaN films and low eddy current losses. We suggest that patterned FeTaN films should be used for the 1~2 GHz-drive inductors.

## SESSION T3: POSTER SESSION
## MATERIALS FOR MAGNETIC DEVICES

Chairs: Bethanie J.H. Stadler, Konrad Bussmann, Edward S. Murdock and William C. Black
Tuesday Evening, April 17, 2001
8:00 PM
Salon 1-7 (Marriott)

**T3.1**
MULTILEVEL MAGNETORESISTANCE IN A STRUCTURE COMBING WITH TWO SPIN-VALVES.
Kebin Li, Yihong Wu, Jinjun Qiu, and Towchong Chong, Data Storage Institute, National University of Singapore, SINGAPORE.

The magnetic and electrical properties as well as the structural characteristics have been studied on a series of samples with a new structure of substrate/SV(1)/$Al_2O_3$5nm/SV(2). Here, SV(1) is either CoFe/IrMn based spin-valve such as $Ta_5/NiFe_2/IrMn_8$/ $CoFe_2/Cu_{2.6}/CoFe_2/Ta_5$ (thicknesses are in nanometers) bottom spin-valve or $Ta_5/NiFe_2/CoFe_{1.5}/Cu_{2.6}/CoFe_2/FeMn_{10}/Ta_5$ top spin-valve and SV(2) is $Ta_5/NiFe_2/CoFe_{1.5}$(or 2)$/Cu_{2.6}/CoFe_2/IrMn_8/Ta_5$ top spin-valve. SV(1) and SV(2) in the structure are decoupled by a $Al_2O_3$ layer with 5nm in the magnetic properties, however, they are in parallel connection in the electrical properties. In a sample with a structure of substrate/$Ta_5/NiFe_2/IrMn_8/CoFe_2/Cu_{2.6}/CoFe_2$/ $Ta_5/Al_2O_3 5/Ta_5/NiFe_2/CoFe_2/Cu_{2.6}/CoFe_2/IrMn_8/Ta_5$, five magnetoresistance states which are related to five magnetization states have been observed after the sample was annealed at T=220°C with a field strength of 1T under high vacuum because of different interlayer coupling fields ($H_{int}$) in the top and bottom CoFe/IrMn based spin-valves ($H_{int}$ is about 12.2Oe in the top CoFe/IrMn spin-valve and 29.3Oe in the bottom one). In a sample with a structure of substrate/$Ta_5$/$NiFe_2$/$CoFe_{1.5}$/$Cu_{2.6}$/$CoFe_2$/$FeMn_1$0/$Ta_5$ /$Al_2O_3$5/$Ta_5$/$NiFe_2$/$CoFe_{1.5}$/$Cu_{2.6}$/$CoFe_2$/$IrMn_8$/$Ta_5$, since the blocking temperature of the CoFe/FeMn based spin-valve ($T_b$ ∼150°C) is lower than that of CoFe/IrMn based spin-valve ($T_b$ ∼230°C), the spins can be easily engineered and therefore various magnetoresistance states can be obtained when the sample is magnetically annealed at different temperatures in a proper annealing sequence. The unique magnetoresistance effect observed in this structure is essentially different from that in a simple dual spin-valve. By properly selecting materials and controlling the magnetically annealing conditions, multilevel giant magnetoresistance (MR) magnetic random access memory (MRAM) cell can be realized, which will significantly improve the MRAM data storage density without increasing any additional processing complexity.

**T3.2**

LASER ABLATED PURE NON-CRYSTALLINE Co THIN FILMS FOR INDUCTORS FOR ULTRA-HIGH FREQUENCIES.

Vicente Madurga, Jose Vergara and Cristina Favieres, Universidad Publica de Navarra, Pamplona, SPAIN.

Co thin films have been prepared by pulsed laser ablation. A Neocera chamber, kept at $10^{-5}$ mbar, was used for the deposition. A circular pure Co disk rotating at 32 rpm was used as the target. The films were deposited on glass, Si, and copper thin film, substrates. The substrates were kept at room temperature during the deposition time of 30 minutes producing samples ≈460 nm thick. These pure Co thin films exhibited a grazing incidence x-ray diffractogram without the characteristic crystalline peaks. The transversal Magneto-Optic Kerr Effect of these samples shown a weak in plane magnetic anisotropy, anisotropy field Han ≈ 10 Oe. An easy direction coercive field of 0.6 Oe was measured. From the Vibrating Sample Magnetometer measurements this soft magnetic behavior was confirmed. The spontaneous magnetization of these films at room temperature was ≈1.0 Tesla. The Bitter technique allowed us to observe the Neel type magnetic domain walls of these samples. After annealing at 900 °C the samples exhibited a Curie temperature of ≈1180 °C and a spontaneous magnetization at room temperature close to 1.8 Tesla. The extrapolated to zero K resistance of these films decreased one order of magnitude from the as deposited samples to the crystallized heated at 900 °C ones. A trilayer Co/Cu(0.8 $\mu$m)/Co on Si substrate was fabricated. Because the resistivity of the deposited Co was ≈40 times higher than that of Cu, no insulation layers between the Co and Cu films were needed. Practically constant inductance and resistance versus frequency until 1.1 GHz were observed. An inductance enhancement due to the magnetic film of ≈ 12 nH/cm was achieved.

**T3.3**

MAGNETOSTRICTION AND MICROSTRUCTURE OF AS-DEPOSITED AND ANNEALED Co THIN FILMS.

Winfried Brückner, Michael Hecker, Jürgen Thomas, Detlev Tietjen, Claus M. Schneider, Institute of Solid State and Materials Research, Dresden, GERMANY.

Cobalt thin films are used as ferromagnetic layers in magnetic multilayers, e.g. Co/Cu multilayers. For comparative investigations, studies on single layers or film configurations with relatively thick individual layers are of interest. The present contribution deals with the correlation of magnetostriction and microstructure of 400 nm thick Co single films. The magnetostriction $\lambda$ was determined by laser-optical substrate-curvature measurements in magnetic fields $\mu_0$H up to 400 mT parallel ($\lambda_{par}$) and perpendicular ($\lambda_{perp}$) to the cantilever beam. The sputtered films were annealed at $T_a$=150, 250, 350, and 450°C for 2 h in high vacuum in connection with stress vs. temperature measurements for obtaining information about kinetics of occurring microstructural processes. The microstructure (phase, texture, grain size) was characterized by x-ray diffraction and transmission electron microscopy. In the as-deposited state and up to $T_a$=150°C, the films reveal at 25 mT nearly (≈90%) saturation magnetostriction of a predominant soft-magnetic component ($\lambda_{par}$=-13×$10^{-6}$ and $\lambda_{perp}$=5×$10^{-6}$). The hysteresis of the $\lambda(\mu_0H)$ curves corresponds to the MOKE curves. Beginning at $T_a$=250 °C and more pronounced at $T_a$=350 and 450°C, the $\lambda(\mu_0H)$ curves do not saturate even up to 400 mT. In this case, $\lambda_{par}$ and $\lambda_{perp}$ amount to about -33×$10^{-6}$ and -42×$10^{-6}$, respectively, the same sign indicating a high volume magnetostriction. The change of the magnetic and magnetostriction behavior at about 250°C is correlated to grain growth. With this grain growth, the grain orientation changes from a nearly statistical distribution to a nearly complete orientation of the hexagonal axis perpendicular to the film plane. The results of the magnetostriction measurements are compared to literature data for Co bulk material with different crystallographic directions. Future investigations will show whether similar microstructural changes in Co-containing multilayers also exist and contribute to the deterioration of the magnetoresistance during annealing at elevated temperatures.

**T3.4**

MICROSTRUCTURE AND MAGNETIC PROPERTIES OF Co-CoO NANOCOMPOSITE FILMS.

Jae Young Yi, M.L. Rudee, Univ of California-San Diego, MS&E, La Jolla, CA.

We studied exchange anisotropy effects on the magnetic properties of nanosize Co particles as potential applications for magnetic storage media. The possibility of enhancing thermal stability and magnetic properties of nanosize ferromagnetic (FM) particles by exchange coupling was investigated. FM Co and antiferromagnetic (AFM) CoO nanocomposite thin films were fabricated by co-sputtering from separate Co and CoO targets. Sputtering conditions were carefully controlled to obtain the desired film compositions. (111) textured CoO and hcp Co phases were observed in x-ray diffraction (XRD) patterns. No conclusive evidence for fcc Co phase was found in the Co-CoO specimens. The crystallite sizes of the CO and CoO calculated from XRD peak broadening were 3∼6 nm and 7∼10 nm, respectively, and proportional to the volume fraction. A broken columnar structure was observed in cross-section transmission electron microscopy images. Each column was believed to be consisted of metal and oxide crystallites. Large exchange anisotropy fields ($H_e$) - compared to bilayer structures and linear type temperature dependence of $H_e$ - were observed in all specimens after field cooling. Very large coercivities were observed at low temperatures due to the exchange coupling. The origin of enhanced coercivity at room temperature was believed to be due to shape anisotropy as well as possible local exchange couplings. The anisotropy energy barrier of the Co was examined by thermoremanent moment (TRM) measurements. A slow decrease with temperature and large TRM at room temperature indicated that the exchange coupling significantly modified the anisotropy energy barrier of the Co crystallites in the CoO matrix. Supported, by NSF Grant DMR-9400439.

**T3.5**

ON THE IRON MANGANITES SYNTHESIS BY THE SOFT CHEMISTRY METHOD.

H. Coradin, S. Guillemet-Fritsch, F. Agnoli, P. Tailhades, A. Rousset, CIRIMAT, UMR CNRS, Universit Paul Sabatier, Toulouse, FRANCE.

Manganese iron oxides with spinel structure find applications in magnetic recording media and electronic devices. Previous work carried on in our Laboratory have shown that it is possible to enlarge the well known properties of these materials, using nanoparticles synthesized by soft chemistry method at low temperature. Recently, the interest of these materials has greatly increased with the discovery of hard magnetic properties in metastable manganese ferrites, while the same ferrites in bulk form are well known to be soft magnetic materials. The aim of this work is to study the iron manganites ($Mn_{3-x}$)$Fe_x$O4) synthesis by soft chemistry method. Oxalate precursor powders of these materials with controlled shape and nanoscopic size are prepared. The main difficulty is to obtain single phase oxides with high Mn content (0.4 < x < 1.3). Only few works have been published on the synthesis of such spinel at low temperature, probably because of the difficulties to obtain the stoechiometric spinel, the weak crystallinity of the samples and the immiscibility gap described by Mason for the natural "wredenburgite". The oxalate precursors are heat treated with a $H_2$/$H_2O$/$N_2$ gas mixture (T < 600°C). The resulting stoechiometric spinel is a metastable phase with high specific surface area and is highly reactive toward oxygen. Therefore, information about the valence states of Mn ions can be obtained by thermogravimetric analysis. This oxide is oxidized in air at low temperature (T < 350°C), in order to produce mixed valence defect manganites $Fe_x$)$Mn_{3-x}$)O(4 d) with a good reproductibility. Although, some problems persist for the higher Mn contents, as the oxygen partial pressure for the reduction must be controlled precisely in order to produce the stoechiometric spinel at low temperature. A low temperature reduction system with oxygen partial pressure controlled by oxygen electrochemical pumping will be developed.

**T3.6**

MODIFICATION OF THE MAGNETIC PROPERTIES OF LONGITUDINAL THIN-FILM MEDIA BY ION-BEAM IRRADIATION.

Jason D. Wright, University of California at Berkeley, Dept of MS&E, Berkeley, CA; Kannan M. Krishnan, Lawrence Berkeley National Laboratory, Materials Science Division, Berkeley, CA.

The modification of conventional longitudinal recording media by ion-beam irradiation is of both scientific and technological interest. In particular, patterning by irradiation through a stencil mask at the 50 nm length scale may fulfill the promise of a commercially viable patterned media architecture. In this context, the magnetic properties and microstructural evolution of high-coercivity longitudinal thin film media were investigated after ion-beam irradiation. TRIM simulations were used to calculate the depth profiles as a function of energy and dose for carbon, nitrogen, and chromium ions and three different

commercial media. Corresponding implantations were carried out and hysteresis curves were measured using a vibrating sample magnetometer (VSM). Using chromium ion implantation at 20 keV, both remanence and coercivity were reduced to zero, i.e., rendering the ferromagnetic thin film paramagnetic at low doses. For $C^+$ implantation at 20 keV, remanence and coercivity were also reduced to varying extent up to doses of $5 \times 10^{16}$ $cm^{-2}$ after which further irradiation had no effect. Slight decreases in remanence and coercivity were observed for 20 keV $N_{2+}$ irradiation. XRD measurements indicate that the hexagonal cobalt alloy phase remains intact after irradiation despite bombardment damage of the surface, revealed by AFM. Further changes in microstructure, including the depth profile of implanted species, were assessed by TEM. Combined with the development of a suitable stencil mask, such chromium ion implantation can be used to develop a viable patterned media consisting of locally defined ferromagnetic and paramagnetic regions. This work is in progress. Work supported by California State DiMI program in partnership with Seagate Technology.
Work at LBNL was supported by DoE under contract number DE-AC03-76SF00098.

### T3.7

IMPROVEMENT OF CRYSTALLOGRAPHIC CHARACTERISTICS OF COCRTA THIN FILM USING DOUBLE UNDERLAYER.
K.H. Kim, Y.J. Kim, Kyungwon Univ, School of Electrical & Electronic Engineering, Kyunggi-do, KOREA; S.H. Kong, S. Nakagawa, M. Naoe, Tokyo Institute of Technology, Dept of Physical Electronics, Tokyo, JAPAN.

Highly c-axis oriented CoCr-based thin films are expected for ultra-high density recording media in perpendicular magnetic recording system. In order to improve dispersion angle of c-axis of CoCr-based thin film for perpendicular magnetic recording media, we prepared trilayered with double underlayer using New Facing Targets Sputtering apparatus. The thickness of magnetic layer CoCrTa and double underlayer, such as interlayer Pt, paramagnetic CoCr, underlayer Ti was fixed 50nm, 20nm, respectively, In order to prepare the thin film, we fixed argon gas pressure 1mTorr, substrate temperature 250°C and input current 0.5A. The crystallographic characteristics of CoCrTa layer with varying interlayer thickness(0-20nm) have been investigated. By the result, the CoCrTa trilayered thin film with interlayer Pt showed good c-axis orientation 3.45°, 3.62° at thickness 5nm, 10nm, respectively. However, CoCrTa thin film using interlayer paramagnetic CoCr showed 8.28°, 8.62° at thickness 5nm, 10nm, respectively.

### T3.8

TANTALUM OXIDE AS A LOW HEIGHT TUNNEL BARRIER FOR MAGNETIC JUNCTIONS.
P. Rottländer, M. Hehn, O. Lenoble, F. Montaigne, A. Schuhl, Laboratoire de Physique des Matériaux, Nancy, FRANCE.

Magnetic tunnel junctions with a thick barrier of low height consisting of tantalum (Ta) oxide were prepared by plasma oxidation of sputter-deposited tantalum. We have studied their magneto-transport properties as a function of thickness, oxidation time and oxidation power of the Ta layer. Barrier heights determined using the Brinkman formula are of some 0.4∼eV and thicknesses of 2.5 – 3.0∼nm for a sputtered 1.4∼nm Ta layer. This high thickness can be explained by comparing the bulk densities of metallic Ta and stoichiometric $Ta_2O_5$. This barrier height was independently confirmed by measuring current - voltage characteristics I(V) as a function of temperature T. Then plotting $[I(V,T) - I(V,0)]/I(V,0)$ as a function of $V$ produces cusps at voltages corresponding to the barrier height. Magnetoresistance (MR) ratios of 2.5% at room temperature and 4% at low temperatures could be observed. The MR ratio is reduced to half of its maximum value at bias voltages of about 0.2∼V at room temperature (0.23∼V at 80∼K), which is much lower than for aluminium oxide. Over or under oxidation of the barrier reduces the TMR signal and gives rise to a considerable noise in the junctions. Especially in apparently over oxidized junctions, the barrier asymmetry of the Brinkman fit depends on the voltage being varied from negative to positive or vice versa. It is attributed to weakly bound ions moving in a $Ta_2O_5$ matrix driven by the electric field across the barrier. This movement can be frozen at lower temperatures and so voltage induced barrier asymmetry can be studied. The low barrier heights of Ta oxide gives the possibility to substantially increase the barrier thickness, as compared to aluminium oxide, and so to decrease the coupling between the ferromagnetic layers as we were able to demonstrate. Furthermore, the low barrier makes it possible to safely study the field emission regime with applied voltages up to two or three times the barrier height.

### T3.9

CoB/Pd MULTILAYER BASED RECORDING LAYERS FOR PERPENDICULAR MEDIA.
Dmitri Litvinov, Mei-Ling Wu, Timothy Klemmer, J. Kent Howard, and Sakhrat Khizroev, Seagate Research, Pittsburgh, PA.

As the storage industry ramps the areal bit densities at increasingly higher rates, thermal instabilities in recording media begin to manifest themselves. Perpendicular recording technology while being technically close to conventional longitudinal recording and the least difficult technology to make the transition to if necessary, addresses the issue of thermal stability for areal bit densities exceeding 100Gbit/in$^2$. Co and Co-alloy based multilayers [1,2] are among the candidates for perpendicular recording media because they exhibit high remanent squareness and easily controlled magnetic anisotropy with both aspects being critical for the thermal stability.
The results of an experimental study of CoB/Pd multilayer based recording layers for perpendicular recording media are presented. CoB/Pd multilayers were deposited by magnetron sputtering from CoB and Pd targets onto glass substrates on an indium tin oxide (ITO) seed layer. The sputtering was done in Kr at 30mTorr. The films exhibited strong perpendicular anisotropies with the coercivities of as deposited films ranging from 3.8 to 7 kOe. Microstructural studies revealed that the films were composed of grain clusters (columns) of ∼15nm diameter isolated by lower density regions potentially serving as an exchange de-coupling material.
Cross-sectional TEM showed that the columns were not completely separated throughout the thickness of the film, but rather continuously coupled to about 1/4 of the column height. No measurable crystalline texture was observed using X-ray diffraction, which further supports the view that the anisotropy arises purely from interfacial effects in the multilayer films.
Aging studies were conducted and showed that, under appropriate conditions, it is possible to achieve a reduction of exchange coupling between the magnetic columns. A comparison between microstructural and magnetic data for as-deposited and aged multilayer films is presented.

1. K. Ho, B.M. Lairson, Y.K. Kim, G.I. Noyes, and S. Sun, “Recording at 300kfci with Perpendicular Co-alloy Multilayers,” IEEE Trans. Magn. 34, 1854 (1998).
2. K. Takano, E. Fullerton, G. Zeltzer, A. Moser, and D. Weller, “CoCr/Pt and CoB/Pt multilayers as perpendicular recording media,” presented at MMM Conference in San Jose (1999).

### T3.10

TUNNELING MAGNETORESISTANCE IN $Ni_{0.8}Fe_{0.2}/LaAlO_3/La_{0.7}Ca_{0.3}MnO_3$ TUNNEL JUNCTIONS.
Jaeyoung Choi, Srinivas V. Pietambaram, Rajiv K. Singh, Department of MS&E, University of Florida, Gainesville, FL; Hyoung-june Kim, Department of Materials Science and Metallurgical Engineering, Hongik University, Seoul, KOREA.

One of the distinguished features of $La_{0.7}Ca_{0.3}MnO_3$ (LCMO) is a ferromagnetic half-metallic state, where only the single spin band crosses the Fermi level. Such a half metallic state can lead to 100% spin polarization of conduction carriers, which is much higher than that of typical ferromagnetic metals such as Co, Ni, or Fe and their alloys. One way of taking advantage of this highly spin polarized nature of these manganites is a spin-dependent tunneling magnetoresistance (TMR) of a magnetic tunnel junction (MTJ), since the TMR ratio depends on the spin polarizations of the two electrodes. Recently, TMR ratios up to 400% have been reported in LSMO/STO/LSMO trilayer structure at low temperature (10 K). Despite of these large TMR values, the obstacle in these systems is that large TMR values are observed at temperatures below 100 K, rapidly vanishing at higher temperatures. Since this temperature is far below the Curie temperature of these manganites ($T_c$ of LCMO and LSMO are approximately 270 K and 370 K, respectively), this premature decrease of TMR brings an important issue for understanding as well as practical applications of these systems. Even though the cause of the rapid TMR loss with temperature is not understood at this moment, the existence of surface dead layer with depressed magnetic order at elevated temperatures is suspected. Since the magnetic properties of these materials are highly sensitive to local crystal properties and the extrinsic strain field induced by lattice mismatch among the grown layers, combination of selected material species, their crystal integrity, and thickness of insulators will be critical for improving the TMR values as well as their temperature dependency. In this paper, we report our studies on the growth, and magnetotransport properties of $Ni_{0.8}Fe_{0.2}/LaAlO_3$ (LAO)/$La_{0.7}Ca_{0.3}MnO_3$ (LCMO) films grown on (100) LaAlO3 substrate as a function of deposition conditions and insulator layer thickness. LCMO and LAO films are grown using a pulsed laser deposition system while NiFe films by sputtering. The films were then lithographically patterned into an MTJ structure and the TMR was measured using superconducting quantum interference magnetometer (SQUID). The effect of deposition temperature, thickness of the barrier layer and post annealing treatments on the TMR values will be discussed in detail.

### T3.11

$YBa_2Cu_3O_7/RE_{1-x}Sr_xMnO_3$ SUPERLATTICES FOR OXIDE

ELECTRONICS. P. Przyslupski[1,2], S. Kolesnik[1,2], I. Komissarov[2], E. Dynowska[2], T. Skoskiewicz[2], and B. Dabrowski[1]. [1]Department of Physics, Northern Illinois University, DeKalb, IL. [2]Institute of Physics, Polish Academy of Sciences, Warszawa, POLAND.

Colossal magnetoresistance (CMR) compounds gained the scientific interest over last few years as materials promising for future oxide electronics applications. The crystal structure of the CMR manganites is similar to that of the perovskite high-temperature superconductors. Therefore, the fabrication of ferromagnetic-superconductor (F/S) heterostructures of both classes of the materials is possible. Ferromagnetic-superconductor superlattices consisting of stacks of alternating ferromagnetic and superconducting layers give rise to novel phenomena. Depending on the relative thickness of F and S layers, one would expect either ferromagnetic or superconducting ground state. Coexistence of ferromagnetism and superconductivity in such structures can also be considered. Proximity effect at the F/S boundary is one of the most interesting properties of F/S superlattices. We report on the magnetic studies of $YBa_2Cu_3O_7$/ $RE_{1-x}Sr_xMnO_3$ (RE = Nd, La, Pr) superlattices. The superlattices have been fabricated by high-pressure dc sputtering method. A series of superlattices with fixed $YBa_2Cu_3O_7$ thickness and varying $RE_{1-x}Sr_xMnO_3$ thickness has been prepared. The presence of superstructure-related satellite peaks in the X-ray diffraction spectra indicate good quality of the obtained superlattices. Magnetization measurements have been carried out for different magnetic field orientations. The superconducting critical temperature of the superlattices decreases on increasing the ferromagnetic layer thickness. Magnetization hysteresis curves measured above the superconducting transition temperature show that the easy axis orientation for the magnetization is either in-plane or out-of-plane, depending on the thickness of the $RE_{1-x}Sr_xMnO_3$ layer. The possibility of the tailoring the magnetic anisotropy of $YBa_2Cu_3O_7/RE_{1-x}Sr_xMnO_3$ superlattices could be useful for future applications as active elements of non-volatile magnetic memory or magnetic field sensors.
Work supported by the ARPA/ONR and the State of Illinois under HECA. Partial support from the Polish Committee for Scientific Research (KBN) under grant No. 2 P03B 10714 is acknowledged.

**T3.12**
COMBINATORIAL ION IMPLANTATION AND MAGNETIC MEASUREMENT OF MATERIAL LIBARARIES IN III-V-BASED MAGNETIC SEMICONDUCTOR. Chang Ming Chen, T. Hasegawa, K. Inaba, X.J. Fan, J. Kasai, Tokyo Inst of Tech, Yokohama, JAPAN.

The success in fabrication of diluted magnetic semiconductor and injection of spin into electronics greatly extended the frontier towards spin-based devices. In order to take advantage of spin-related phenomena in semiconductors, creation and manipulation of the spin polarization of carriers is critical for device application. One way to achieve this goal is discovery of novel magnetic semiconductor with high magnetism in a wide temperature range and good interface with semiconductor. In this paper, we will first report the employment of combinatorial ion implantation to rapidly preparation of materials libraries in III-V-based semiconductor, in a combination of high-throughput magnetic characterization using conventional SQUID and scanning SQUID microscopy. Ion implantation is a non-equilibrium process, where the doping atoms get driven into the solid by a violent use of their excess kinetic energy. In this way, high concentration of magnetic element in semiconductor host or high oriented magnetic nanocrystallites that is unattainable by more conventional methods may be formed. We perform an implantation of Fe and Mn with various doses into GaAs substrate in a combination of combinatorial approach, which increases the possibility of novel material discovery. Following different annealing processes, we gain an understanding of the material's structure-property relationship. We also report effect of UV light irradiation on magnetism of the libraries, which is an alternative way to manipulate spin production.

## SESSION T4/U3: JOINT SESSION HARD FERRITES/COLOSSAL MAGNETO-RESISTANCE MATERIALS
Wednesday Morning, April 18, 2001
Golden Gate B3 (Marriott)

**8:30 AM *T4.1/U3.1**
ATOMIC AND NANOENGINEERED FERRITE SYSTEMS: NEW HORIZONS IN LOW DIMENSIONS. V.G. Harris, Naval Research Laboratory, Washington, DC.

Spinel ferrites are attractive materials for high frequency (1 MHz $\leq f \leq$ 500 MHz) applications where low core losses are essential. Further, these materials are the only low-loss magnetic materials available for microwave frequency ($f \geq$1 GHz) applications. An essential property of the ferrites is their insulating properties that limit eddy current losses and other forms of conduction losses. Other attractive properties are their high permeability, low anisotropy fields, low FMR linewidths, and low magnetostriction. However, their ferrimagnetic nature limits their intrinsic magnetization. This has the effect of limiting the power loads and efforts to reduce component size at the MHz frequencies, and their broadband utility at the microwave. In recent years, trends in ferrite research have involved processing of ferrite nanoparticles for core fabrication for MHz frequencies, and as films for monolithic magnetic integrated circuits for nonreciprical microwave devices. In both cases the ferrites are processed in low dimensional form where surface phenomena dominate (in nanoparticles), and nonequilibrium processing conditions in films. In this paper, we discuss the nature of nonequilibrium cation inversion (i.e. disorder) in particle and film systems and its effect on the magnetic, electronic and loss characteristics. This discussion will address the challenges associated with the atomic design of ferrite systems, as well as nanoengineering of composites designed to overcome the intrinsic limitations of ferrite systems.

**9:00 AM T4.2/U3.2**
DIRECT AND REAL-TIME OBSERVATION OF SUB-MICRON DOMAIN DYNAMICS IN MAGNETICALLY BIASED STRONTIUM FERRITE PERMANENT MAGNETS BY ROOM TEMPERATURE SCANNING MICRO-HALL PROBE MICROSCOPY. A. Sandhu, N. Iida, Tokai Univ, Dept of Electrical Engineering, JAPAN; H. Masuda, Toei Kogyo Ltd, Tokyo, JAPAN; A. Oral, Bilkent Univ, Dept of Physics, TURKEY; S.J. Bending, Univ. of Bath, Dept of Physics, UNITED KINGDOM.

The development of ferromagnetic materials for high performance permanent magnets requires a fundamental understanding of the behavior of magnetic domains in external bias fields. We have developed a new room temperature scanning micro-Hall probe microscope (RT-SHPM) system for such purposes and will report on the imaging of domain movement in Sr ferrite permanent magnets (SFM) in external bias fields. The RT-SHPM system enables the highly sensitive, extremely fast, non-invasive, and quantitative measurement of localized surface magnetic fields on the micron-scale. A 0.8 x 0.8 $\mu$m GaAs/AlGaAs micro-Hall probe (300K Hall coefficient =0.3$\Omega$/G and field sensitivity=0.04 G/$\sqrt{Hz}$) with an integrated STM tip for precise vertical positioning was used as a magnetic field sensor. External bias fields (Hex) of up to 3000 Oe were applied in steps of 400 Oe parallel to the easy and hard axes of carefully polished 400 $\mu$m thick thermally demagnetized Sr ferrite permanent magnets (Hc=2570 Oe; Br=2870 G). 50x50 $\mu$m areas were imaged at a height of 0.3 $\mu$m above the SFM surface for each Hex, with scan speeds of $\sim$1 frame/second enabling almost real-time imaging in synchronization with bias field changes. RT-SHPM imaging for Hex applied along the easy axis of SFMs showed (i) the existence of 8-15 $\mu$m sized domains with a surface magnetic field of $\pm$226G at Hex=0; (2) domains to move only above a critical bias field of $\pm$700 Oe; (3) the measured surface magnetic field to decrease with increasing bias fields to a value of 170 G at Hex=3000 Oe. The details and physical interpretation of these and related results for bias fields along the hard direction and imaging during demagnetization of the SFM from the remanent state will be discussed. Our results demonstrate the RT-SHPM system to be a valuable tool for the quantitative study of micro-magnetic phenomena in ferromagnetic materials.

**9:15 AM T4.3/U3.3**
ADVANCES IN THE LOW TEMPERATURE PREPARATION OF LANTHANUM STRONTIUM MANGANITE POWDERS. Sophie Guillemet-Fritsch, Herve Coradin, Patricia Baradat, Philippe Tailhades, Abel Rousset, CIRIMAT/LCMIE, Universite Paul Sabatier, Toulouse, FRANCE.

In recent years, the doped perovskite lanthanum strontium manganites have attracted much attention due to the colossal magnetoresistance (CMR) properties. It has been shown that the microstructure, and especially the grain size, plays a significant role on the intrinsic CMR properties. So the synthesis methods are very important for obtaining polycrystalline materials with special microstructure. In the present work perovskite-type compounds of general formula $La_{1-x}Sr_xMnO_3$ were prepared by the thermal decomposition of precursor powders. Two different kinds of precursors, carbonates and citrates have been prepared by low temperature, i.e. "Chimie douce" technique. The careful control of the chemical and the hydrodynamic parameters during the synthesis process allows to obtain small particles (30 nm for citrates)and narrow size distribution. A pure perovskite phase is observed after a low temperature thermal treatment, starting from 550°C. The structure is a function of the strontium content and the temperature. Moreover it depends also on the nature of the precursors used. It has been suggested that this behavior results from the different atmosphere due to the release of $CO_2$, CO and $H_2O$ species during the decomposition process. The "Chimie douce" technique is a powerful tool to control the particle size and the surface area but also to a certain extent the structure of such perovskite materials.

**9:30 AM T4.4/U3.4**
Abstract Withdrawn.

**9:45 AM T4.5/U3.5**
CRYSTAL STRUCTURE AND MAGNETIC PROPERTIES OF THE DOUBLE PEROVSKITE $(Sr_{2-x}Ca_x)FeMoO_6$. Ting-Shan Chan[1], Ru-Shi Liu*,[1] , Chih-Hung Shen [1], Ravi Gundakaram[1], Jauyn Grace Lin[2], Chao-Yuan Huang[3], Jin-Ming Chen[4], Ling-Yun Jang[4]. [1]Department of Chemistry, National Taiwan University, Taipei, TAIWAN. [2]Center for Condensed Matter Sciences, National Taiwan University, Taipei, TAIWAN. [3]Center for Condensed Matter Sciences, Department of Physics and Department of Electrical Engineering, National Taiwan University, Taipei, TAIWAN. [4]Synchrotron Radiation Research Center, Hsinchu, TAIWAN.

A new series of ordered double perovskite oxides $(Sr_{2-x}Ca_x)FeMoO_6$ displaying colossal magnetoresistance has been synthesized by solid state reaction. A monotonous decrease of the lattice constants ($a$ and $c$) has been found with increasing x, which arises from the variation of chemical pressure in the compounds. This result is consistent with the fact that the $Ca^{2+}$ ion is smaller than the $Sr^{2+}$ ion. The resistivity decreases with increasing x, showing that the hole concentration may increase due to the application of chemical pressure. Moreover, the growth of the particle size with increasing Ca doping has also been observed. The valence states of Fe and Mo was determined by the X-ray absorption near-edge structure (XANES) and extended fine structure (EXAFS) spectroscopies at the Fe and Mo edges. The results compared to the standard samples show that the valence states of Fe ($3d^5$) and Mo ($4d^1$) are $^{3+}$ and $^{5+}$ respectively. Based on our studies, we can understand that the chemical pressure is an important factor in controlling the colossal magnetoresistance in the new ordered double perovskite oxide series $(Sr_{2-x}Ca_x)FeMoO_6$.

**10:30 AM *T4.6/U3.6**
CRITICAL-STATE PHASE-CONTROL IN COLOSSAL MAGNETORESISTANCE MATERIALS. Y. Tokura, Tsuoshi Kimura, Department of Applied Physics, University of Tokyo, Tokyo, JAPAN, and Joint Research Center for Atom Technology (JRCAT) and Correlated Electron Research Center (CERC), Tsukuba, JAPAN.

Control of electronic parameters via modifications of composition, structure, and lattice strain in perovskite type manganese oxides produces novel magnetoelectronic properties, including colossal magnetoresistance (CMR). Close interplay among spin, charge, orbital, and lattice is responsible for this, producing rich and complex electronic/magnetic/orbital phases. With use of order-disorder phenomena in the charge and orbital sectors, unconventional phase control is also possible, such as photo- and current-induced insulator-metal and/or antiferromagnetic-ferromagnetic transitions. Recent results of such an study on single crystals and thin films of CMR oxides are presented.

**11:00 AM T4.7/U3.7**
THE INFLUENCE OF SINGLE GRAIN BOUNDARY JUNCTIONS ON THE MAGNETORESISTANCE IN GRANULAR PEROVSKITE MANGANITE FILMS. Robert Gunnarsson, Zdravko Ivanov, Chalmers Univ of Technology, Dept of Microelectronics and Nanoscience, Gothenburg, SWEDEN; Roland Mathieu, Peter Svedlindh, Dept of Materials Science, Uppsala Univ, Uppsala, SWEDEN.

We have examined single grain boundary junctions (GBJs) as well as GBJ arrays in Sr-doped (33%) lanthanum-manganite thin films. The films were deposited by pulsed laser deposition (PLD) on symmetric bi-crystals with 8.8o, 18.4° and 45° misorientation angles. Microbridges, with a width of a few hundred nanometers and crossing the artificial grain boundary of the bi-crystal, were patterned by Ar-ion milling through a resistive mask. Magnetoresistance and noise measurements of the GBJ were performed in a wide range of temperatures and magnetic fields. The measurements on single GBJ reveal a switching, i.e. steps in the magnetoresistance near the coercive field. We show that the switching originates from the magnetic domain structure of the bridge at the bi-crystal interface. With a multi-domain model the magnetoresistive behaviour of a single junction can be described. The noise measurements show that the grain boundary noise, which has a Debye-Lorentzian frequency-dependence, is additional to the normal 1/f-noise seen in bulk perovskite manganites.

**11:15 AM *T4.8/U3.8**
ANISOTROPIC MAGNETOCALERIC EFFECT IN NANO STRUCTURED MAGNETIC CLUSTERS. X.X. Zhang, Department of Physics, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, CHINA.

We have systematically studied the magnetic entropy change, -DSM (H,T), in the Fe8 molecular crystals in a wide temperature range. Since the Fe8 crystals are composed of a huge number of (Avogadros constant) identical, non-interacting, aligned, anisotropic magnetic clusters with spin 20mB, it is a model system for the study of the fundamental properties of the nanostructured magnetic materials. The isothermal magnetization curves have been measured at the different angles between the applied magnetic field and the magnetic easy axes of the clusters. From the isothermal magnetization data, the temperature and field dependence of the magnetic entropy change or magnetocaloric effect (MCE) have been obtained. It is found that the magnetic anisotropy ploys a very important role in the determination of the magnetocaloric effect.
The maximum and minimum MCE are observed when the applied magnetic fields are parallel and perpendicular to the easy axis respectively in the whole temperature range. The magnetic entropy change and other properties of a system composed of isotropic magnetic clusters have been obtained by the numerical methods in order to illustrate the magnetic anisotropy effect.

**11:45 AM T4.9/U3.9**
NANOSCALE MAGNETIC DOMAIN STRUCTURE IN COLOSSAL MAGNETORESISTANCE MATERIALS ISLANDS. Yan Wu and Yuri Suzuki, Department of MS&E, Cornell University, Ithaca, NY.

The doped perovskite manganites have received an enormous amount of attention recently because they exhibit colossal magnetoresistance (CMR) and may be half metallic, with complete spin polarization at the Fermi level. The magnetic and magnetoresistive responses are extremely sensitive to lattice strain and thus to structural distortion. As a result many groups have studied partially and fully strained CMR films. We have chosen to study the effects of strain in CMR islands where we can tune the strain state through variation of island aspect ratio. We have fabricated sub-micron sized islands of $La_{0.7}Sr_{0.3}MnO_3$. Magnetization loops indicate a characteristic field that reflects shape anisotropy effects. We have used magnetic force microscopy to image the magnetic domain states of these individual islands in zero field after saturation in different directions. The stripe magnetic domain states that we observe are a result of the competition among shape anisotropy, strain anisotropy, magnetocrystalline anisotropy and magnetostatic energies. The evolution of domains in a magnetic field reveals the importance of shape anisotropy as well as magnetostriction in determining the micromagnetics in such small CMR structures. Our understanding of the micromagnetics provides a foundation for the analysis and implementation of thin film magnetoresistive devices made of this class of materials.

SESSION T5: DEVICES
Chair: William C. Black
Wednesday Afternoon, April 18, 2001
Golden Gate C3 (Marriott)

**1:30 PM *T5.1**
ELECTRON SPIN RESONANCE TRANSISTORS, FOR QUANTUM COMMUNICATION AND COMPUTING. Eli Yablonovitch, UCLA, Los Angeles, CA.

We apply the full power of modern electronic band structure engineering and epitaxial heterostructures to design a transistor that can sense and control a confined electron spin. Spin resonance transistors may form the technological basis for quantum information processing in the new century. This new type of transistor will be similar in size to the transistors on the SIA Roadmap, but their design will emphasize the manipulation of the electron spin on a single donor ion in the gate insulator. The SPIN TRANSISTOR is expected to be the enabling device for quantum information processing, and quantum communication. One and two qubit operations are performed by applying a gate bias. The bias electric field pulls the electron wave function between layers of different alloy composition. Owing to the variation of the g-factor (Si:g=1.995, Ge:g=1.563), this displacement changes the spin Zeeman energy, allowing single-qubit operations. By displacing the electron even further, the overlap with neighboring qubits is affected, which allows two-qubit operations. Certain Silicon-Germanium and III-V alloys allow a qubit spacing as large as 200 nm, which is well within the capabilities of current lithographic techniques. We discuss the possible extensions of these concepts to semiconductor quantum communication based on spin-dependent selection rules in spin-dependent opto-electronic transceivers.

**2:00 PM T5.2**
INHOMOGENOUS CURRENT DISTRIBUTION IN MAGNETORESISTIVE TUNNEL JUNCTIONS. Yun Li, Stanford University, Department of MS&E, Stanford, CA; R.J.M. van de

Veerdonk, Jian Chen, Janusz Nowak, Seagate Technology, Inc, Bloomington, MN.

Magnetoresistive tunnel junction is a great candidate for magnetic reading when the magnetic recording density goes beyond 100 Gbit per square inch. However, in order to compete against the current technology, GMR spin valve, the resistance area product (RxA) has to be reduced to ~10 Ohm.um2 range for the impedance match. In the low resistance area product regime as junction areas decrease, the tunneling magnetoresistance (TMR) increases the apparent RxA decreases. The junction size effects are attributed to the inhomogeneous current distribution in electrodes and/or inside the junction area. The effect is noticible when junction resistance is comparable or lower than the electrode resistance. A one-dimensional analytical solution is given for a two-terminal configuration. In addition, two-dimensional finite element calculations were performed for a four-terminal cross strip geometry. From the modeling work, it is clear that the measured TMR is always lower than the intrinsic TMR and the measured RxA is always higher than the intrinsic RxA.

**2:15 PM T5.3**
GROWTH OF NiFe AND CoFe ALLOYS ON ALUMINUM OXIDE IN MAGNETIC TUNNEL JUNCTIONS. J.M. Slaughter, R. Whig, G. Steiner, J. Janesky, and S. Tehrani, Motorola Labs, Physical Sciences Research Laboratories, Tempe, AZ.

The tunneling and magnetic properties of high-quality magnetic tunnel junction (MTJ) material with ultra-thin top magnetic layers have been used to study the growth of Ni(81)Fe(19), several CoFe alloys, and Co on the amorphous aluminum oxide tunnel barrier. Studies of bottom-pinned MTJs with varying free layer thickness, from 5 $\AA$ to 40 $\AA$, show systematic changes in the junction resistance, Neel coupling, loop shape, and tunneling magnetoresistance which are used to determine the growth mode of the free layer. Maximum MR values are 30% to 50% depending on the materials. Our data show that the free layer typically nucleates as superparamagnetic islands which coalesce to form a continuous film between 9 and 15 $\AA$. The MTJ situation is quite different from GMR spin valve growth in which the top magnetic layer is grown on a polycrystalline metal spacer material such as Cu. In the spin valve case, the orientation and texture of the entire stack can be controlled by seed layer(s) at the bottom. In the MTJ case, the barrier interrupts the grain growth and the top layer nucleates on an amorphous surface causing the loss of any epitaxial relationship to the bottom electrode. The crystallinity in turn affects the magnetic properties. For example, CoFe(x) free layers, with x= 0%-18% had high coercivity (Hc) when grown directly on the AlOx but had quite low Hc and high Hk when a thin layer of NiFe is used as a template. Results for several alloys and templates are reported. The implications for MRAM and read head technology are discussed.
This work supported in part by DARPA.

**2:30 PM T5.4**
TUNNELING MAGNETORESISTANCE IN PLANAR-TYPE DOUBLE FERROMAGNETIC TUNNEL JUNCTIONS. Yasushi Takemura, Yokohama National University, JAPAN; Jun-ichi Shirakashi, Akita Prefectural University, JAPAN.

An enhancement of tunneling magnetoresistance (TMR) by Coulomb blockade has been observed in low temperature measurements. Small tunnel junctions whose charging energy (e2/2C, C: junction- and self-capacitance) is larger than thermal energy are required for the phenomenon. This requirement of C<0.3aF for room temperature (RT) operation can not be achieved by normally fabricated multilayer-type tunnel junctions, because their junction area is limited by lithography techniques. We have proposed planar-type tunnel junctions fabricated by AFM nano-oxidation technique. When a negative bias is applied on the AFM tip, metals are oxidized by an electrochemical reaction between metals and water in air. The selectively oxidized region can be utilized as a potential barrier of planar-type ferromagnetic tunnel junctions. This AFM oxidation technique also fabricates ferromagnetic electrodes of planar-type junctions with 10 nm order scale. We have calculated the I-V characteristics and TMR ratio in double ferromagnetic tunnel junctions under Coulomb blockade by Monte Carlo analysis. By reversing the magnetization of island (center) electrode parallel/antiparallel to that of side electrodes in double junction, TMR ratio of 24% enhanced by Coulomb blockade is calculated assuming the spin polarization of 0.23 for ferromagnetic electrodes. It is also found that TMR is enhanced at room temperature when the island electrode is smaller than 11 nm. The fabrication of Ni- and NiFe-based nano-structures by AFM oxidation and proposed device structures are also discussed.

**3:15 PM *T5.5**
ANTIFERROMAGNETICALLY-COUPLED MAGNETIC MEDIA LAYERS FOR THERMALLY-STABLE HIGH-DENSITY RECORDING. Eric E. Fullerton, D.T. Margulies, M. Schabes, IBM Almaden Research Center, San Jose, CA; M.F. Doerner, IBM Storage Technology Division, San Jose, CA.

The combination of signal-to-noise requirements, write field limitations, and thermal activation of small particles is thought to limit the potential areal density of the longitudinal media and is commonly referred to as the "superparamagnetic limit". Recording media composed of antiferromagnetically coupled (AFC) magnetic recording layers is a promising approach to extend areal densities of longitudinal media beyond these perceived limits. The recording medium is made up of two ferromagnetic recording layer separated by a nonmagnetic layer whose thickness is tuned to couple the layers antiferromagnetically. For such a structure, the effective areal moment density (Mrt) of the composite structure is given by the difference between the ferromagnetic layers allowing the effective magnetic thickness to scale independently of the physical thickness of the media. This allows AFC media to maintain thermal stability even for low Mrt values. Experimental realization of this concept using CoPtCrB alloy layers that demonstrates thermally stable low-Mrt media suitable for high-density recording will be discussed.

**3:45 PM T5.6**
THE INFLUENCE OF MAGNETIC DIPOLE COUPLING ON THE PERFORMANCE OF TMR ELEMENTS. S. Tegen, I. Mönch, J. Schumann, H. Vinzelberg, C.M. Schneider, O. de Haas, Inst. f. Festkörper- und Werkstofforschung (IFW) Dresden, Dresden, GERMANY.

Tunneling magnetoresistance (TMR) is of increasing technological importance for applications in magnetic sensors or random access memories (MRAM). The magnitude of the conductivity change in a TMR device is determined by the quality of the insulating barrier and the spin polarization at the ferromagnet/insulator interfaces. Equally important, however, is an independent magnetization reversal of the magnetic electrodes which may be affected by any type of interlayer coupling. Of particular importance in this context is the effect of dipolar magnetic coupling (also known as Néel-coupling or "orange-peel" coupling) induced by the interfacial and surface roughness of the layers. We therefore studied the influence of this dipolar coupling in $Co/AlO_x/Ni_{80}Fe_{20}$ TMR layers and contacts. The roughness of the individual layers was directly determined from in-situ STM investigations. We find a close correspondence between the values for the coupling fields determined by MOKE and the ones computed from the Néel-coupling model on the basis of the measured morphology parameters. We also confirm an increase of the dipole coupling between the magnetic layers with decreasing barrier thickness as predicted by the model. Deviations from the theoretical prediction occur for the case of thinner soft magnetic layers. This can be understood by a reduced magnetisation in very thin films. We demonstrate the importance of the dipolar coupling for the understanding of the magnetic behaviour of TMR elements by comparing TMR curves for morphologically optimised and non-optimised structures.

**4:00 PM T5.7**
REALIZATION OF HIGH SENSITIVE FIELD SENSORS BASED ON SPIN-DEPENDENT TUNNELING. Henri Jaffres, D. Lacour, F. Nguyen Van Dau, F. Petroff, A. Vaures, J. Humbert, UMR CNRS/THOMSON-CLR, Orsay Cedex, FRANCE.

Recent advances in the physics of spin-dependent tunneling across a thin insulating barrier pave the way for a new technology of magneto-electronics devices such as sensors, read head or memories. This is made possible by the development of alumina tunnel junctions that offer large magneto-resistance at room temperature associated with a large resistance per unit area. The realization of high sensitive sensors requires a perpendicular arrangement of the two magnetizations which is only able by a perfect and independent control of each anisotropy. Ideally, the so called-hard layer is pinned along a fixed direction by mean of the unidirectional exchange bias induced at the interface with an antiferromagnet (AF). Under the extern field, the signal modulation is then produced by a slight rotation of the softer electrode from its easy direction perpendicular to the exchange bias. Following this argument, we have developed a concept of sensors working at room temperature and based on crossed exchange bias and step-bunching anisotropy originating from an artificial modulation of the substrate topography. The softer layer is played by a sputtered Co (NiFe) film grown on misoriented Si(111) substrate. The top Co layer is hardened after deposition of an AF material (CoO, IrMn and others) and annealing in the presence of a saturating magnetic field along the perpendicular to the steps. We present magneto-transport results of such sensors. Their response and thermal behavior will be analyzed and correlated to the magnetic properties of each electrode. Discussions will be led in sight to optimize either the sensitivity or the precision of the angular detection.

**4:15 PM T5.8**
EFFECT OF SPIN-POLARIZED CURRENT INJECTED IN ELECTRODEPOSITED MAGNETIC NANOWIRES OF CONTROLLED MORPHOLOGY. J.-E. Wegrowe, X. Hoffer, D. Kelly, Ph. Guittienne, J.-Ph. Ansermet, Ecole Polytechnique Federale de Lausanne (EPFL), IPE, SWITZERLAND.

The direct effect of high current density on magnetization states is studied on various electrodeposited magnetic nanowires of controlled morphology. Three kinds of samples have been studied. (1) homogeneous Ni nanowires, (2) copper nanowires containing n [Co(10 nm)/Cu(10 nm)] bilayers, n going from 5 down to 2, and (3) nanowires composed of both a homogeneous Ni part and a multilayered Co/Cu part. Three different experimental protocols were adopted for this study. (a) A DC current is injected. Giant magnetoresistance hysteresis loops are performed with current density up to about $10^7$ A/cm$^2$. A modification of the hysteresis has been observed. A ramp of the current density at fixed external field was also performed, showing a hysteretic behavior linked to the magnetization states. (b) Pulsed current is injected (0.5 $\mu$ s) close to unstable states of the magnetization. The effect of the current is to force the magnetization to reach a more stable state. The states reached after the current injection are studied as a function of the magnetic configurations and are shown to depend on the direction of the spin polarization of the incident current. (c) A pulsed current is injected (0.5 $\mu$s up to some tens $\mu$s), and time resolved measurements are performed. Deviation from the thermal activation law (at fixed potential-barrier height) was evidenced and quantified at high current density. In the case of the quasi-static measurements (a), the modification of the hysteresis could be described in terms of exchange torque produced by the spin-polarized current on a magnetic layer. In contrast, the measurement of irreversible magnetic transition (b) and (c) are more likely described in terms of spin transfer between the current and the magnetization due to spin-flip scattering.

**4:30 PM T5.9**
IN-SITU CHARACTERIZATION OF ULTRA-SMALL MAGNETIC JUNCTIONS MADE BY ELECTROCHEMICAL TECHNIQUES. A. Sokolov, J.R. Jennings, C-S Yang, J. Redepenning, B. Doudin Dept. of Physics and Astronomy, Dept. of Chemistry, University of Nebraska Lincoln, Lincoln, NE.

We use template synthesis to make magnetic wires of diameters down 30 nm. Using a plating/anodization/plating sequence, we are able to synthesize ultra-small insulating junctions. They are of interest for magnetoresistance effects, in particular when investigating spin-dependent blockade effects due to impurities in the barrier. We use electrochemical impedance spectroscopy to characterize in-situ the growth of the oxide barrier. We are able to deduce the thickness and its evolution with anodization time. For NiO barrier, we can also estimate the density of impurities from the bias dependence of the impedance spectrum, and adapt the anodization process to minimize the impurity concentration. A reduction of two orders of magnitude has been obtained The most critical part of the synthesis is the plating of the top layer. Non-aqueous electrochemistry is necessary to avoid the dissolution of the oxide barrier. Impedance spectroscopy is used for investigating how the insulating junction has been modified by the top layer deposition.

**4:45 PM T5.10**
REVERSAL PROCESSES IN ION-IRRADIATION PATTERNED Co/Pt MULTILAYERS. Greg J. Kusinski, Kannan M. Krishnan, Gareth Thomas, Gregory Denbeaux, Dept of MS&E, University of California, Materials Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, CA; Bruce D. Terris, IBM Almaden Research Center, San Jose, CA; Dieter Weller, Seagate Technology, Pittsburgh, PA.

(111) textured $(Co_{0.3nm}/Pt_{1nm})_{10}$ multilayers with perpendicular anisotropy were grown on electron transparent SiN windows using electron beam evaporation. These multilayers were patterned into magnetic sub-micron arrays by ion beam irradiation through a stencil mask and by a direct Ga Focused Ion Beam writing. Two complementary electron and photon magnetic imaging techniques were utilized to study the reversal processes of the patterned magnetic arrays. Lorentz transmission electron microscopy, sensitive to the in-plane magnetization, revealed magnetically soft ion-irradiated areas. X-ray transmission microscope at the Advanced Light Source, utilizing element specificity (Co $L_3$ absorption edge) and magnetic contrast due to magnetic circular dichroism (MCD), was used to image the reversal of perpendicular magnetization with a 25 nanometer resolution. Samples imaged at remanance, after saturation in a polar direction, showed significant decrease in intensity for irradiated regions as a result of the change of the easy axis of magnetization from out of plane to in plane. The same area imaged at 750eV, (off the Co edge), showed no contrast indicating no topographical changes due to the patterning. Reversing the applied field direction resulted in partial switching of the un-irradiated areas at fields below the sample coercivity ($H_{Cperp}$ = 6.3kOe). The reversal originated at the edges of the patterns and propagated into the non-irradiated surrounding regions. Details of the magnetizing experiment including the reversal mechanism for the samples exposed to different irradiation doses are discussed in the paper. These results are correlated with the microstructure, which was investigated using conventional, high resolution and energy filtered transmission electron microscopy (TEM).

## SESSION T6: SPINS IN SEMICONDUCTORS
Chair: Konrad Bussmann
Thursday Morning, April 19, 2001
Golden Gate C3 (Marriott)

**8:30 AM *T6.1**
$Ni_2MnIn$ FOR SEMICONDUCTOR SPIN INJECTION. R.H. Victora and K.A. Kilian, University of Minnesota, Dept. of Electrical and Computer Engineering, Minneapolis, MN.

The emerging field of "spintronics" would benefit greatly from the discovery of a practical material system which permits the successful injection of spins from a ferromagnet into a semiconductor. Requirements include properly positioned bands near the Fermi level of the bulk material and a substantially non-scattering interface. We use a first-principles electronic structure method that employs the linearized augmented Slater-type orbital (LASTO) formalism to examine these issues. Based on our calculation of the bulk band structures, we find that the first criterion is well satisfied for the combination of $Ni_2MnIn$ and InAs where the minority spin electrons traveling near the zone center can conserve both energy and momentum while crossing into the semiconductor, yet the majority spins will be strongly reflected. The second criterion requires the calculation of the magnetic and electronic structure for a complete interface. We find, for a 20 atom supercell based on the (100) interface that the distortion of the $Ni_2MnIn$ magnetic structure by the semiconductor is minimal. For example, the maximum decrease in polarization is 0.20 on a Mn atom, which is only a six percent decrease from the bulk value of 3.51. Charge transfer from the metal to the InAs is more significant, with the largest amount (approximately 0.6 e per formula unit) occuring for an In terminated semiconductor. Examination of the density of states projected near the 2-dimensional Brillouin zone center suggests that the overall scattering produced by interface states may be tolerable.

**9:00 AM *T6.2**
MAGNETISM, STRUCTURE AND SPIN POLARIZATION OF $Co_2MnSi$ AND $Co_2MnGe$ HEUSLER FILMS AND SINGLE CRYSTALS: HALF-METALLIC FERROMAGNETS? M.P. Raphael, S.F. Cheng, B.N. Das, B. Ravel, B. Nadgorny, G. Trotter, E.E. Carpenter, and V.G. Harris, Materials Physics Branch, Naval Research Laboratory, Washington, DC.

Magnetoelectronic devices rely upon an imbalance in the number of majority and minority carriers to add additional degrees of freedom to traditional logic devices. The ideal magnetoelectronic device consists of ferromagnetic materials that exhibit complete spin polarization at the Fermi surface (i.e. half-metallic ferromagnets). One promising class of materials is the Heusler alloys, some of which have been predicted by first principles band theory to be half-metallic. Here we report on the magnetic, structural and spin polarization properties of two such Heusler alloys, $Co_2MnSi$ and $Co_2MnGe$. We have studied single crystals, grown by a tri-arc Czrochalski method, and thin films grown by d.c. magnetron sputter deposition. Single crystal boules, typically 5 mm in diameter and 3-4 cms in length, are studied by Laue backscattering diffraction and XRD. Thin films have been characterized for long-range and short-range chemical ordering by XRD and x-ray absorption fine structure (XAFS), respectively. All samples have been studied using SQUID magnetometry, digital scanning calorimetry, electron microscopy, energy dispersive x-ray spectroscopy, and point contact Andreev reflection (PCAR). Pure phase (space group: $L2_1$) films have been grown in the temperature range of 570K to 770K in a pressure range of 30 to 60 mTorr. The Curie temperatures were determined by DTA as 1003K and 920K for the Si and Ge alloys, respectively. The saturation magnetization per formula unit (at T= 10K) were measured by SQUID as $5.01\mu_B < \mu < 5.15\mu_B$ for both alloys whereas theoretical predictions indicate $5.0\mu_B$. Spin polarization (P) of single crystals and thin films measured by PCAR at 4K have values ranging from 50-60% depending upon the processing hystories. These results suggest that the Heusler alloys may not be half-metallic. Alternatively, the P may be limited by antisite defects. However, their measured P is enhanced compared with Fe, Co and permalloy and therefore may be of use in magnetoelectronic devices.

**9:45 AM <u>*T6.3</u>**
EFFICIENT ELECTRICAL SPIN INJECTION AND REALIZATION OF SPIN-LED. <u>B.T. Jonker</u>, Y.D. Park*, A. Hanbicki*, R.M. Stroud and B.R. Bennett, Naval Research Laboratory, Washington, DC; G. Itskos, M. Furis, G. Kieoseoglou and A. Petrou, State University of NY, Buffalo, NY. *NRL/NRC postdoctoral associate.

Electrical spin injection into a semiconductor is a prerequisite for realizing the potential of semiconductor-based spintronic devices. This has been an elusive goal, however, and only modest effects ($\leq$ 1%) have been obtained. We report highly efficient electrical spin injection from a magnetic contact into a GaAs-based light emitting diode (LED) heterostructure a spin-LED [1] in which the spin injection efficiency exceeds 50%. The samples are grown by MBE, and the semimagnetic semiconductor ZnMnSe serves as a source of spin-polarized electrons which are injected via an applied bias voltage into a GaAs quantum well. Radiative recombination of spin polarized carriers results in the emission of circularly polarized light. The quantum selection rules relate the optical polarization to the carrier spin polarization, enabling a quantitative measure of spin injection efficiency. The measured circular polarization of the electroluminescence (EL) exceeds 50%, demonstrating that highly efficient spin transport occurs across the ZnMnSe / AlGaAs interface despite the large 0.5% lattice mismatch. The EL lineshape consists of multiple components whose relative polarization provides insight into spin relaxation mechanisms. We compare results from ex situ and in situ contacts, and with those obtained for carefully lattice matched systems and for hole injection.
Work supported by ONR and the DARPA SpinS program.
[1] B.T. Jonker, US patent # 5,874,749 (awarded 2/99).

**10:15 AM <u>T6.4</u>**
AB INITIO CALCULATIONS FOR STRUCTURAL AND ELECTRONIC PROPERTIES OF MnGaAs. <u>Leeor Kronik</u>, Manish Jain, and James R. Chelikowsky, Dept. of Chemical Engineering and Materials Science, Minneapolis, MN; Vitaliy V. Godlevsky, Dept. of Physics, Rutgers University, Piscataway, NJ.

Ferromagnetic semiconductors, especially III-V semiconductors with a magnetic ion impurity content, have recently attracted much attention due to their potential in making use of both charge and spin densities on the same chip. In order to realize this potential, one must understand the consequences of the impurity content on the electronic structure. Here, we present ab initio calculations, based on a pseudopotential approach within a spin-polarized density functional theory framework, for the electronic structure of MnGaAs. Our simulations assume a realistic Mn content of several percent and allow for atomic relaxation effects. Therefore, they allow a direct comparison to experimental data. We find the Mn-As bond to be stretched with respect to the Ga-As bond, in agreement with experiment. We observe no Jahn-Teller distortion effects and find the structural relaxation to have little effect on the electronic properties. We find a significant distribution of Mn-related acceptor states in the lower part of the bandgap. Therefore, there are no states in the vicinity of the Fermi level in one spin-polarization and Mn-related states in the other spin-polarization. Hence, the electronic structure of Mn-doped GaAs can be considered to be a semiconducting analog for the predicted half-metallic behavior of the (experimentally inaccessible) zincblende MnAs crystal.

**10:30 AM <u>T6.5</u>**
EPITAXIAL GROWTH OF DILUTE MAGNETIC SEMICONDUCTORS: GaMnN AND GaMnP. <u>M.E. Overberg</u>, C.R. Abernathy, S.J. Pearton, Univ of Florida, Dept of Materials Science, Gainesville, FL; F. Sharifi, A.F. Hebard, N. Theodoropoulou, Univ of Florida, Dept of Physics, Gainesville, FL; S. von Molnar, P. Xiong, M. Anane, Florida State Univ, Dept of Physics and MARTECH, Tallahassee, FL.

Dilute magnetic semiconductors (DMS) offer the use of the spin degree of freedom of the electron in addition to its charge in device applications. Controlling the phase of the spin wavefunction within these devices would potentially enable the development of high speed logic and memory, quantum-based communication, and electro-optic switches and modulators. To date, current work in this "spintronics" area has focused upon (Ga,Mn)As, (In,Mn)As, and (Ga,Mn)Sb. The drawbacks for these materials are Curie temperatures below room temperature, limiting their potential application. However, recent theoretical calculations have predicted a Curie temperature for GaMnN of roughly 400 K(1). The potential for spin related phenomena coupled with the application potential of nitrides to high temperature and high power devices would make a GaMnN-based spin-FET highly desirable. In this paper, we will report for the first time on the growth of both GaMnN and GaMnP thin films by gas source molecular beam epitaxy (GSMBE). Mn levels up to 41% as determined by Auger electron spectroscopy (AES) have been obtained in GaMnN. X-ray diffraction (XRD) shows no evidence of second phase formation in either $Ga_{0.95}Mn_{0.05}N$ or $Ga_{0.95}Mn_{0.05}P$. Addition of Mn to the GaN changes the conductivity from highly conductive n-type to highly resistive, suggesting that at least some of the Mn behaves as a deep acceptor. Nominally semi-insulating GaMnN with a Mn concentration of 4.5% shows paramagnetic behavior with a saturation moment per Mn of 3.9 Bohr magnetons, suggesting that much of the Mn is substitutional. The addition of carbon to the GaMnN makes the material n-type and produces what appears to be a ferromagnetic phase, but with a low Curie temperature. Similar studies on GaMnP will be discussed in this talk as will the effect of adding Mg to both materials.
1 Dietl et al. SCIENCE Vol. 287 11February 2000 pp. 1019-1022.

**10:45 AM <u>*T6.6</u>**
TRANSMISSION ELECTRON MICROSCOPY STUDIES OF ZnMnSe/AlGaAs/GaAs SPIN-LEDs. <u>Rhonda M. Stroud</u>, Y.D. Park†, B.T. Jonker and B.R. Bennett, Naval Research Laboratory, Washington, DC; G. Itskos, M. Furis, G. Kioseoglou and A. Petrou, State University of New York at Buffalo, Buffalo, NY. †NRL/NRC postodoctoral associate.

Efficient spin injection across heteorepitaxial interfaces is a key obstacle to achieving practical spin-polarized electronic devices. To help understand how interfacial microstructure affects the injection efficiency in spintronic structures in general, we are using a ZnMnSe/AlGaAs/GaAs spin-LED structure as a model system. These spin-LEDs consist of a ZnMnSe layer grown heteroepitaxially by molecular beam epitaxy on an AlGaAs-GaAs quantum well LED. The efficiency of the injection of spin-polarized current from the ZnMnSe layer into AlGaAs is determined by measurement of the optical polarization of light emitted by recombination of carriers in the AlGaAs-GaAs quantum well. Injection efficiencies exceeding 50% have been obtained for some samples. Transmission electron microcopy (TEM) studies indicate that the dominant defects in this system are stacking faults originating at the ZnMnSe/AlGsAs interface. Preliminary data confirms an increase in the injection efficiency when the density of these stacking faults decreases. We will present a thorough characterization of the microstructure of the ZnMnSe/AlGaAs interface as studied by cross-sectional TEM and correlate these data with growth conditions and injection efficiency.

**11:15 AM <u>T6.7</u>**
BALLISTIC SPIN-POLARIZED ELECTRON TRANSPORT IN SPIN-VALVE STRUCTURES. Atsufumi Hirohata, Wen-Siang Lew, Yong-Bing Xu, Christian Guertler, <u>Tony Bland</u>, Univ of Cambridge, Cavendish Lab, Cambridge, UNITED KINGDOM; Stuart Holmes, Toshiba Res Europe Ltd, Cambridge Res Lab, Cambridge, UNITED KINGDOM.

Future spintronic devices will require both spin injection from a ferromagnet (FM) to a semiconductor (SC) and spin detection from a SC to a FM [1]. We previously reported highly efficient spin detection associated with spin filtering of ballistic electrons across single layer FM/SC Schottky interfaces using photoexcitation at room temperature [2]. Here we extend the earlier study to test our model of the spin filtering mechanism with a spin-valve structure, in which the FM layers can be switched independently. We fabricated samples of Au/Co/Cu/NiFe/*n*-GaAs (100) and attached two Al electrical contacts to the Au layer and one ohmic contact to the bottom of the substrate. The samples were characterized by magneto-optical Kerr effect (MOKE), magnetoresistance (MR) and *I-V* measurements. Circularly polarized light incident at an angle $\theta$ from the sample plane normal generated spin-polarized electrons in the SC, which tunnel through the Schottky barriers into the FM layers according to the applied bias. A helicity-dependent photocurrent, dependent upon the relative magnetization configuration in plane between the two FM layers (parallel or anti-parallel) was measured for the angle range of $0 \leq \theta \leq 45°$. In the case of $\theta$=0, the photon helicity is orthogonal to the FM magnetization and no spin dependence is expected, while the spin dependence of the transmission is expected to increase for increasing $\theta$. For the case of 2 nm Au/2 nm Co/3 nm Cu/4 nm NiFe/GaAs, for instance, an almost constant difference ($\sim$a few 100 $\mu$A) between the helicity-dependent photocurrent for parallel and anti-parallel configurations is observed at zero bias for $\theta$=45°, which corresponds to the spin-dependent photocurrent passing from the SC to the FM. At $\theta$=0, on the other hand, no helicity-dependent photocurrent is detected as expected. We also compare these results with those of samples with a single FM layer. These results demonstrate the importance of ballistic spin filtering in the spin-dependent transport and hold promise for the development of spintronic devices.
[1] M. Johnson, *IEEE Spectrum* **37**, 33 (2000).
[2] A. Hirohata *et al.*, *J. Appl. Phys.* **87**, 4670 (2000); J.A.C. Bland *et al.*, *IEEE Trans. Magn.*, in press.

**11:30 AM <u>T6.8</u>**
FERROMAGNETIC AND STRUCTURAL PROPERTIES OF Mn-IMPLANTED p-GaN. N. Theodoropoulou[1], A.F. Hebard[1],

S.J. Pearton[2], C.R. Abernathy[2], S.N.G. Chu[3], K.P. Lee[2], R.G. Wilson[4], A.G. Rinzler[1] and W. Gebicki[5]. [1]Department of Physics, University of Florida, Gainesville, FL. [2]Department of MS&E, Univ. of Florida, Gainesville, FL. [3]Bell Laboratories, Lucent Technologies, Murray Hill, NJ. [4]Consultant, Stevenson Ranch, CA. [5]Faculty of Physics, Warsaw University of Technology, Warsaw, POLAND.

Direct implantation of Mn ions into p-GaN epi layers was performed at temperatures of 350°C (to avoid amorphization) and doses designed to produce 0.1-5 at.% Mn. The samples were annealed at 700°-1000°C. For doses $\geq$ 3at.%, large ( 10nm) precipitates and platelet structures were observed in addition to the implant damage induced dislocation loops. These structures are suggested to be either GaMn or $MnN_x$ phases. When these are present, there is a hysteresis in the magnetic moment of the films which disappears at around 250K. A rough calculation from the saturation magnetization yields approximately 0.2 Bohr magnetons per Mn. At lower doses the material does not show any ferromagnetism. The direct implantation approach may be attractive for some spin-injection structures based on GaN.

**11:45 AM T6.9**

CHALCOPYRITE MAGNETIC SEMICONDUCTORS: AN AB–INITIO STUDY OF THEIR STRUCTURAL, ELECTRONIC AND MAGNETIC PROPERTIES. S. Picozzi, A. Continenza, Dip. Fisica, Univ. L'Aquila, L'Aquila, ITALY; W.T. Geng, Y.J. Zhao and A.J. Freeman, Materials Research Center (Supported by the U.S. National Science Foundation) and Dept. of Phys. and Astron., Northwestern Univ., Evanston, IL.

A great effort is being devoted to explore *new, advanced magnetic semiconductors* based on crystal structures that transcend the limitations (such as defect formation, and too low operating temperatures for spin injection and ferromagnetic properties) of the magnetic zinc-blende systems explored so far (*e.g.* $Ga_xMn_{1-x}As$). Within this context, we performed ab–initio full–potential linearized augmented plane wave (FLAPW)[1] simulations for several Mn doped *chalcopyrite* systems like $ZnGeAs_2$, $CdGeAs_2$ and $CdGeP_2$. We present results obtained for structural, electronic and magnetic properties as a function of Mn concentration, and we discuss the effect of cation (*i.e.* Zn vs Cd) and anion substitutions (*i.e.* As vs P) on the magnetic properties of these systems. Our studies are particularly timely in view of the report by Medvedkin et al. G.A. Medvedkin et al, Jpn. J. Appl. Phys. 39, L949 (2000) of room temperature ferromagnetism in highly concentrated $CdGeP_2$.

[1]H.J.F.Jansen and A.J.Freeman, Phys. Rev. B **30**, 561 (1984).