Wednesday Morning, October 17, 2007

Magnetic Interfaces and Nanostructures

Room: 619 - Session MI-WeM

Magnetic Thin Films and Nanostructures

Moderator: S.H. Liou, University of Nebraska, Lincoln

8:00am **MI-WeM1 Surface Stability and Electronic Structure of Half-Metallic MnSb**, ***S.J. Jenkins***, University of Cambridge, UK **INVITED**

Half-metallic materials, which exhibit complete spin-polarisation at the Fermi level, hold great promise for device applications in the field of spintronics. Amongst a variety of potential drawbacks, however, one of the most pressing is a lack of knowledge concerning surface and interface properties. In particular, the relationship between the stability of different surface/interface phases and the presence of surface/interface-localised electronic states is of great importance.[1,2] We have performed first-principles density functional calculations aimed at elucidating this relationship for various surfaces of the half-metallic zincblende phase of MnSb, demonstrating that it is essential to account for the possibility of reconstruction in determining whether half-metallicity is retained at the surface.[3]

[1] S.J. Jenkins and D.A. King, Surf. Sci. Lett. 494, L793 (2001).
[2] S.J. Jenkins, Phys. Rev. B 70, 245401 (2005).
[3] S. Mollet and S.J. Jenkins, J. Phys.: Cond. Matter (invited, in press).

8:40am **MI-WeM3 Magnetic and Structural Properties of Epitaxial FeRh Thin Films Grown by MBE**, *Y. Ding*, ***D.A. Arena***, Brookhaven National Laboratory, *L.H. Lewis*, Northeastern University, *J. Dvorak*, Montana State University, *C. Kinane, M. Ali, C.H. Marrows, B.J. Hickey*, University of Leeds, UK

Thin films of FeRh alloys with near equiatomic composition and CsCl type ordering exhibit an intriguing antiferromagnetic (AFM) to ferromagnetic (FM) first-order phase transition near 100° C. This easily accessible phase transition has generated interest in using FeRh films as a temperature-tunable AFM pinning layer in exchange-biased magnetic structures.[1] The AFM to FM transition is associated with the dramatic increase of the saturation magnetization M_s, along with temperature hysteresis of M_s, and a variation in the lattice parameter. We have grown high quality, epitaxial FeRh films on MgO(100) via molecular beam epitaxy (MBE); film thickness ranged from ~200 Å to 1000 Å. The films are characterized with a combination of laboratory-based magnetometry and synchrotron-based x-ray diffraction (XRD) and x-ray magnetic circular dichroism (XMCD). Magneto-optic Kerr effect measurements and SQUID magnetometry confirm the AFM to FM transition in the films. Temperature dependent XRD indicates an expansion of the out-of-plane lattice parameter across the phase transition which mirrors the change in M_s. XMCD spectra were collected in conventional total electron yield (TEY) mode, which probes the near-surface region (probe depth ~50 Å - 100 Å) and in indirect transmission mode (ind-trans), where the oxygen K-edge fluorescence from the MgO substrate is monitored as the photon energy is swept through the Fe $L_{2,3}$ core levels. For the Au capped films, TEY scans reveal a FM near-surface region even at room temperature, while the ind-trans mode data are consistent with a bulk AFM state at ambient temperatures which transforms to a FM state above 100° C. The choice of capping layer also affects the room-temperature magnetism in the near-surface region as the MgO capped films do not exhibit an appreciable XMCD signal in TEY mode.

[1]Thiele. et al., Appl. Phys. Lett.,82, 2859 (2003).

9:00am **MI-WeM4 Properties of Epitaxial Co_2MnSi on Vanadium**, ***G.J. Mankey***, *M.J. Walock, C.A. Culbert, Z. Lu, M. Pathak, Z.T. Reddy, P. LeClair, S. Gupta, W.H. Butler*, University of Alabama

There is a consensus that read sensors for hard drives will transition from tunnel magnetoresistance based sensors to all metal current perpendicular to the plane giant magnetoresistive sensors. To achieve this goal, a new generation of high spin polarization materials are required. Half-metallic Heusler alloys, combined with carefully chosen spacer materials, are prime candidates for incorporation into these devices. However, robust half-metallic behavior must be established and confirmed. Recently, we have investigated the electronic structure of $L2_1$ full Heusler alloys in detail. We can, theoretically, devise an infinite number of periodic systems that are half-metallic, with the hope that at least a handful will be experimentally accessible. Our preliminary calculations of the electronic structure of these materials suggest that they have a robust half-metallic nature. These theoretical results are combined with an experimental study of the half-metallic compound, Co_2MnSi. Epitaxial films are deposited using magnetron sputtering on low-index, single-crystal vanadium substrates and their crystal structure, electronic structure and magnetic properties are determined. Films processed under different deposition conditions are compared to determine the optimum conditions for producing half-metallic single-crystal films. This work is funded by NSF-DMR 02-31985.

9:20am **MI-WeM5 High Magnetization FeCo/Pd Multilayers**, ***M.J. Walock****, The University of Alabama, *H. Ambaye*, Oak Ridge National Laboratory, *M. Chshiev*, The University of Alabama, *F.R. Klose*, Oak Ridge National Laboratory, *W.H. Butler, G.J. Mankey*, The University of Alabama

A high saturation magnetization is advantageous in magnetic recording. For the 3d ferromagnets, the peak of the Slater-Pauling curve corresponds to BCC FeCo, with a saturation magnetization of 2.45 T. Recently, a magnetization of 2.57 T in the FeCo layers of a [40 nm $Fe_{70}Co_{30}$ /1.7 nm Pd]x25 superlattice has been reported.[1,2] This result may be attributed to an enhanced Fe moment due to interfacial strain and an accompanying induced moment in the Pd. We have fabricated multilayer samples with varying superlattice periodicity and interlayer thicknesses to determine the nature of the enhanced moment in this intriguing thin film system. Magnetic characterization experiments show an enhanced magnetic moment in the multilayers as compared to a film containing the same amount of FeCo. However, since the magnetization is defined as the magnetic moment divided by the sample volume, the sample exhibits an overall reduction in the magnetization when the volume of the Pd layers is also taken into account. Our experimental findings are also supported by theoretical calculations which identify the origin of the increased magnetic moment in the multilayer system. Polarized neutron reflectivity experiments will be used to determine the lateral distribution of the magnetization in a number of superlattice samples.[3].

[1] K. Noma, M. Matsuoka, H. Kanai, Y. Uehara, K. Nomura, and N. Awaji. IEEE Trans. Magn. 42, 140 (2006).
[2] ibid. 41, 2920 (2005).
[3] This project was funded by grants from the DOE, the INSIC EHDR Program, and NSF-DMR 0213985 .

9:40am **MI-WeM6 Induced Spin Polarization of Copper Spin 1/2 Molecular Layers**, ***D.S. Wisbey****, *D. Feng*, University of Nebraska-Lincoln, *A.N. Caruso*, North Dakota State University, *C.M. Silvernail*, University of Minnesota, *J. Belot*, University of Nebraska-Lincoln, *E. Vescovo*, National Synchrotron Light Source, *P.A. Dowben*, University of Nebraska-Lincoln

Substrate induced spin polarization was observed in molecular layers of $C_{24}H_{36}N_2O_4Cu$ ($Cu(CNdpm)_2$) deposited on cobalt (111). Extra molecular interactions between these Cu 1/2 molecules and the ferromagnetic substrate are implicated while the $Cu(CNdpm)_2$ molecular layers have an opposite spin polarization compared to the Co(111) substrate near the Fermi edge. The spin-polarized photoemission results are seen to be consistent with magnetometry and mean field (Ginzburg-Landau) models. The spin asymmetry favors select molecular orbitals, suggesting that the local spin 1/2 moment of copper is enhanced by contributions from select molecular orbitals.

10:40am **MI-WeM9 Controlling Magnetic Anisotropy and Probing Magnetic Structure in Magnetic Nanoparticles and Ferromagnetic/Antiferromagnetic Bilayers**, ***M.-T. Lin***, National Taiwan University **INVITED**

Controlling the magnetic orientation and imaging magnetic structure are two of crucial issues in both aspects of fundamental science and application for magnetic nanomaterials. In particular, tuning perpendicular magnetic anisotropy by the more concise and efficient process draws a lot of attentions due to the possible application for perpendicular medium with high storage density. In this work, an enhanced perpendicular magnetic anisotropy of ferromagnetic thin films is demonstrated by introducing an antiferromagnetic (AF) underlayer. A new kind of spin-reorientation transition is also observed with varying thickness of the AF layer. This finding is shown to be related to the strength of the AF coupling of the AF layer. Controlling the magnetic anisotropy can be also important in the magnetic domain imaging with in-plane sensitivity by spin-polarized scanning tunneling microscopy (SP-STM). A simple method by using a ring-shaped magnetically coated wire as the tip of SP-STM is shown to be able to have the spin contrast easily in the in-plane direction of the film. A well-defined magnetization orientation of magnetic tip is achieved due to controlled anisotropy caused by geometrical asymmetry. Finally, magnetic

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coupling and magnetic structure in magnetic self-aligned Fe particles grown on the single crystalline oxide layer $Al_2O_3/NiAl(100)$[1,2] will be also discussed. With help of the technique of scanning electron microscopy with polarization analysis (SEMPA) the magnetic domain is imaged, revealing a vortex structure, which is suggested to be attributed to a dipole-dipole interaction. Furthermore, capping the magnetic particles with non-magnetic metallic layer (Cu) can enhance the magnetic coupling, and in turn the Curie temperature of the system.[3] This finding can also be confirmed in the enhanced spin contrast observed by SEMPA for magnetic particles with capping layer. The magnetic coupling under magnetic particles is shown to be able to propagate through the Cu layer.

[1] W.C. Lin, C. C. Kuo, M.F. Ro, K. J. Song, and Minn-Tsong Lin, Appl. Phys. Lett. 86, 043105 (2005).

[2] W. C. Lin, S. S. Wong, P. C. Huang, C. B. Wu, B. R. Xu, C. T. Chiang, H. Y. Yen, and Minn-Tsong Lin, Appl. Phys. Lett. 89, 153111 (2006).

[3] W. C. Lin, P. C. Huang, K. J. Song, and Minn-Tsong Lin, Appl. Phys. Lett. 88, 153117 (2006) .

11:20am **MI-WeM11 Fabrication and Real Time Characterization of Highly Anisotropic Magnetic Nanostructures**, ***J.R. Skuza****, *R.A. Lukaszew*, The University of Toledo, *C. Clavero*, Instituto de Microelectrónica de Madrid - IMM (CNM - CSIC), Spain, *D.A. Walko*, Argonne National Laboratory, *R. Clarke*, University of Michigan, Ann Arbor

The FePt binary alloy system exhibits several chemically ordered phases (i.e., $L1_0$ and $L1_2$) depending on the Fe:Pt stoichiometry. This chemical ordering affects the crystallographic structure of the alloy and hence the magnetic anisotropy. For example, in thin films of this alloy, the $L1_0$ phase exhibits strong perpendicular magnetic anisotropy when the ordering axis is in the growth direction (~10^7 erg/cc), while the $L1_2$ phase exhibits in-plane magnetic anisotropy. Thus, suitable combinations of these chemically ordered phases have been proposed for the next generation of magnetic recording media with tilted magnetization. A significant challenge for this latter application is to achieve chemically ordered nanostructures that can further push the present super-paramagnetic limit. Here, we report on our recent magnetic and real time thermal annealing studies of nanostructured FePt thin films. FePt nanocomposite thin films were obtained by implanting Fe^+ ions into epitaxial Pt thin films using the Toledo Heavy Ion Accelerator (THIA). The size and penetration depth of the resulting Fe nanoclusters were tailored by modifying the implantation conditions (i.e., ion beam energy and implantation dose). Upon annealing these nanocomposite samples at the Advanced Photon Source at Argonne National Laboratory, we observe within minutes the onset of the $L1_2$ phase at ~400° C with further re-ordering and formation of the $L1_0$ phase at ~500° C. Further data analysis shows that the activation energy of the $L1_0$ phase in these nanocomposite samples is ~1.0 eV. Our magnetic measurements show a strong out-of-plane component of the magnetic anisotropy after the annealing treatment consistent with the formation of the $L1_0$ phase.

This work was partially supported by the National Science Foundation (DMR Grant #0355171), the American Chemical Society (PRF Grant #41319-AC), and the Research Corporation Cottrell Scholar Award. Use of the Advanced Photon Source was supported by the U. S. Department of Energy, Office of Science, Office of Basic Energy Sciences, under Contract No. DE-AC02-06CH11357. The authors would like to acknowledge M. S. Brown for his assistance during ion implantation.

11:40am **MI-WeM12 Effects of Preheat Treat on the Anisotropy and Particle Size of Sr(TiMn)2Fe8O19 Magnetic Powders**, ***H.Y. He***, Shaanxi University of Science & Technology, China

The excellent properties of Ti-Mn-substituted ferrite are largely dependent on the characters of multidomain ferrite powders except for Ti-Co-substitution rate. Preheat treatment can influences the formation process of Ba(TiMn)2Fe8O19 powders and further influences the anisotropy of the powders. However this effect has not be reported previously. Ultrafine substituted M-type Sr(TiMn)2Fe8O19 powders were synthesized successfully by sol-gel method. The hydroxide precursor particles were formed in gel solution containing ethanol and water at a ratio of 1:1 and NaOH as coprecipitation agent. The effects of preheat treatment on particle size and c/a value of Sr(TiMn)2Fe8O19 nano powders were studied using XRD and SEM. XRD analysis indicated single phase substituted M-type Sr-ferrite Sr(TiMn)2Fe8O19 were formed by either preheating precursors at 300oC and 400oC respectively for 1h or non-preheating followed by calcining at 900oC for 2h respectively. The particle sizes of powder were changed from 40.8nm to 39.8nm and 41.1nm when the samples were preheated at 300oC and 400oC respectively. Calculation of c/a value with XRD data indicated that the The c/a ratio changed from 3.9145 to 3.9183 and 3.9153 at the preheating temperatures of 300oC and 400oC respectively. A largest c/a value was achieved at preheating temperature of 300oC. SEM analyses revealed that particles were platelet and the decrease in aspect ratio in morphology was accordant to the increase in the c/a ratio with change from non-preheating to preheating at 400oC and to preheating at 300oC.

12:00pm **MI-WeM13 Surface Functionalization of Single Iron Oxide Magnetic Nanoparticles (SPIONs) for Targeted Magnetic Resonance Imaging (MRI)**, ***E. Amstad***, *E. Reimhult*, *S. Zurcher*, ETH Zurich, Switzerland, *J.A. Hamilton*, Boston University Medical Campus, *J.Y. Wong*, Boston University, *M. Textor*, ETH Zurich, Switzerland

Commercially available negative magnetic resonance (MR) contrast agents often consist of multiple iron oxide cores embedded in a macromolecular matrix such as dextran. An alternative to the reversibly binding dextran is PEG-gallol or PEG-dopamine. The latter two molecules have a considerably higher binding affinity towards iron oxide nanoparticles compared to dextran, leading to enhanced particle stability and smaller particle diameters. Because PEG-gallol and PEG-dopamine adsorb on iron oxide in a well defined way, particles can be stabilized individually. Moreover, surface modifications of such PEGylated particles can be achieved by using PEG-chains that bear functional groups. Superparamagnetic iron oxide nanoparticles have been synthesized by an aqueous precipitation reaction and were stabilized individually using PEG-gallol and PEG-dopamine. Particle size, thermal stability and magnetic properties of these individually stabilized PEGylated particles have been compared with Feridex, a commercially available negative MR-contrast agent. To functionalize the former particles, iron oxide cores were coated with a combination of biotinylated PEG-dopamine and PEG-gallol. Neutravidin, a biotin-binding protein, served as a linker between the PEGylated particles bearing biotin sites and biotinylated functional groups. Neutravidin is an attractive linker for research purposes because any biotinylated ligand can be attached to it. Moreover, the number of ligands bound to one particle can easily be varied if neutravidin is used as an intermediate layer. In a first approach, these neutravidin coated PEGylated nanoparticles were targeted against atherosclerotic sites by attaching a custom-synthesized biotinylated peptide sequence to them.[1] E-selectin is a transmembrane protein expressed on inflamed endothelial cells.[2] It thus is an early marker for atherosclerosis. The blood half-life time of these functionalized superparamagnetic iron oxide nanoparticles has been determined in vivo in rabbits using magnetic resonance imaging (MRI).

[1] Martens, C.L., et al., Peptides Which Bind to E-Selectin and Block Neutrophil Adhesion. Journal of Biological Chemistry, 1995. 270(36): p. 21129-21136.

[2] Choudhury, R.P., V. Fuster, and Z.A. Fayad, Molecular, cellular and functional imaging of atherothrombosis. Nature Reviews Drug Discovery, 2004. 3(11): p. 913-925.

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Wednesday Afternoon, October 17, 2007

Magnetic Interfaces and Nanostructures

Room: 619 - Session MI-WeA

Nanomagnetic Imaging and Spectroscopy

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Magnetic Interfaces and Nanostructures

Room: 619 - Session MI-ThM

Magnetic Semiconductors I

Moderator: A.T. Hanbicki, Naval Research Laboratory

8:00am **MI-ThM1 DMS Ferromagnets: Extrapolating from (III,Mn)V Materials**, ***A.H. MacDonald***, University of Texas at Austin, *T. Jungwirth*, Czech Academy of Sciences, *J. Sinova*, Texas A&M University, *J. Kucera*, *J. Masek*, Czech Academy of Sciences **INVITED**

The body of work on (III,Mn)V diluted magnetic semiconductors (DMSs) started during the 1990's achieved a good understanding of the origins of ferromagnetism in these materials, and of the relationship between magnetic properties and the materials science of growth and defects. From the fundamental point of view, (Ga,Mn)As and several other (III,Mn)V DMSs are now regarded as textbook examples of something which is rare, robust ferromagnets with dilute magnetic moments coupled by delocalized charge carriers. Both local moments and itinerant holes are provided by Mn, which makes the systems particularly favorable for realizing this unusual ordered state. Advances in growth and postgrowth-treatment techniques have played a central role in the field, often pushing the limits of dilute Mn-moment densities and the uniformity and purity of materials far beyond those allowed by equilibrium thermodynamics. In (III,Mn)V compounds, material quality and magnetic properties are intimately connected. I will review[1] some of this progress and use it as a spring board to discuss magnetism in other semiconductors with dilute local moments.[2]

[1] Tomas Jungwirth et al. Rev. Mod. Phys. 78, 809 (2006).
[2] Work suported by the Department of Energy under Grant No. DE-FG03-02ER45958.

8:40am **MI-ThM3 Onset of Nonlinear Transport and Two-Level Fluctuation through a Pinned Domain Wall in Patterned Lateral GaMnAs Constrictions**, ***S.W. Cho****, *H.K. Choi, J.S. Lee, T. Hwang, Y.D. Park*, Seoul National University, Korea

We report on the electrical transport measurements across clean lateral geometrical constrictions in diluted magnetic semiconductor GaMnAs. Constrictions are realized by e-beam lithography to define SiO_x etch masks to pattern nanometer-sized constrictions without plasma etching processes. DC transport behavior across the nanoconstrictions changes from ohmic to non-ohmic below temperatures corresponding to epifilm T_C. The nonlinear IV characteristics fit well with adapted transport equation accounting for spin-flop processes across the domain wall, analogous to pn junctions.[1] Fits to theory also indicate the domain walls to be smooth and wide, inhospitable to tunneling transport, and supported by magnetoresistance behavior dominated by anisotropic magnetoresistance-like response similar to Giddings et al. observations.[2] Extending the 'spin diode' concept of Vignale and Flatté,[3] we conduct a series of dynamic measurements and observe a distinct two-level behavior dependent on bias conditions similar to certain behaviors found in bipolar junctions such as shot noise and random telegraph noise.

[1]G. Vignale and M.E. Flatté, PRL 89, 098302 (2002).
[2]A.D. Giddings et al., PRL 94, 127202 (2005).
[3]M.E. Flatté and G. Vignale, APL 78, 1273 (2001).

9:00am **MI-ThM4 Intrinsic Vacancy Chalcogenides as Dilute Magnetic Semiconductors: Theoretical Investigation of TM-Doped Ga_2Se_3**, ***I.N. Gatuna****, F.S. Ohuchi, M.A. Olmstead*, University of Washington

The quest to functionalize semiconductors with additional magnetic properties through synthesis of dilute magnetic semiconductors (DMS) has led to a deeperunderstanding of semiconductor physics and the development of new magneticmechanisms. However, most current DMS materials (e.g., Mn-doped GaAs) are magnetic only well below room temperature, and/or have only limited compatibility with existing silicon electronics. We have investigated transition metal (TM) doping of the intrinsic vacancy semiconductor Ga2Se3 to address both scientific and technical goals. The intrinsic vacancies of this III-VI, zinc-blende-based semiconductor open possibilities for self-compensation as well as supply highly anistropic and polarizable band edge states. Ga2Se3 is also closely lattice matched to Si and may be grown heteroepitaxially on Si with high quality interfaces. Our first principles computations of X:Ga2Se3 (X = Mn, V, Cr, concentrations 5% to 16%) reveal that X atoms hybridize with neighboring Se in the p-d hybridization typical of III-V and II-VI DMS materials. This hybridization spin-polarizes states near the Fermi level in these T =0 calculations, and lowers the energy of the Se lone-pair orbitals that neighbor vacancies, reducing their prominent role in determining the properties of intrinsic Ga2Se3. There are distinct differences between substitution on a vacancy or for a Ga. Anisotropic, hole-like conductivity is predicted when X is located in a Ga site, while for X situated in a vacancy, a half-metallic state with an isotropic conductivity appears likely. Our calculations suggest that Mn offers the best choice for the dopant, perhaps because its 3d5 electronic configuration offers a large (~ 0.5 eV) separation of spin up and spin down states near the Fermi level, reducing the metallic densities of states at the Fermi level for all doping concentrations. The large energy splitting suggests that doped Ga2Se3 may be a suitable material for spintronics applications athigher temperatures than these T = 0 initial calculations.

This work was supported by NSF grant DMR 0605601, the Japan Science Promotion International Program, NIMS (Japan) - UW Joint Research Pact and NIMS (Japan) Internal Research Fund.

9:20am **MI-ThM5 Heteroepitaxial Growth and Electronic Structure of Mn:Ga_2Se_3 Thin Films on Si(100):As: Exploration of a Candidate Dilute Magnetic Semiconductor**, ***T.C. Lovejoy****, E.N. Yitamben*, University of Washington, *T. Ohta*, Lawrence Berkeley National Laboratory, *F.S. Ohuchi, M.A. Olmstead*, University of Washington

Magnetic thin film semiconductors grown on nonmagnetic semiconductors (NMS) may provide a route to injection of spin polarized electrons into the NMS. The lack of magnetic materials with both a high Curie temperature and spin-preserving transport into electronic materials (e.g., silicon) is currently the primary obstacle to the development of useful spintronic devices. A relatively unexplored class of dilute magnetic semiconductor is transition metal doped III-VI semiconductors. Group III-VI semiconductors such as Ga_2Se_3 have intrinsic vacancies which lead to highly anisotropic growth, and which may lead to a high degree of magnetic anisotropy if the films can be made ferromagnetic through suitable doping. Scanning tunneling microscopy (STM), low energy electron diffraction (LEED) and photoemission spectroscopy (PES) have shown the addition of small quantities of manganese, about one percent, has a pronounced effect on the growth morphology and electronic properties of Ga_2Se_3 on arsenic passivated Si(100). Co-deposition of Mn and GaSe on Si(100):As results in tall, highly anisotropic, rectangular, Mn-rich islands with edges parallel to the [011] and [0-11] substrate crystal directions. Deposition of a pure Ga_2Se_3 layer before the doped material results in a different and more laminar structure. While islands still form, these islands are much shorter and wider with seemingly random shapes subject to the constraint that every piece of the perimeter lies along the same two crystal directions. These two structures can be easily distinguished by their LEED patterns where the first case shows 1x1 spots with streak features characteristic of the undoped Ga_2Se_3 structure, whereas the second case transitions to clear 1x1 spots with no other features. The effect of small concentrations of Mn on the band structure of thin film Ga_2Se_3 is equally pronounced. The Mn doping adds a new peak in the valence band about 4.2eV below the Fermi level, an area where pure Ga_2Se_3 has a low density of states.

This work was supported by NSF grant DMR 0605601. TCL acknowledges support from NSF/NCI IGERT DGE-0504573. Some of the research was pursued at the Advanced Light Source, which is supported by the DOE under contract DE-AC02-05CH11231.

9:40am **MI-ThM6 Investigation of Cr:Ga2Se3 as a Candidate Dilute Magnetic Semiconductor for Silicon Based Applications**, ***E.N. Yitamben****, T.C. Lovejoy, I.N. Gatuna, F.S. Ohuchi, M.A. Olmstead*, University of Washington

The intrinsic vacancy semiconductor Ga2Se3, which may be grown epitaxially on Si, poses several interesting issues for the study of dilute magnetic semiconductors. Substitution of transition metal impurities may occur on either occupied or vacant cation sites in the defected zincblende lattice. For dopants with different valence from the host cation, this may result in self-compensation of donors and acceptors, while an isoelectronic impurity can either add electrons by inserting into a vacancy, or minimally disturb the band structure by replacing a Ga. To probe the interrelationship between magnetism and free carriers in this new class of dilute magnetic semiconductors, we have performed both theoretical and experimental investigations of Cr-doped Ga2Se3 grown epitaxially on Si(001):As. Scanning tunneling microscopy shows nucleation of anisotropic islands, with the area between islands similar to pure Ga2Se3. The size and shape of the islands is dependent both on Cr concentration and on whether or not a pure Ga2Se3 buffer layer is deposited first. Despite the similar intrinsic valence between Cr and Ga, addition of a few percent Cr to Ga2Se3 results in metallic bands with minimal dispersion and leads to significant changes of the Se local environment, as measured with high resolution photoemission spectroscopy. These results may indicate Cr substituting into a vacancy rather than replacing Ga, or possibly creating local areas of CrSe,

***** Falicov Student Award Finalist

which computations show to be half-metallic. At higher concentrations, X-ray absorption and photoemission show two distinct Cr environments.

This work was supported byt NSF grant DMR 0605601. TCL acknowledges support from NSF/NCI IGERT DGE-0504573. Some of the research was pursued at the Advanced Light Source, which is supported by the DOE under contract DE-AC02-05CH11231.

10:00am **MI-ThM7 Giant Excitonic Zeeman Splittings in Transition Metal Doped CdSe Quantum Dots**, ***P.I. Archer***, *D.R. Gamelin*, University of Washington

We report the first direct observation of sp-d dopant-carrier exchange interactions in colloidal doped wurtzite CdSe nanocrystals. Doped diluted magnetic semiconductor quantum dots (DMS-QDs) were prepared by thermal decomposition of an inorganic precursor cluster in the presence of $TMCl_2$ (TM^{2+} = Mn^{2+} or Co^{2+}) in hexadecylamine and were characterized by multiple spectroscopic and analytical techniques. Using magnetic circular dichroism spectroscopy, successful doping and the existence of giant excitonic Zeeman splittings in both Mn^{2+}- and Co^{2+}-doped wurtzite CdSe quantum dots are demonstrated unambiguously.

10:20am **MI-ThM8 Size-Dependent Excited State Dynamics in Mn^{2+}-Doped CdSe Quantum Dots**, ***R. Beaulac***, *P.I. Archer, V.A. Vlaskin, D.R. Gamelin*, University of Washington

Colloidal Mn^{2+}-doped II-VI quantum dots are interesting materials for the study of magnetic and luminescent phenomena in quantum confined semiconductor nanostructures. In recent years, several reports have described luminescence, absorption and magnetism of Mn^{2+}-doped ZnS, CdS and ZnSe quantum dots. In general, the emission properties of these nano-scale materials behave much like their bulk counterparts, showing a size insensitive Mn^{2+} ligand-field emission with a long lifetime. In contrast, Mn^{2+}-doped CdSe nanoparticles are expected to behave differently from bulk because of the possibility of size-tuning the band-gap energy from below to above the Mn^{2+} emitting level. For this reason, Mn^{2+}-doped CdSe offers an interesting opportunity for fundamental studies of quantum confinement effects in doped semiconductors. Curiously, although photoluminescence spectra of self-assembled Mn^{2+} quantum dots prepared by vacuum deposition have been reported, the Mn^{2+} is either absent of only tentatively reported, even for high Mn^{2+} concentrations. Moreover, CdSe excitonic emission is observed despite the fact that the energy gap is greater than the Mn^{2+} excitation energy. We recently presented a new method for preparing colloidal doped CdSe quantum dots.[1] Importantly, these particules show a giant Zeeman splitting of their excitonic transitions, as is expected for diluted magnetic semiconductors. Here we will describe the temperature-dependent photoluminescence of these particles, which gives insight into the energy transfer dynamics in Mn^{2+}-CdSe quantum dots. A kinetic model will be described that explains the paradoxical absence of Mn^{2+} emission in Mn^{2+}-doped CdSe quantum dots reported previously.

[1] Archer, P. I.; Santangelo, S. A.; Gamelin, D. R., Nano. Lett., 7, 1037-1043 (2007).

10:40am **MI-ThM9 Structural and Magnetic Properties of Mn-implanted 3C-SiC**, ***K. Bouziane***, Sultan Qaboos University, Oman

Unlike many Dilute Magnetic Semiconductors particularly Si based ones,[1] very little attention has been paid to SiC despite its potential for high-power, high-temperature electronics and its large compatibility with the mature Si technology. With its wide bandgap, excellent transport properties and dopability, it might be a promising candidate for spintronic applications. Due to a limited solubility of Mn in the host SiC materials, we have used Mn+ implantation (energy of 80 keV and dose of 5x1015 cm^{-2}) to achieve higher Mn atomic concentration of 1.8 % in micrometric thick 3C-SiC films; aiming to enhance the Curie temperature. We have used Rutherford backscattering (RBS) and X-ray diffraction (XRD) techniques to asses the defects introduced by Mn–implantation, as well as magnetometry to investigate the magnetic properties. RBS measurements on single SiC indicate high concentration of defects at a depth of about 45 nm from the surface, with Mn randomly distributed in the host SiC material. XRD spectra show no indication of formation of secondary alloying phase. Both single and polycrystalline implanted samples were found to be ferromagnetic at room temperature with a magnetic moment per Mn atom of about 0.37μB and 0.5μB, respectively. The amorphous layer was recrystallized after annealing at 750 °C for 10 min as indicated by RBS results, yielding an enhancement of magnetic moment. First principle calculation using Full-Potential Linearized-Augmented-Plane-Wave method for different environments and vacancy configurations was performed to better understand and establish a correlation between the structure/microstructure and magnetic properties of single and polycrystalline Mn-implanted 3C-SiC.

[1]M. Bolduc et al., Phys. Rev. B 71 (2005) 033302.

Magnetic Interfaces and Nanostructures

Room: 619 - Session MI-ThA

Magnetic Semiconductors II

Moderator: J. Shen, Oak Ridge National Laboratory

2:00pm **MI-ThA1 Ferromagnetism and Dopant Ordering in Semiconducting, Epitaxial Ti-doped α-Fe_2O_3 Hematite**, ***T.C. Droubay***, Pacific Northwest National Laboratory, *A. Celik-Aktas*, University of Wisconsin-Milwaukee, *K.M. Rosso*, Pacific Northwest National Laboratory, *S.M. Heald*, Argonne National Laboratory, *S.H. Cheung, C.M. Wang*, Pacific Northwest National Laboratory, *M. Gadjardziska-Josifovska*, University of Wisconsin-Milwaukee, *S.A. Chambers*, Pacific Northwest National Laboratory

The classical visualization of a ferromagnetic semiconductor is the random substitution of a fraction of the original atoms within the semiconductor lattice with magnetic atoms, most commonly transition metal ions. An alternate approach which has not garnered much attention until recently is the ordered substitution of non-magnetic metal ions into an otherwise antiferromagnetic semiconductor lattice. Ti-doped α-Fe_2O_3 has been suggested as such a material if Ti(IV) substitutes preferentially in one magnetic sublattice, effectively creating a ferrimagnetic semiconductor. To examine the ordering more fully, we have used oxygen plasma-assisted MBE to grow Ti-doped hematite on α-Al_2O_3(001) for various dopant levels between the endpoints Fe_2O_3 and $FeTiO_3$. Excellent heteroepitaxy was achieved by first growing a Cr_2O_3 buffer layer to grade the lattice mismatch. Fe was predominantly found to be in the +3 charge state by Fe K-shell XANES and Fe 2p photoemission, except at concentrations nearing x = 0.15. Ti was found to be exclusively in the +4 charge state and to uniformly substitute for Fe(III) in the hematite lattice by Ti K-shell XANES and EXAFS, accompanied by a significant site distortion. The resultant epitaxial films for low dopant concentration are magnetic at room temperature albeit with a fraction (~0.5 μ_B/Ti atom) of the 4 μ_B/Ti saturation magnetization expected if a magnetic ordered phase had nucleated exclusively. DFT predicts that the magnetically ordered and magnetically random structures are nearly iso-energetic which explains the weak normalized moment. We have investigated the atomic structure of the low-doped epitaxial ferromagnetic films using high-resolution TEM and electron diffraction analysis. HRTEM and electron diffraction confirm the lack of long-range chemical ordering of Ti along the [001] direction. HRTEM images show weak but discernable lines in $(Ti_xFe_{1-x})_2O_3$ along the growth direction with an average in-plane periodicity of ~0.94nm. Electron diffraction patterns corroborate this ordering by displaying additional diffraction spots perpendicular to the growth direction. These satellite spots are suggestive of Ti dopant ordering in the basal plane. A proposed atomic model of the dopant ordering including DFT calculations will be discussed in relation to the observed experimental electronic and magnetic properties.

2:20pm **MI-ThA2 Carrier-Dopant Exchange Interactions in Colloidal Mn^{2+}:ZnO Quantum Dots**, ***S.T. Ochsenbein***, *K.M. Whitaker, W.K. Liu, D.R. Gamelin*, University of Washington

Magnetically doped semiconductor nanocrystals present an interesting motif for possible spintronics applications. In such so-called diluted magnetic semiconductors (DMSs) the interaction between charge carriers and the dopant ions is the key factor defining their spintronics functionality. Ferromagnetism in some DMSs is attributed to carrier-mediated interaction between the dopant ions for example,[1] and thus depends strongly on carrier-dopant interactions. The effect of quantum confinement in DMS nanostructures on carrier-dopant interactions has been the subject of theoretical considerations,[2] but experimental investigations are scarce. We present experimental results addressing electron-Mn^{2+} interactions in colloidal Mn^{2+}:ZnO nanocrystals. Photochemical injection of conduction band electrons[3] allows the interaction between these quantum confined electrons and the Mn^{2+} ions to be studied by electron paramagnetic resonance (EPR) spectroscopy and magnetic measurements. The microscopic origins of the resulting perturbed magnetic properties will be described.

[1] Dietl, T.; Ohno, H.; Matsukura, F., Phys. Rev. B 2001, 63, 195205.
[2] Bhattacharjee, A. K., Phys. Rev. B. 1998, 58, 15660.
[2] Liu, W. K.; Whitaker, K. M.; Kittilstved, K. R.; Gamelin, D. R., J. Am. Chem. Soc. 2006, 128, 3910. .

2:40pm **MI-ThA3 Growth and Properties of Epitaxial Co- and Mn-doped ZnO Films**, ***T.C. Kaspar***, *T.C. Droubay, Y.J. Li, M.H. Engelhard, P. Nachimuthu, V. Shutthanandan, Z. Zhu*, Pacific Northwest National Laboratory, *S.M. Heald, D.J. Keavney*, Argonne National Laboratory, *C.A. Johnson, D.R. Gamelin*, University of Washington, *S.A. Chambers*, Pacific Northwest National Laboratory

Doping ZnO with transition metal ions may be a promising route to realize dilute magnetic semiconductors which are ferromagnetic above room temperature. Although several groups have reported room temperature ferromagnetism in both Co:ZnO and Mn:ZnO, significant controversy persists as to whether the observed ferromagnetism is intrinsic to doped ZnO or is due to extrinsic factors such as secondary phase formation. Of particular concern is the formation of ferromagnetic Co metal clusters in Co:ZnO, and potentially ferromagnetic Zn-Mn oxides in Mn:ZnO. The difficulty lies in the small quantity of secondary phase required to explain the observed weak ferromagnetism, often comprising less than 5% of the dopants (which themselves are generally only 10% or less of the total cations in the material). Conventional materials characterization techniques, such as x-ray diffraction (XRD) and transmission electron microscopy (TEM), can be insensitive to the small volume fraction of secondary phase involved, making detection difficult. Spectroscopic techniques, particularly x-ray absorption (XAS), can provide much more information on the charge state and local environment of the dopant. However, the detection limit at the K-edge is about 5% of the dopants for metal formation; oxide secondary phases can be more difficult to detect. A related issue concerns the determination of the location and role of p-type dopants in ZnO, since ferromagnetic ordering is only expected in Mn:ZnO when the material is p-type. Here we present a detailed study of Co:ZnO and Mn:ZnO thin films deposited by pulsed laser deposition. The ZnO quality and majority dopant behavior were probed by conventional characterization techniques such as XRD, TEM, and XAS, which indicated dopant substitution for Zn in ZnO. The possibility of a small fraction of secondary phase formation was investigated with several techniques including x-ray linear dichroism, Raman spectroscopy, and x-ray photoelectron spectroscopy (XPS) sputter depth profiling. In Co:ZnO, localized Co metal formation at the film surface under reducing conditions was not detectable by K-edge XAS but was clearly observed by XPS sputter depth profiling. The presence and location of the potential p-type dopants N and Li were investigated by secondary ion mass spectrometry and nuclear reaction analysis. The implications of secondary phase formation on ferromagnetism in Co:ZnO and Mn:ZnO will be discussed.

3:00pm **MI-ThA4 Manipulating Ferromagnetism in Co^{2+}:ZnO by Controlling Interstitial Zinc Concentrations**, ***C.A. Johnson***, *D.R. Gamelin*, University of Washington

Demonstration of reproducible intrinsic high-temperature ferromagnetism in diluted magnetic semiconductors (DMSs) is an important step toward their use in devices. Recently it has become apparent that understanding the defects in Co^{2+}:ZnO is paramount to understanding the microscopic origins of its ferromagnetism. We will describe that Co^{2+}:ZnO films can be made ferromagnetic by annealing under Zn vapor to create the Zn_i lattice defect.[1] Oxidation of the Zn-treated Co^{2+}:ZnO films at elevated temperatures results in a controlled quenching of the ferromagnetism as the Zn_i migrates out of the lattice and is oxidized.[2] These changes can be followed kinetically using both magnetic measurements and magnetic circular dichroism spectroscopy. These results demonstrate that ferromagnetism of Co^{2+}:ZnO thin films can be controlled by controlling Zn_i concentrations and provide new insights into the microscopic origins of this interesting magnetism.

[1] Schwartz, D.A. and D.R. Gamelin, Adv Mat, 2004. 16 2115-2118.
[2] Kittilstved, K.R., Schwartz, D.A., Tuan, A.C., Heald, S.M., Chambers, S.A., Gamelin, D.R., Phys Rev Let, 2006. 97 0372203.

3:40pm **MI-ThA6 Optimal Dopant Control of High-Tc Diluted Magnetic Semiconductors via Subsurfactant Epitaxy or n-p co-doping***, ***Z. Zhang***, Oak Ridge National Laboratory and University of Tennessee **INVITED**

Recent developments of diluted magnetic semiconductors (DMS) seem to suggest that one must rely on nano-phase separations inside the DMS films of III-V and column-IV semiconductors in order to achieve high magnetic ordering temperatures (Tc>300K). Here we present two conceptually new and intriguing approaches to enhance substitutional doping of Mn in Ge and Si, based on first-principles calculations. One is via subsurfactant epitaxy, the other is via n-p co-doping. In the former case, the resultant materials exhibit homogeneous distributions of substitutional Mn dopants with Tc>300K, as observed experimentally. In the latter case, we find that co-doping faciliates the efficiency of Mn substitutional occupation, and

observe dramatically enhanced anisotropy in the ferromagnetic coupling between the dopants. These results will be compared in connection with the recent developments of the field emphasizing the importance of nano-columns within the DMS.

*Work done in collaboration with Wenguang Zhu, Hanno Weitering, Changgan Zeng, Enge Wang, Tim Kaxiras, Mina Yoon, Klaus van Benthem, and Matthew Chrisholm. Supported by US. NSF (Grant No. DMR-0606485), the NSF of China, and by the Division of Materials Sciences and Engineering, Office of Basic Energy Sciences, US Department of Energy, under contract DE-AC05-00OR22725 with ORNL, managed and operated by UT-Battelle, LLC.

4:20pm **MI-ThA8 Formation Mechanism of Self-assembled Nanocolumns in (Ge,Mn) Epitaxial Films***, ***W. Zhu***, University of Tennessee, *M. Yoon,* University of Tennessee and ORNL, *Z. Zhang*, ORNL and University of Tennessee

The spatial distribution of magnetic dopants in diluted magnetic semiconductors is critical in determining the magnetic property of the materials. Traditionally, the magnetic dopants were viewed to be homogeneously distributed in the host semiconductors. Recently, self-assembled Mn-rich nanocolumns were observed experimentally in (Ge,Mn) epitaxial films, which exhibit remarkable magnetic properties.[1] Here, we propose a microscopic formation mechanism for the nanocolumns, involving the interplay between the electrostatic attractions of oppositely charged Mn ions and effective long-range repulsions due to elastic effect. Based on first-principles calculations and kinetic Monte Carlo simulations, we show that the proposed mechanism can successfully explain the formation of the self-assembled Mn-rich nanocolumns in the (Ge,Mn) epitaxial systems. We also discuss the potential applicability of the proposed model to other related systems.

*Work supported by US. NSF (Grant No. DMR-0606485), and by the Division of Materials Sciences and Engineering, Office of Basic Energy Sciences, US Department of Energy, under contract DE-AC05-00OR22725 with ORNL, managed and operated by UT-Battelle, LLC.

[1] M. Jamet et al., Nat. Mater. 5, 653 (2006); A. P. Li et al., Phys. Rev. B 75, 201201(R) (2007).

4:40pm **MI-ThA9 Ferromagnetism in Mn Doped Ge Thin Films**, ***J. Yu***, *J. Lu, K.G. West, L. He, R. Hull, S.A. Wolf*, University of Virginia

Ferromagnetism in Group IV semiconductors produced by transition metal doping is of great interest due to their potential applications in spintronics. In this study, we use ion implantation to introduce Mn ions into Ge. 0.5~4 at. % Mn ion was implanted into 200 nm Ge thin films. Both single implantation and dual implantation were used to prepare samples. The dual ion implantation was performed at 75 °C to improve the uniformity of Mn distribution and avoid formation of a ferromagnetic Mn5Ge3 phase which forms at higher implant temperatures. The implantation damage to Ge was healed by rapid thermal annealing at temperatures ranging from 300 to 800 °C in forming gas. Moment vs. Temperature showed that the ferromagnetic transition temperature was ~ 60 K for 4% samples annealed at 300 °C for 1.5 minutes. The saturation moment at 5K is 0.12 Bohr magnetons per Mn. Transport measurements using the Van der Pauw method were performed to study the correlation between the magnetization and resistivity of Mn:Ge. Significant magnetoresistance and anomalous Hall effect were observed on samples annealed at 300 °C for 1 and 1.5 minutes. The normal and anomalous Hall coefficients are both calculated and confirmed with transport measurement. Cross-section TEM study is underway to determine the phase composition and the distribution of Mn ions in this dual implanted sample annealed at 300°C.

5:00pm **MI-ThA10 Atomic and Electronic Structure of Manganese Alloys on Ge(100) Surface**, ***H. Kim***, *G.E. Jeong, K.H. Chung, S.-J. Kahng*, Korea University

Ferromagnetic metals on semiconducting surfaces are promising for spintronics application. The surface structures of Mn5Ge3(111) alloy on Ge(100) surfaces were studied with scanning tunneling microscope. The plateau structures of Mn5Ge3 were prepared by solid phase epitaxy. Clear hexagonal atomic structures were observed on top of the plateau structures. In support of diffraction experiments and previous theoretical predictions, we were able to confirm that the plateau structures are Mn5Ge3 alloys with the top surfaces along (111) directions. Several atomic patterns, with strong bias-energy dependence, were observed in topography images. As the patterns are compared with theoretical predictions, it is believed that the atomic structures of second layers were observed at certain energy levels. Three types of defect structures were observed in STM images, whose atomic structures will be discussed.

Magnetic Interfaces and Nanostructures

Room: 619 - Session MI-FrM

Spin Injection, Transfer, and Tunneling

Moderator: G.J. Mankey, University of Alabama

8:00am **MI-FrM1 High-Efficiency Spin Injection through the Depleted Edge of a Magnetic Semiconductor**, ***M.E. Flatté***, The University of Iowa **INVITED**

Dilute ferromagnetic semiconductors are composed of magnetic dopants (such as Mn) that interact strongly with each other through a host nonmagnetic semiconductor (such as GaAs) over distances of order one nanometer to establish the ferromagnetic state. The interaction is mediated by holes, which at low concentrations are bound to the dopants and at high concentrations become mobile. Theoretical and experimental studies of the Curie temperature and carrier spin polarization of $Ga_{1-x}Mn_xAs$ find them to depend strongly on the hole density, and a local mean-field theory has been developed that quantitatively accounts for many of the bulk properties of these materials in terms of the mean hole density. However, the properties near the edges of magnetic semiconductors, where the carrier concentration and dopant concentration are changing rapidly over the interaction's length scale of a nanometer, cannot be accounted for within a local mean-field theory. A theory of magnetic interactions in the highly depleted regime has been built on the foundation of a quantitatively-accurate theory of the interaction energy of a single pair of widely-separated Mn dopants in GaAs. Predictions from this theory of the interaction between Mn dopants have been confirmed by experimental measurements via scanning tunneling microscopy. This theory also provides a new explanation of the origin of the unusual magnetic anisotropies in strained low-doped (even insulating) ferromagnetic $Ga_{1-x}Mn_xAs$. The resulting theory for the edges of a magnetic semiconductor suggests that the carrier spin polarization at those edges should be much larger than in the bulk of the material, and may even approach 100%. Measurements of carrier transport across highly-depleted $Ga_{1-x}Mn_xAs$ suggest that these very high spin polarizations are real, and that they may provide an alternate pathway to nearly 100% efficient spin injection.

8:40am **MI-FrM3 Spin Injection in Organic Spintronics**, ***C.-J. Sun***, Oak Ridge National Laboratory, *B. Hu*, University of Tennessee, Knoxville, *J. Shen*, Oak Ridge National Laboratory

Organic spintronics is an emerging field of nanoscale electronics involving the detection and manipulation of electronic spins in heterostructures that consist of organic and magnetic materials.[1] Compared to conventional inorganic spintronics, organic spintronics offer distinct advantages such as ease of device fabrication and intrinsic low spin scattering rate and high spin coherence over both time and distance.[2] These characteristics make organic spintronic devices plausible to operate at room temperature.[3] In this study, we fabricated spin valve devices that uses Co thin films and a manganite thin film as two ferromagnetic electrodes and an organic molecule layer as the spacer layer. A modified superconducting quantum interference device (SQUID) is used to measure local tunneling magneto-resistance (TMR) and determine spin injection efficiency as a function of thickness of Co thin films, bias voltage, and operating temperature. The mechanism of spin injection from Co thin films is addressed.

[1]Z. H. Xiong, D. Wu, Z.V. Vardeny, and J. Shi, "Giant magnetoresistance in organic spin-valves", Nature 427, 821 (2004).

[2]Alexander R. Rocha, Victor M. Garcia-Suarez, Steve W. Bailey, Colin J. Lambert, Jaime Ferrer, Stefano Sanvito, "Towards molecular spintronics", Nature Mater. 4, 335(2005).

[3]V. Dediu, M. Murgia, F. C. Matacotta, C. Taliani, S. Barbanera, "Room temperature spin polarized injection in organic semiconductor", Sol. Stat .Comm. 122, 181(2002). .

9:00am **MI-FrM4 Edge Emitting Spin-Lasers**, ***A.T. Hanbicki***, *G. Kioseoglou, O.M.J. van 't Erve, C.H. Li, I. Vurgaftman, J.R. Meyer, B.T. Jonker*, Naval Research Laboratory

Using a spin polarized current to drive a laser promises to provide threshold reduction, increased polarization of the output light, and intensity stabilization. Optically and electrically driven surface emitting lasers using InGaAs active regions have proven that indeed, spin currents can lead to threshold reduction.[1,2] We have designed and fabricated edge emitting structures based on the Fe/AlGaAs/GaAs spin injecting system to simplify and further understand this process. Samples were designed and grown to enable fabrication of either surface emitting spin-LEDs or edge emitting lasers. Specifically, a wide GaAs quantum well (QW) was grown between thick Al(35%)GaAs barriers. A 1500 Å QW serves as both a recombination region for surface emitting electroluminescence measurements and as a laser cavity for edge emitting structures. The top cladding layer is also 1500 Å, thick enough to prevent absorption by the spin injecting source, Fe, but thin enough to preserve spin injection into the recombination region. In the surface emission geometry, the behavior was similar to our standard wide-QW spin-LED structures.[3] At low temperature, emission in dominated by an H-band feature,[4] and by 20 K the emission is mainly from the bulk recombination feature. With the magnetization saturated out-of-plane, we measure electron polarizations of 24%. Cleaved cavity, gain-guided, edge emitting lasers show robust emission, however, the quality of cleaved interface greatly influences the emission spectrum.

[1]Rudolph et al., Appl. Phys. Lett. 82 (2003)
[2]Holub et al., Phys. Rev. Lett. 98 (2007)
[3]van 't Erve et al., Appl. Phys. Lett. 89 (2006)
[4]Kioseoglou et al., Appl. Phys. Lett. 87 (2005)

9:20am **MI-FrM5 High Frequency Nanoscale Spin Transfer Devices**, ***S.E. Russek***, National Institute of Standards and Technology **INVITED**

Spin transfers effects become important in multilayer magnetic devices whose dimensions are below 100 nm. The transfer of electron spin momentum can induce switching of magnetic layers or microwave precession of the magnetization. Spin transfer, coupled with giant magnetoresistance and tunneling magnetoresistance, can be used to develop new types of magnetic random access memory (SpinRAM), spin transfer nano-oscillators (STNOs), and spin transfer nano-detectors (STNDs). In this talk I will review high-speed spin transfer switching in nanoscale magnetic SpinRAM devices and the effects of thermal fluctuations and defects on the switching process. Next, I will present data on the linewidths, tunability, and phase control of STNOs, including data for both single domain oscillators and vortex oscillators. STNOs and STNDs have the advantage of small size, high tunability, broad frequency range (2 GHz to 100 GHz), and CMOS compatibility. However, there are intrinsic limitations in the linewidth due to thermal fluctuations, limitations due to the required applied fields, and limitations due to the sensitivity to nanoscale defects and patterning. I will discuss these challenges and the progress made towards making practical spin transfer devices for use in high-frequency communication and signal processing applications.

10:00am **MI-FrM7 Low Resistance Synthetic Antiferromagnet Coupled Spin Valves**, ***Z.R. Tadisina***, *S. Gupta, A. Highsmith, P. LeClair, T. Mewes, G.B. Thompson*, The University of Alabama

The magnetic properties of current-perpendicular-to-the-plane (CPP) giant magnetoresistive (GMR) spin valves employing synthetic antiferromagnet (SAF) pinning have been investigated. The standard CPP spin valve structure, with a ferromagnetic (F) layer pinned by an antiferromagnet (AF), exhibits high electrical resistance, the antiferromagnet typically being a high resistivity material. We have investigated pinning with a Co/Ru/Co SAF trilayer only, with no additional AF pinning. Elimination of the AF-induced parasitic resistance yields a higher GMR ratio. The full-film properties have been optimized using vibrating sample magnetometry (VSM) and current-in-plane (CIP) magnetotransport measurements, and related to CPP spin valve properties after patterning. A theoretical simulation of the M-H and R-H loops of the SAF-pinned spin valves is compared with these experimental results. Interlayer exchange energies for the SAF obtained from experimental measurements for the various structures were used in the theoretical simulations to improve the fit and optimize the structure. The thermal stability of various SAF structures and the corresponding SAF-pinned spin valves have also been studied and compared with those of AF+SAF-pinned and hard magnet-pinned spin valves reported on previously.[1] Structural characterization of the layers and interfaces have been carried out by high-resolution transmission electron microscopy (HRTEM). Three-dimensional atomic scale characterization of the interdiffusion between layers has been conducted using a Local Electrode Atom Probe (LEAP).

[1] "A Novel Scheme for Pinning Magnetic Layers in Current Perpendicular to the Plane Spin Valve Devices", C. Papusoi, Z. Tadisina, S. Gupta, H. Fujiwara, G.J. Mankey, and P. LeClair, presented at 53rd AVS International Symposium, San Francisco, CA, November 12-17 (2006).

10:20am **MI-FrM8 Fabrication Technology for Magnetic Random Access Memory**, ***M.C. Gaidis***, *E.A. Joseph, E.J. O'Sullivan, S. Assefa*, IBM

Magnetic Random Access Memory (MRAM) offers the potential of a universal memory – it can be simultaneously fast, nonvolatile, dense, and high-endurance. Depending on application, these qualities can make MRAM more attractive than SRAM, DRAM, flash, and hard drive memories, with a market measured in the billions of dollars. Small-scale demonstrations have realized much of the potential of MRAM, but scaling the memory to competitive sizes or embedding the memory with logic

circuitry creates unique processing challenges. The building of MRAM memories in back-end-of-line (BEOL) circuitry imposes additional requirements on processes which conform to existing semiconductor fabrication facility standards. This presentation provides an overview of the basic MRAM structure and operation, followed by a discussion of MRAM-specific processing techniques and developments to obtain high yield across 200mm substrates. The potential for scaling MRAM for future generations with spin-momentum-transfer (SMT) devices will be discussed in this framework. Practical limitations on SMT scaling, and SMT adaptation of conventional MRAM processing will be reviewed.

10:40am **MI-FrM9 Beyond Fe-MgO-Fe: Alternative Barriers and Systems**, ***P. LeClair***, University of Alabama **INVITED**

Magnetic tunnel junctions have been an intensely active area of research since the first reliable demonstrations of tunneling magnetoresistance (TMR). However, there are only a few systems to date that experimentally show a large TMR effect at room temperature. One of the most recent and effective are ordered Fe/MgO/Fe(001) trilayers (bcc FeCo-based alloys may also be substituted for pure Fe). This system was initially predicted theoretically by Butler et al. to exhibit large TMR, and later experimentally verified by Yuasa et al and Parkin et al. The nearly four-fold improvement in magnetoresistance over earlier polycrystalline/amorphous structures has been attributed to the complex energy band matching between Fe and MgO. This promotes the tunneling of electrons from specific ("delta-1") bands in Fe(001) which exist only for majority spin electrons. The MgO tunnel barrier thereby acts as a 'spin filter.' At the most basic level, the tunneling rates for specific metallic states are controlled by the symmetry of the insulating barrier, which gives a general mechanism for large TMR. In this talk, I will try to outline the theoretical and experimental criteria for large TMR effects based on this 'spin filtering' effect, and attempt to answer the questions "Why does the Fe-MgO system work so well?" and "Is Fe-MgO a unique system?" Both experimental and theoretical considerations are crucial for realizing large TMR effects in realistic structures, and both viewpoints are necessary to explain the (initially surprising) large TMR effects in, e.g., CoFeB/ MgO/CoFeB. I will review our recent work on predicting and fabricating new TMR systems analogous to Fe-MgO-Fe, with a particular focus on alternative tunnel barriers, including organic systems. Finally, I will discuss spin-polarized tunneling characterization methods, in particular Meservey-Tedrow tunneling. This work is supported by the National Science Foundation.

11:40am **MI-FrM12 High Frequency Magnetic Properties of Amorphous and Crystalline CoFeB**, ***M. Pathak***, University of Alabama, *P. Janssen,* Eindhoven University of Technology, The Netherlands, *L. Wen, H. Lee, J.L. Weston, T. Mewes, P. LeClair*, University of Alabama

The recent demonstrations of extraordinarily large tunneling magnetoresistance effects in CoFeB-MgO-CoFeB trilayer structures has generated an enormous interest in the magnetic and structural properties of CoFeB alloys. In particular, the amorphous to crystalline transition plays a crucial role in realizing large magnetoresistive effects. From an application point of view (e.g., hard disk read heads), a clear understanding of the high frequency magnetic properties of these materials is required. To this end, we have studied the ferromagnetic resonance properties of CoFeB thin films up to 40GHz. We sputter deposited $Co_{56}Fe_{24}B_{20}$ films of different thickness ranging from 5nm to 40nm on oxidized Si(100) substrates, and studied the magnetization damping and crystallization as function of film thickness and annealing temperature. FMR data from 0-7 GHz were obtained using a network analyzer with both frequency and field swept, and from 7-40 GHz using rectangular shorted waveguides. FMR results suggest an increase in damping (α=0.0068 to α=0.013) with decreasing film thickness, which is more pronounced after annealing. The observed increase in coercivity with decreasing thickness after annealing (e.g. 375°C) suggests crystallization of $Co_{56}Fe_{24}B_{20}$, which is confirmed by VSM, XRD, and TEM analysis.

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