

**MRS 07 Fall Meeting Symposium I**  
Nanoscale Magnetic Materials and Applications  
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**Executive summary:**

Nanostructured magnets share many of the basic principles as for other nanostructured materials such as geometric confinement, physical proximity, and chemical self organization. These principles are illustrated by means of several examples drawn from the quests for ultrastrong permanent magnets, ultrahigh-density magnetic information storage, and biomedical applications. This symposium addresses the challenges and scientific problems in magnetic nanostructures, from the fundamental issues to fabrication and applications. This symposium has provided a forum for physicists, chemists and materials scientists/engineers and bio-physicists, to present current research on advanced magnetic materials and applications and to initiate collaborative interactions between them. This symposium has also been a good opportunity for young scientists (graduate students and postdoctoral fellows) to present their research results and interact with established members of their own and other scientific fields.

**Session topics:****Topics included:**

- Magnetic ordering at Nanoscale
- Exchange coupling and exchange bias
- Ferromagnetic nanoparticles
- Self assembly of magnetic nanoparticles
- Patterned media for magnetic recording
- Magnetic thin-film and nanowire devices for information technologies
- Exchange-coupled hard/soft bilayers for recording media applications
- Exchange-coupled nanocomposite permanent magnets
- Hard magnetic thin films and devices
- Rare-earth transition-metal permanent magnets
- Nanostructured soft magnets
- Emergent magnetic materials for energy-related applications
- Novel processing techniques for magnetic nanostructures
- Biomedical applications of magnetic nanoparticles

### **Invited speakers:**

**S. D. Bader** (Argonne National Lab, on nanomagnetism), **E. Brück** (Univ. of Amsterdam, The Netherlands, on magnetocaloric materials), **J. M. D. Coey** (Trinity College-Dublin, Ireland, on spintronic materials), **R. Cowburn** (Imperial College London, United Kingdom, on spintronic logic devices), **N. Dempsey** (Lab. Louis Neel, CNRS-Grenoble, France, on hard magnetic thin films), **J. Gao** (Univ. of Texas Southwestern Medical Center, biomedical application of magnetic nanoparticles), **A. Gupta** (Univ. of Alabama, on multifloics), **K. A. Gschneidner Jr.** (Iowa State Univ., on magnetocaloric materials and devices), **J. W. Harrell** (Univ. of Alabama, on ferromagnetic nanoparticles for data storage), **S. Jin** (Univ. of California – San Diego, on patterned recording media), **R. W. McCallum** (Ames National Lab, on processing of advanced permanent magnetic materials), **O. Mryasov** (Seagate Technology, on high areal density recording media), **K. O'Grady** (Univ. of York, United Kingdom, on exchange biased materials), **S. S. Parkin** (IBM Almaden Research Ctr., on racetrack storage memory), **J. Shield** (Univ. of Nebraska, on exchange coupled nanocomposite magnets), **T. Shima** (Tohoku Univ., Japan, on high performance magnetic thin films), **I. Schuller** (Univ. of California-San Diego, on magnetic nanostructures), **R. D. Shull** (National Inst. of Standards and Technology, on nanocomposite magnetic materials), **I. Takeuchi** (Univ. of Maryland, on combinatorial investigation of nanocomposite magnets), **J. P. Wang** (Univ. of Minnesota, on high areal density recording media), **S. X. Wang** (Stanford Univ., on biomagnetic sensors), **X. Wang** (Hong Kong Univ. Of Scie. & Techno., on spin dynamics), **Z. L. Wang** (Georgia Inst. of Technology, on magnetic nanostructure characterizations), **H. Zeng** (State Univ. of New York-Buffalo, on magnetic nanoparticles), **Y. Zhu** (Brookhaven National Lab, on characterization of advanced magnetic materials).

### **Symposium Organizers:**

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## **Final report:**

### **I. Primary Objectives and Scope of the Symposium**

Magnetic materials and devices have played a major role in science and technology for much of the twentieth century. The aim of Symposium I, Nanoscale Magnetic Materials and Applications, was to bring together materials researchers working on magnetic phenomena at the nanoscale to discuss recent progress in the materials research and applications.

*The financial support provided by ONR, DARPA, Quantum Design, Springer and other sponsors enabled to have a symposium reception for all the invited speakers and session chairs during the conference and in addition to give partial travel support to seven international invited speakers and an invited speaker from industry (Dr. S.S. Parkin, IBM).*

### **II. Symposium highlights:**

A total of one hundred seventy abstracts were submitted to this symposium and thirty invited speakers gave their talks in the symposium. This was one of the few largest symposia among all the forty symposia in the MRS 07 Fall meeting. To accommodate as many presentations as possible, 15 sessions (including three poster sessions) were arranged. The turnout of the tutorial and sessions in magnetic nanoparticles, bulk magnets, nanowires, and biomedical applications was very high.

Emerging nano-science techniques (i.e. lithography and self assembly) provides dimensional control that goes beyond that achievable in bulk materials. The resulting revolution in magnetic materials and devices over the last 20 years is quite dramatic with many opportunities for materials research as outlined by S. Bader (ANL).

Current magnetic nano-technologies have their roots in the development of bulk materials, such as permanent magnets where the functionality is derived from a complex two-phase microstructure. Invited speakers R. W. McCallum (Iowa State U.) and J. Shields (U. Nebraska) discussed the state of the art in two-phase permanent magnet. In a contributed talk, C. Rong from the University of Texas–Arlington presented for the first time their results in bulk SmCo/Fe nanocomposite with full density fabricated by warm compaction. The isotropic bulk nanocomposite magnets have energy product of 16 MGOe which are about 70% enhancement compared to the single-phase counterpart.

A number of talks described new applications arising from the ability to control magnetism at the nanoscale. Recent developments in manipulating domain walls in magnetic wires using fields and currents opens the door for new logic and storage devices as described by R. Cowburn (Imperial College, UK) and S. S. P. Parkin (IBM). I. K. Schuller (UCSD) and M. Coey (U. Dublin, Ireland) each described recent advances in the understanding of temperature on magnetic tunnel junctions that provide the basis for emerging memory and sensor applications. N. M. Dempsey (Institute Neel, France) reviewed the progress in using nano-patterned hard magnetic films provide unique opportunities for MEMS and magnetic levitations. An emerging field is bio-magnetism where magnetic nano-particles are used to tag interesting biological molecules as



discussed by J. Gao (UTSouthwest Medical Center) described using functionalized particles for magnetic imaging and drug delivery while S. Wang (Stanford) outlined approaches for magnetic sifters and micro-fluidic devices for molecular biology applications.

In the *MRS meeting scene-Day 5* the following news was reported:

#### Symposium I: Nanoscale Magnetic Materials and Applications

Magnetic nanowires and nanorods could be used for localized cancer treatments in humans. By localizing these near cancer cells and using MRI with AC magnetic fields, it is possible to generate local heating resulting in cancerous cells weakening or dying, leaving behind living healthy cells. This is one of the motivations behind the work of Jenny Morber of Georgia Tech in developing iron oxide nanowires and nanorods. She described the use of pulsed laser deposition to form these structures. Single crystals of  $\text{Fe}_3\text{O}_4$  and  $\alpha\text{-Fe}_2\text{O}_3$  were formed. Interestingly, in addition,  $\epsilon\text{-Fe}_2\text{O}_3$  phase was also observed. This phase has not been talked about since the 1950s and is a metastable phase of hematite. This represents a new reaction pathway for this phase.  $\epsilon\text{-Fe}_2\text{O}_3$  has very interesting properties and should have useful magnetic properties. However, it was mixed in with other phases and it was difficult to isolate it. It may also not be water soluble. Therefore a wet synthesis technique was used to form  $\epsilon\text{-Fe}_2\text{O}_3$  using PEG-1000. Work on this is promising and continuing. Though it still has unreacted parts among the nanowires, this does overcome other problems encountered using PLD. Future plans for study by Morber include biocompatibility and MRI heating studies.

The question Stuart Parkin of IBM, Almaden, is trying to answer is whether it is possible to build a solid state memory device with the storage capacity of current disk drives. His goal is to build a solid state memory device with no moving parts that has 100 times lower cost compared to conventional memory devices with moderate to high performance. He described the current-induced motion of magnetic domain walls confined to nanostructures, in this case nanowires of permalloy, wherein the domain wall serves as the logic gate or memory element. This novel storage-class memory will use magnetic domains to store information in a "magnetic race-track". The magnetic race track is comprised of tall columns of magnetic material arranged perpendicular to the surface of a silicon wafer. The domains are shifted up and down the race-track by nanosecond long pulses of spin polarized current using the phenomenon of spin momentum transfer. Parkin described current-induced resonant excitation and motion of domain walls in the nanowires. The injection of spin polarized current below a threshold value through a domain wall confined to a pinning potential results in its precessional motion within the potential well. Using a short train of current pulses, whose length and spacing are tuned to this precession frequency, the domain wall's oscillations could be resonantly amplified. This allows for the motion of domain walls with much reduced spin polarized currents, more than five times smaller than in the absence of resonant amplification. For the near term, horizontal racetrack memories have been constructed since they are easier to build. Parkin indicated that these are still better than the densest NAND flash devices currently available. The physics behind these structures are very



interesting and he touched upon some of the physics aspects. His group has thus demonstrated the fundamental concept of a magnetic racetrack memory device.

### **III. Interactions/Networking /Training Experiences**

There were 5 days of oral presentation sessions with each session topic highlighted by two invited speakers. Invited talks were chosen to educate researchers about the state-of-the-art in nanoscale magnetic materials. The symposium also utilized three full evenings for poster sessions. Both oral and poster sessions were well-attended, providing opportunities for student presenters and attendees to interact and network with researchers from other fields.

### **IV. Contributions to Education and Outreach**

Prof. Shouheng Sun and Prof. J. Ping Liu gave a tutorial “Magnetic Nanoparticles and Nanocomposite Magnets” on November 26. More than fifty graduate students and other interested audience attended the tutorial. The tutorial covered main aspects of the “bottom-up” fabrication of nanocomposite magnets. The talks started with chemical synthesis of monodisperse magnetic nanoparticles of FePt, SmCo, Fe, and CoFe with size and shape control. Examples of the morphological, structural and magnetic characterizations of the magnetic nanoparticles were given. The talks also outlined other techniques in magnetic nanoparticle preparation, including the newly developed surfactant-assisted ball milling and salt-matrix annealing. The talks further elaborated the fundamental concepts of exchange-coupled nanocomposite magnets and illustrated how to use self-assembly and advanced engineering processing techniques to fabricate bulk nanocomposite magnets with enhanced energy products. Applications of magnetic nanoparticles and nanocomposite magnets were also briefly discussed. The short course offered the attendee important basics on research in magnetic nanoparticles and nanocomposite magnets.

### **V. Contributions within the discipline**

This symposium contributed to the dissemination of frontier research on nanoscale magnetic materials through numerous oral and poster presentations over 5 days. Topics ranged from fundamental nanomagnetism to bulk magnets processing and applications.

### **VI. Contributions to other disciplines**

Presentations on applications and devices based on nanoscale magnetic materials provided a forum for highlighting the impact of nanoscience and nanotechnology in other fields such as biomedicine and energy conversion.



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# Symposium I: Nanoscale Magnetic Materials and Applications

## SYMPOSIUM I



### I: Nanoscale Magnetic Materials and Applications

November 25 - 30, 2007

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Symposium Proceedings Series.

\* Invited paper

## TUTORIAL

I: Magnetic Nanoparticles and Nanocomposite Magnets  
Sunday November 25, 2007  
8:30 AM - 12:00 PM



## Room 206 (Hynes)

The tutorial covers the main aspects of the "bottom-up" fabrication of nanocomposite magnets. It will start with the chemical synthesis of monodisperse magnetic nanoparticles of FePt, SmCo, Fe, and CoFe with size and shape control. Examples of the morphological, structural, and magnetic characterizations of the magnetic nanoparticles will be given. Other techniques in magnetic nanoparticle preparation will also be outlined, including the newly developed surfactant-assisted ball milling and salt-matrix annealing. The tutorial will elaborate on the fundamental concepts of exchange-coupled nanocomposite magnets, demonstrating how to use self assembly and advanced engineering processing techniques to fabricate bulk nanocomposite magnets with enhanced energy products. Applications of magnetic nanoparticles and nanocomposite magnets will be briefly discussed. The tutorial will offer the attendee important basics on research in magnetic nanoparticles and nanocomposite magnets.

**Instructors:****J. Ping Liu**

University of Texas-Arlington

**Shouheng Sun**

Brown University

## SESSION I1: Nanomagnetism, Theoretic Aspects

Chair: Dave Sellmyer

Monday Morning, November 26, 2007

Commowealth (Sheraton)

**8:30 AM I1.1**

**Domain Wall Formation and Domain Wall Resistivities in  $\text{Co}_c\text{Fe}_{1-c}$  and  $\text{Co}_c\text{Ni}_{1-c}$ .** Peter Weinberger, Center for Computational Materials Science, Vienna, Austria.

In using the fully relativistic versions of the Screened Korringa-Kohn-Rostoker method and of the Kubo-Greenwood equation equilibrium domain wall widths and corresponding domain wall resistivities are calculated for  $\text{Co}_c\text{Fe}_{1-c}$  and  $\text{Co}_c\text{Ni}_{1-c}$  making use of a multi-scale approach. It is found that in  $\text{Co}_c\text{Fe}_{1-c}$  the domain wall width becomes rather large at about  $c=0.4$ , but does not show an obvious singularity in the vicinity of the bcc to fcc phase transition. In  $\text{Co}_c\text{Ni}_{1-c}$  the domain wall width varies much less with respect to the concentration. Furthermore, it is demonstrated that as compared to the homogeneous infinite systems the anisotropic magnetoresistance is reduced in the presence of a domain wall. This reduction is rather big for  $\text{Co}_c\text{Ni}_{1-c}$ , while for  $\text{Co}_c\text{Fe}_{1-c}$  it is only of the order of 1 - 2%.

**8:45 AM I1.2**

**Magnetization Reversal in Small FePt:Fe Particles.** Ralph Skomski<sup>1</sup>, J. Ping Liu<sup>2</sup>, Chuan-bing Rong<sup>2</sup> and David J. Sellmyer<sup>1</sup>; <sup>1</sup>Nebraska Center for Materials and Nanoscience, and Department of Physics and Astronomy, University of Nebraska, Lincoln, Nebraska; <sup>2</sup>Department of Physics, University of Texas, Arlington, Texas.

Using a salt-matrix annealing method, it has recently become possible to produce small Fe-Pt nanoparticles with a very narrow size distribution [1]. The size of the particles, about 3 nm, and the high anisotropy of L10-ordered FePt make these particles the smallest ever-produced particles with stable room-temperature ferromagnetism. However, the magnetization reversal in these particles is little understood. The main reason is the involvement of several types of ordering, namely disordered, ordered, partially ordered, and coexistence of ordered and disordered phases. Furthermore, the anisotropy near the surface of Fe-Pt particles is known to differ from the bulk anisotropy. We present micromagnetic simulations for nanoparticles of varying size and structure. The considered geometries include core-shell particles with a shell of reduced anisotropy, hemispherical hard-soft composites, and coated hemispheres. The parameters varied are the anisotropy of the involved phases and the thickness of the shell. In some cases, different structures yield nearly identical hysteresis loops, so the understanding of the particles require additional structural and magnetic information, such as magnetic-viscosity measurements and high-resolution TEM. In fact, the most important parameter is the uniaxial anisotropy averaged over the particles, with relatively small corrections due to structural and magnetic inhomogeneities. In our simulations, differences are also resolved by separately monitoring the magnetizations of the ordered and disordered phases, which makes these computer experiments a viable tool for the investigation of two- and multiphase nanostructures. — This research is supported at Nebraska by DOE and NCMN, and at Texas by DARPA/ARO and DoD/MURI. — [1] C. B. Rong, D. R. Li, V. Nandwana, N. Poudyal, Y. Ding, Z. L. Wang, H. Zeng and J. P. Liu, Adv. Mater. 18, 2984 (2006).

**9:00 AM I1.3**

**Surface Induced Reduction of Magnetization in Nanoparticles with Competing Exchange Interactions.** Christopher Westman<sup>1</sup>, Joshua Koch<sup>1</sup>, Renat Sabirianov<sup>1</sup> and Hao Zeng<sup>2</sup>; <sup>1</sup>Physics, University of Nebraska at Omaha, Omaha, Nebraska; <sup>2</sup>Physics, University at Buffalo, the State University of New York, Buffalo, New York.

Magnetic properties of nanoparticles are a subject of active research because of their potential applications in magnetic memory, spintronics and biomedical fields. Magnetic nanoparticles frequently exhibit the reduction of saturation magnetization. A model based on competing exchange interactions is presented for the investigation of nanoparticle magnetization. The ferromagnetic (FM) and antiferromagnetic (AFM) exchange interactions contribute differently at the nanoparticle surface and interior, leading to reduced ferromagnetic order at the surface. This model predicts an unconventional temperature dependence of magnetization and a magnetically "dead layer" at finite temperatures. The competing exchange interactions are modeled with nearest neighbors being FM and second nearest neighbors AFM. We use Heisenberg model Hamiltonian and Monte Carlo method to find magnetization, susceptibility and related properties as function of temperature. This is confirmed by temperature dependent magnetization and Mössbauer measurements of FePt nanoparticles. The effects are sensitive to particle size and surface terminations.

**9:15 AM I1.4**



**Two Different Magnetization Reversal Modes in Iron Oxide Nanotubes of Systematically Varied Geometry.** Julien Bachmann<sup>1</sup>, Juan Escrig Murua<sup>2</sup>, Jing Jing<sup>1</sup>, Dora Altbir<sup>2</sup>, Ulrich Goesele<sup>1</sup> and Kornelius Nielsch<sup>1</sup>; <sup>1</sup>Experimental Department II, Max Planck Institute of Microstructure Physics, Halle, Germany; <sup>2</sup>Departamento de Fisica, Universidad de Santiago de Chile, Santiago, Chile.

Ordered arrays of Fe<sub>3</sub>O<sub>4</sub> nanotubes have been prepared by combining a self-limited gas-solid chemical reaction (atomic layer deposition, or ALD) with the use of a structured substrate as a template, namely porous anodic alumina. With these tools, the length, diameter, and wall thickness of the tubes can be tuned accurately between 1 and 5  $\mu\text{m}$ , between 40 and 160 nm, and between 1 and 40 nm, respectively. Such arrays give rise to a ferromagnetic response that strongly depends on geometry. Systematic variations of the tube wall thickness result in non-monotonic changes in coercive field. Given a constant set of the other structural parameters, a certain value of the wall thickness can be found which optimizes the quality of the magnetic response. Theoretical modeling of the magnetization reversal between the two magnetically saturated states is in quantitative agreement with the experimental data. It shows that for thin tubes the reversal occurs by propagation of a "vortex" domain boundary from one extremity of the tube to the other, while in thicker ones it is driven by propagation of a "transverse" domain boundary. The optimal wall thickness thus corresponds to the geometry of the crossover between the vortex and transverse modes of magnetization reversal. Finally, such a crossover is predicted to be a general phenomenon on similar size scales. Thus, it will play an important role for the design and optimization of ferromagnetic nanostructures to be developed into high-density data storage platforms.

#### 9:30 AM \*I1.5

**Theoretical Limit on the Minimal Switching Field and the Switching Current in Magnetization Reversal.** Xiangrong Wang, Hong Kong University of Science & Technology, Kowloon, Hong Kong, China.

Efficient and controlled magnetization switching is one of the important issues in magnetic data storage. It is desirable that a bit has a large switching field during the memory state and a small switching field during the write operation. In terms of magnetization reversal of a magnetic nanostructure by either a magnetic field or a spin polarized electric current, important issues are to lower critical currents (fields) required to reverse a magnetization and to design a current (field) pulse such that the magnetization can be switched from one state to another fast. Many strategies have been proposed and examined both theoretically and experimentally with better and improved results. How much further improvement can one make? This question cannot be answered without knowing the theoretical limit of critical currents (fields) required to reverse a magnetization with an arbitrary polarized current (field). At the moment, other than comparing one reversal scheme with another, one has no objective criteria in evaluating infinite number of possible reversal schemes. In this talk, we shall present the theoretical limit of the minimal magnetization switching current (field) and the optimal current (field) pulse for the fastest reversal for Stoner particles. The results are based on the nonlinear dynamical Landau-Lifshitz-Gilbert equation, and they can be used as benchmarks to evaluate different reversal strategies besides other possible usages. References: 1) Z.Z. Sun and X.R. Wang, Phys. Rev. B 71, 174430 (2005). 2) Z.Z. Sun and X.R. Wang, Phys. Rev. B 73, 092416 (2006). 3) Z.Z. Sun and X.R. Wang, Phys. Rev. B 74, 132401 (2006). 4) Z.Z. Sun and X.R. Wang, Phys. Rev. Lett. 97, 077205 (2006). 5) X.R. Wang and Z.Z. Sun, Phys. Rev. Lett. 98, 077201 (2007). 6) T. Moriyama, R. Cao, J.Q. Xiao, J. Lu, X.R. Wang, Q. Wen, and H.W. Zhang, Appl. Phys. Lett. 90, 152503 (2007)

#### SESSION I2: Magnetoresistance, Principles and Devices

Chair: Xiangrong Wang

Monday Morning, November 26, 2007

Commonwealth (Sheraton)

#### 10:30 AM \*I2.1

**Magnetic Tunneling: Pitfalls, Temperature Dependence and Novel Phenomena.** Ivan Schuller<sup>1</sup>, Igor Roshchin<sup>1</sup>, Casey Miller<sup>1</sup>, Zhi-Pan Li<sup>1</sup> and Johan Akerman<sup>2</sup>; <sup>1</sup>Physics Department, University of California - San Diego, La Jolla, California; <sup>2</sup>Department of Microelectronics and Applied Physics, Royal Institute of Technology, Kista, Sweden.

Electronic tunneling in metal-insulator-metal junction has been an active field of research for many years. In the last 10 years these type of studies have been revitalized with the advent of principally magnetic tunneling and the development of novel devices which rely on these type of structures. I will describe a comprehensive series of experiments and numerical simulations to address important issues magnetic tunnel junctions in which at least one of the electrodes is magnetic. The important issues that will be addressed include: 1) How can tunneling be distinguished from pinhole conduction 2) The impact of roughness on the extracted parameters 3) What is the role of temperature 4) When does the WKB approximation break down 5) What novel effects can be expected and are observed. Work supported by the US-DOE.

#### 11:00 AM I2.2

**Large Current Suppression Induced by Magnetic Molecular Channels on the Exposed Sides of Magnetic Tunnel Junctions.** Pawan Tyagi<sup>1</sup>, Bruce J. Hinds<sup>1,2</sup>, Dongfeng Li<sup>2</sup> and Stephen M. Holmes<sup>2</sup>; <sup>1</sup>Chemical and Materials Engg., University of Kentucky, Lexington, Kentucky; <sup>2</sup>Department of Chemistry, University of Kentucky, Lexington, Kentucky.

Fabrication of electronic spin devices based on magnetic molecules coupled between magnetic metal electrodes is a difficult task due to the lack of a reliable fabrication process for molecular-scale electrodes. We have successfully fabricated magnetic molecular junctions (MMJ) by bridging organometallic magnetic molecules across the tunnel barrier of magnetic tunnel junctions (MTJ) [Ta/Co/NiFe/Al<sub>2</sub>O<sub>3</sub>(~2nm)/NiFe] on the exposed side edges of the pattern. The critical dimension of the molecular electrode is set by the thickness of the insulating Al<sub>2</sub>O<sub>3</sub> layer. Surprisingly, molecule attachment on bare magnetic tunnel junction reduced its current from 1 $\pm$ 0.5 $\mu\text{A}$  to 2 $\pm$ 1nA (100mV bias and room temperature) due to changes in the magnetic ordering of the electrodes. This phenomenon was observed on over 105 devices. A large number of control experiments including using different bridging molecules, oxidation of metal electrodes, variation in the composition of magnetic electrodes and alternative preparation of the exposed edge MTJ were performed. In-plane magnetization and cooling to 77 K further decreased the MMJ current to 1-10pA level (100mV bias). Magnetic ordering of electrodes after molecule attachment is observed by magnetic force microscopy (MFM) suggesting that the device current reduction by 6 orders is due to the molecule producing strong antiferromagnetic coupling between the top and bottom magnetic electrodes. SQUID- magnetometer studies confirmed antiferromagnetically coupled layers. The central metal core of the molecule is tethered ~1.2nm from the ferromagnetic electrode by an alkane tunnel barrier that forces electron conduction through well defined molecular states of the core. Molecules directly assembled on individual magnetic electrodes (non-bridging) did not produce analogous changes in magnetic ordering.



Magnetic measurements suggests that dramatic current reduction is due to the appearance of unusually high degree of spin polarization (>99.99%) in magnetic electrodes due to the molecule mediated strong antiferromagnetic coupling between two ferromagnetic electrodes of MMJ.

#### 11:15 AM I2.3

**Nanoscaled Magneto-electronical Sensors for Mechanical Measurements.** Eckhard Quandt<sup>1,2</sup>, Dirk Meyners<sup>1</sup> and Jochen Puchalla<sup>2</sup>; <sup>1</sup>Faculty of Engineering, University of Kiel, Kiel, Germany; <sup>2</sup>Smart Materials, caesar, Bonn, Germany.

Recently, highly sensitive strain gauges were developed, which are based on nanoscaled TMR (tunnel magnetoresistance) effects combined with the inverse magnetostriction. TMR structures generally possess a symmetrical characteristic which reflects the switching fields of the soft and hard layers, respectively. This characteristic can be changed by a stress field if the soft layer is replaced by a suitable magnetostrictive layer leading to a stress induced rotation of the magnetostrictive layer with respect to the reference layer. This approach illustrates an interesting, highly sensitive mechanism in order to detect mechanical variables with a high spatial resolution as well as an unrivaled high gauge factor. In addition, the feasibility of an integrated cost-effective fabrication using CMOS circuits and SMM membranes compatible is of great interest e.g. for the automotive industry. In this presentation, the basics, the fabrication and the features of these nanoscaled magneto-electronical sensors will be discussed in view of an integrated pressure sensor for automotive applications. Grants by the German Federal Ministry of Education and Research, funding program Nanoelectronics (contract numbers 13N7943, 13N8492 13N9083) are gratefully acknowledged.

#### 11:30 AM I2.4

**MgO-based Magnetic Tunnel Junctions.** Michael Coey, Gen Feng, Jia-Feng Feng, P. Stamenov, K. Oguz and S. van Dijken; School of Physics / CRANN, University of Dublin, Trinity College, Dublin 2, Ireland.

We have prepared a series of single and double barrier MgO tunnel junctions by sputtering. The ferromagnetic layers in the stack are produced in a Shamrock sputtering tool, and the MgO is prepared from a target-facing-target source in a second chamber without breaking the vacuum. A typical single-barrier stack is: Ta(5)/Ru(50)/Ta(5)/NiFe(5)/IrMn(10)/CoFe(2)/Ru(0.8)/CoFeB(t1)/MgO(t2)/CoFeB(3)/Ta(5) with  $0.5 < t1 < 3$  and  $1.5 < t2 < 3$  nm. Magnetic annealing in 800 mT at 250 - 400 °C increases the TMR of the as-deposited patterned structures dramatically, with magnetoresistance values of up to 280 % for  $t1 = 3$  nm and  $t2 = 2.5$  nm. A sign reversal of the TMR has been observed when  $t1 < 2$  nm with inverted TMR as high as 75 % The origin of this effect is the imbalance of the synthetic antiferromagnet. The temperature and field dependence of the tunnel magnetoresistance and the tunneling anisotropic magnetoresistance will be discussed, and some aspects of their 1/f noise reviewed. Double-barrier tunnel junctions with IrMn-pinned artificial antiferromagnets top and bottom, and a central CoFeB free layer, exhibit TMR of more than 100 %. The bias dependence is asymmetric after low temperature magnetic anneals due to dissimilar CoFeB/MgO interfaces. The effect is reduced by half for a bias of 1.88V, and the largest output voltage of 0.62 V is obtained after annealing at 300 °C.

#### SESSION I3: Exchange Coupling & Exchange Bias

Chairs: Eric Fullerton and J. Ping Liu  
Monday Afternoon, November 26, 2007  
Commowalth (Sheraton)

#### 1:30 PM I3.1

**Angular Dependence of Perpendicular Exchange Bias in FeMn/(FeNi/FeMn)<sub>n</sub> Multilayers.** Li Sun and Hao Xing; Mechanical Engineering, University of Houston, Houston, Texas.

Angular dependence of exchange bias has been extensively studied to reveal the field induced interactions between the FM and AFM layers. Most of the studies dealt with in-plane angular dependence of magnetization hysteresis for FM/AF layers with intrinsic shape anisotropy after longitudinal field-cool. Recent study showed that perpendicular exchange bias can be established in ferromagnetic (FM)/ antiferromagnetic (AF) multilayers with intrinsic in-plane ferromagnetic anisotropy through perpendicular field cool. The induced anisotropy along the magnetic hard axis processes the same interfacial nature as conventional exchange bias along the easy axis. Angular dependent investigation reveals that the competition between induced anisotropy and the intrinsic ferromagnetic shape anisotropy magnetic for different geometries greatly influence magnetization reversal behavior of exchange biased multilayers. An analytical model based on Stoner-Wohlfarth coherent rotation considering the competition between perpendicularly induced anisotropy and in-plane shape anisotropy has been developed.

#### 1:45 PM I3.2

**Exchange Bias of Ni/FeF<sub>2</sub> Bilayers as a Function of the Antiferromagnetic Thickness.** Rafael Morales<sup>1,2</sup> and Ivan K. Schuller<sup>1</sup>; <sup>1</sup>Physics Department, University of California San Diego, La Jolla, California; <sup>2</sup>Departamento de Fisica, Universidad de Oviedo, Oviedo, Spain.

The exchange interaction between ferromagnetic (FM) and antiferromagnetic (AF) spins at the interface of FM/AF thin films generates a shift of the hysteresis loop known as the exchange bias field  $H_{EB}$ . This phenomenon has often been modeled as a purely interfacial effect. In this work we demonstrate that exchange bias (EB) does not only depend on the spin configuration at the interface, but also on the magnetic structure within the AF. A wedge of FeF<sub>2</sub>, 200 nm to 600 nm thick, was deposited on a Ni thin film and protected by an Al layer. This way the same interfacial properties for all AF thicknesses is guaranteed, and the dependence of  $H_{EB}$  on the AF thickness observed in this system cannot be attributed to a different quality of the interface, but to the existence of a spin configuration in the bulk of the AF. This particular system exhibits positive EB at high cooling fields ( $H_{FC}$ ) and negative EB at low  $H_{FC}$ . The dependence of  $H_{EB}$  with the AF thickness is mirrored from positive to negative EB. Between these two states there is a gradual transition that can be tuned by intermediate cooling fields. Although the magnitude of  $H_{EB}$  depends on the AF thickness, there is a certain  $H_{FC}$  that nulls EB for all thicknesses at the same time. Work supported by US-DOE and European Marie Curie OIF.

#### 2:00 PM I3.3

**Factors Affecting Exchange Bias in Polycrystalline Metallic Thin Films.** Luis Eugenio Fernandez-Outon, Gonzalo Vallejo-Fernandez and K.



O'Grady; Department of Physics, The University of York, York, United Kingdom.

Exchange bias occurs when a ferromagnetic ( $F$ ) layer is in contact with an antiferromagnetic ( $AF$ ) layer. When the system is field cooled (set) through the Néel temperature of the  $AF$  ( $T_N$ ) the  $AF$  layer causes a unidirectional anisotropy in the  $F$  leading to a shifted hysteresis loop along the field axis by an amount  $H_{ex}$  [1]. A universal theory to explain this effect has not been established. For all applications  $AF$ s are sputtered granular films with grain boundary effects and rough interfaces [2]. It is well known that  $AF$ s and hence exchange bias are not stable over time and can be unstable over short times. In this work we present a detailed study of the exchange bias phenomenon in metallic polycrystalline systems. The use of careful measurement protocols where all the measurements are made at a thermal activation free temperature ( $T_{NA}$ ) makes it possible to distinguish between bulk and interface effects contributing to the loop shift. All the results are interpreted in terms of a granular model where the energy barrier to reversal within the  $AF$  is grain volume dependent. We will show how this affects setting in metallic  $AF$ s at  $T < T_N$ . We have used this interpretation to explain the  $AF$  thickness dependence of the exchange field and the role of the  $AF$  grain size. The grain size was determined by TEM images and measuring over 500 grains for each sample. The grain size distribution within the  $AF$  has been shown to determine the distribution of energy barriers to reversal. The exchange field has been shown to both increase and decrease with the  $AF$  grain size depending on the system studied. We are able to explain both types of behaviour using a grain volume model. Samples with composition  $Si/Cu(10nm)/CoFe(2.5nm)/IrMn(t_{AF})/Ta(10nm)$  have been prepared using a HiTUS sputtering system. The thickness of the  $AF$  layer  $t_{AF}$  was varied between 3 and 12nm. Since the  $AF$  is set by a thermal activation process all large grains may not be set at  $T < T_N$ . Small grains will be disordered by thermal energy above a given temperature known as  $T_{NA}$ . Hence, the exchange field has been shown to be due to the stable and set fraction at finite temperatures. We have also observed the ordering of interface spins at low temperatures for both FeMn and IrMn  $AF$ s. We can order these spins via the setting field and in different orientations at the interfaces of a trilayer. Ordering of interfacial spins leads to an increase in  $H_{ex}$  of up to 30%. The magnetic data and its interpretation will be presented in the full paper. [1] W.H. Meiklejohn, and C.P. Bean, Phys. Rev., 102 p.1413 (1956) [2] M.J. Carey, N. Smith, B.A. Gurney, J.R. Childress and T. Lin, J. Appl. Phys., 89 p.6579 (2001) [3] J. Noguees, I.K. Schuller, J. Magn. Magn. Mat., 192 p.203 (1999)

#### 2:30 PM 13.4

**Influence of Vicinal Steps and Interface Roughness on Uniaxial Anisotropy and Exchange Bias in Permalloy Thin Films.** Rantej Bali and Mark G Blamire; Materials Science & Metallurgy, University of Cambridge, Cambridge, United Kingdom.

Vicinal steps have been shown to induce uniaxial anisotropy [1], enhancement in magneto-resistance (MR) [2] and two-staged switching [3] in ferromagnetic thin films. However, most of these studies are restricted to epitaxial films and have limited application. We stress upon the importance of vicinal steps by studying the combination of step-induced anisotropy and exchange bias in polycrystalline films. We have observed the directed rotation of ferromagnetic easy axis in sputter deposited permalloy films on high and low angle vicinal sapphire substrates. Variation of the squareness ratio in angular space in the presence of deposition field, uniaxial step-induced anisotropy and exchange bias can be modelled. Deposition of the antiferromagnet CoMn induced exchange bias which was controlled by field cooling through the blocking temperature of  $\sim 360$  K. The angular distribution of exchange bias was found to be a function of orientation of vicinal steps, cooling field orientation and also vicinal step height and interface roughness. Interface roughness was controlled by laser-ablating  $Al_2O_3$  onto the vicinal sapphire substrates prior to sputtering permalloy, and observing the oscillating intensity of the specular spot in reflection high energy electron diffraction (RHEED). The polycrystalline system presented here is commonly used in devices, and the realistic experimental conditions include step-induced anisotropy and exchange bias in the presence of interface roughness and is therefore of practical value. References [1] Weber W. et al, Phys. Rev. Lett. 76 (11) 1940 (1996) [2] Arora S.K., Phys. Rev. B 72 134404 (2005) [3] Mireles, H. C. & Erskine, J. L., Phys. Rev. Lett. 87, 037201 (2001)

#### 2:45 PM 13.5

**The Effect of Varying Crystallinity and Thickness of the Magnetic Hard Layer on the Exchange Coupling in Fe/CoPt Soft-hard Magnetic Bilayers.** Hiroyuki Oguchi<sup>1</sup>, Antonio Zambano<sup>1</sup>, Samuel E. Lofland<sup>2</sup>, Daniel Josell<sup>3</sup> and Ichiro Takeuchi<sup>1</sup>; <sup>1</sup>Department of Materials Science and Engineering, University of Maryland, College Park, Maryland; <sup>2</sup>Department of Physics and Astronomy, Rowan University, Glassboro, New Jersey; <sup>3</sup>National Institute of Standards and Technology, Gaithersburg, Maryland.

Exchange-coupled hard/soft magnetic nanocomposites are being pursued for synthesis of future permanent magnets with high energy products. To gain a better understanding of the exchange coupling behavior between the soft and hard magnetic layers, we are using the high-throughput approach where a large number of samples are fabricated and measured simultaneously. Fe/CoPt magnetic bilayers are grown on MgO(110) substrates in a combinatorial electron-beam deposition chamber. The CoPt hard layer is grown on a Pt buffer layer at temperatures in the range of 600°C to 650°C with various post-annealing conditions. (100) and (112) oriented phases are observed by x-ray diffraction. The crystallinity of those phases changes depending on the growth conditions. On the hard layer, the polycrystalline Fe soft layer with a continuously varying thickness is deposited at room temperature. The magnetic hysteresis loop for each Fe thickness is measured using a magneto-optical Kerr effect (MOKE) system. Drastically changing hysteresis loops for CoPt hard layers with different crystallinities reveal that a very small magnetically soft region in the hard layer can affect the exchange coupling interaction with the soft layer. In order to find the optimum thickness of the hard layer, we have also fabricated Fe/CoPt bilayers thin-film libraries where in one direction the thickness of the soft layer is continuously changed and the thickness of the hard layer is changed in the other direction. Changing magnetic hysteresis loops show that optimum thickness of the hard layer for the exchange coupling is about 15 nm. This work is supported by ONR MURI N00014-05-1-0497.

#### 3:30 PM 13.6

**Cooling Field Dependent Magnetic Depth Profiles in Exchange-coupled Superlattices.** M. R. Fitzsimmons<sup>1</sup>, C. Dufour<sup>2</sup> and K. Dumesnil<sup>2</sup>; <sup>1</sup>LANSCE, LANL, Albuquerque, New Mexico; <sup>2</sup>Laboratoire de Physique des Matériaux, Université Henri Poincaré Nancy I, Vandoeuvre les Nancy, France.

In DyFe<sub>2</sub>/YFe<sub>2</sub> superlattices, competition between ferromagnetic and antiferromagnetic coupling leads to an antiparallel arrangement of magnetization across the DyFe<sub>2</sub>/YFe<sub>2</sub> interface in low fields. The equilibrium configuration is a giant ferrimagnet, while a strong external field alters this arrangement by introducing magnetic domain walls parallel to the DyFe<sub>2</sub>/YFe<sub>2</sub> interface [1-2]. In addition to exchange coupling, the anisotropy in DyFe<sub>2</sub> plays an important role in determining the most energetically favored structure. Recently, we investigated the magnetization of [DyFe<sub>2</sub>



(3nm)/YFe<sub>2</sub>(12nm)] as a function of field cooling. Remarkably, for 1T field cooling, the macroscopic magnetization loops at 12K show very large shifts (of order 2 T) parallel to the applied field axis (i.e., exchange bias), and a large negative shift (~25%) along the magnetization axis. For larger cooling fields, the shifts become small. From compound-selective hysteresis loops measured by XMCD (X-Ray Magnetic Circular Dichroism), we found that: i) when the sample was cooled in 7T, the Dy moment along the field axis was negligible at 12K; ii) when the sample was cooled in a low field, the Dy moment was opposite to the cooling field direction. Depending on the cooling field, the PNR (Polarized Neutron Reflectivity) results show i) a dramatic change in the spin asymmetry of the Bragg reflections (i.e., whether the spin up reflectivity is larger or smaller than the spin down reflectivity), ii) and the presence of spin flip scattering. Using a novel approach that combined micromagnetic simulation and analysis of PNR measurements, we obtained the depth dependence of magnetization across the DyFe<sub>2</sub>/YFe<sub>2</sub> interfaces. From this analysis we learned that the small net Dy magnetization measured by XMCD for large cooling field is due to a tilted magnetization and extension of the domain walls into the magnetic layers. An interfacial region consisting of DyFe<sub>2</sub> and YFe<sub>2</sub> can be frozen when cooling to low temperature. [1] K. Dumesnil et al. *Journal of Physics, Condensed Matter* 17 No 21 (2005) [2] M.R. Fitzsimmons et al. *Phys. Rev. B* 73, 134413 (2006)

### 3:45 PM \*I3.7

**High-throughput Investigation of Exchange-coupled Hard/soft Magnetic Bilayers.** Ichiro Takeuchi, University of Maryland, College Park, Maryland.

The high-throughput techniques allow simultaneous measurements of a large number of samples with continuously changing parameters. This talk will provide an overview of the high-throughput method as applied to investigation of exchange coupled hard/soft magnetic bilayer systems. By including composition variation as one of the parameters, the library approach can substantially increase the scope of the traditional gradient thickness method for rapidly mapping the dependence of physical properties on changing parameters. For instance, to elucidate the dependence of exchange coupling behavior of hard/soft magnetic bilayer systems on various micromagnetic constants, the coupling length ( $\lambda$ ) and the nucleation field (HN) were systematically measured on five thin film libraries made of soft-magnetic/hard-magnetic bilayers [1]. Hysteresis loops of CoPt/FexCo<sub>1-x</sub> (0 $\leq$ x $\leq$ 1), CoPt/Ni, CoPt/Fe, Sm<sub>2</sub>Co<sub>7</sub>/(Fe, Co or Ni), and Sm<sub>2</sub>Co<sub>7</sub>/Ni were measured using a magneto-optical Kerr effect (MOKE) set up. Some of the libraries were also measured using XMCD. We find that the dominant factors determining  $\lambda$  and HN are the hard layer magnetic constants and the saturation magnetization (M) of the soft layer. HN and  $\lambda$  display a direct correlation with the domain wall width of the hard layer and have an anticorrelation with M of the soft layers. They were found to not depend on exchange stiffness (A) and anisotropy (K) constants within the group of soft layer materials studied here. Comparison of the results with models will be presented. Recent results on the effect of varying interface conditions and interface layers as well as the effect of varying the hard layer crystallinity will be discussed. Implications of the present results on energy products of nanocomposite magnets will be discussed. The key contributors to the present work include A. Zambano, H. Ohguchi, S. E. Lofland, D. Josell and J. P. Liu. This work is supported by ONR MURI N00014-05-1-0497. [1] Zambano et al., *Phys. Rev. B* 75, (2007) 144429.

### 4:15 PM I3.8

**Influence of Interfacial Non-magnetic Materials on Soft-hard Phase Interactions in Nanocomposite Magnets.** Antonio Javier Zambano<sup>1</sup>, H. Oguchi<sup>1</sup>, I. Takeuchi<sup>1</sup>, Y. Choi<sup>2</sup>, J. P. Liu<sup>3</sup>, S. E. Lofland<sup>4</sup>, D. Josell<sup>5</sup> and L. A. Bendersky<sup>5</sup>; <sup>1</sup>Department of Materials Science and Engineering, and Center for Superconductivity Research, University of Maryland, College Park, Maryland; <sup>2</sup>Materials Science Division, Argonne National Laboratory, Argonne, Illinois; <sup>3</sup>Department of Physics, University of Texas at Arlington, Arlington, Texas; <sup>4</sup>Department of Physics, Rowan University, Glassboro, New Jersey; <sup>5</sup>NIST, Gaithersburg, Maryland.

The determination of the mechanisms that affect the exchange interaction is critical for the improvement of nanocomposite magnets. One of the possible effects comes from the presence of nonmagnetic regions among the hard and soft magnetic phases. One-dimensional bilayer systems are simple useful tools to establish the importance of those effects. We have used the high-throughput approach<sup>1</sup> to systematically study thin soft-magnetic/non-magnetic/hard-magnetic trilayer systems. We have examined thickness gradient effects of nonmagnetic impurity layers, such as Cu and Ti, on the interaction between hard magnetic CoPt and a soft magnetic Fe layer. On single chips, multiple samples were grown by e-beam evaporation varying the impurity thickness from 0 to 50 Å typically. The magnetic hysteresis loop for each sample was rapidly measured using the magneto-optical Kerr effect (MOKE). Selected samples were also studied by X-ray magnetic circular dichroism (XMCD). The results indicate that there is an oscillatory behavior of the intensity of the exchange coupling interaction depending on the nonmagnetic layer thickness. We will discuss how the crystalline characteristics of the hard layer affect this behavior and, in some cases, give rise to a significant dipole interaction contribution. We will also talk about the general advantage of using the presence of nonmagnetic material to actually improve the hard/soft phase ferromagnetic interaction. This work is supported by ONR MURI N00014-05-1-0497. 1. Zambano *et al.*, *Phys. Rev. B* 75, 144429 (2007).

### 4:30 PM I3.9

**Micromagnetic Simulation of the Competition Between Exchange and Magnetostatic Interactions in Composite Magnets.** Chuanbing Rong and J. Ping Liu; Department of Physics, University of Texas at Arlington, Arlington, Texas.

Recently, it was reported that the anisotropic hot-pressed composite magnets, which contained coarse Fe grains with size larger than the critical dimension for exchange interaction, exhibited a single-phase demagnetization behavior with enhanced remanence  $M_r$  and maximum energy product (BH)<sub>max</sub>[1-3] which was attributed to long-range magnetostatic (dipolar) interaction. In this work, we studied the size dependent magnetostatic and exchange interactions and their effect on the demagnetization behavior of the hard-soft composite magnets by micromagnetic finite-element simulation. The numerical results give a direct study on the distributions of the magnetostatic field and magnetizations, as well as the effect of exchange coupling and magnetostatic energies on the hysteresis loops. It was confirmed that the magnetostatic interaction improves the squareness of the hysteresis loop when the soft phase layer is perpendicular to the applied field. However, the improvement of (BH)<sub>max</sub> of the composite magnets comparison with single-phase can be obtained only when the size of soft-phase layer is small enough since the contribution of exchange coupling energy drops fast with increasing size while that of magnetostatic energy almost remains unchanged. This means that the control of the soft-phase dimension is still the key issue to achieve enhancement of the (BH)<sub>max</sub> of a composite magnets. [1]M. Gabay, M. Marinescu, and G. C. Hadjipanayis, *J. Appl. Phys.* 99, 08B506 (2006). [2]D. Lee, S. Bauser, A. Higgins, et al., *J. Appl. Phys.* 99, 08B516 (2006). [3]A. M. Gabay, and G. C. Hadjipanayis, *J. Appl. Phys.*, 101, 09K507 (2007).

### 4:45 PM I3.10

**Activation Energy for Crystallization in Nanocrystalline Exchange Coupled Alloys.** Matthew A. Willard<sup>1</sup>, Maria Daniil<sup>1</sup> and Juan G.



Saavedra<sup>2,1</sup>; <sup>1</sup>Multifunctional Materials Branch, U. S. Naval Research Laboratory, Washington, District of Columbia; <sup>2</sup>Department of Mechanical Engineering, University of Puerto Rico, Mayagüez Campus, Washington, Puerto Rico.

Nanocrystalline soft magnetic alloys have been studied for their excellent magnetic performance as core materials in inductor applications. These materials are processed using a rapid solidification technique, typically melt spinning, resulting in an amorphous alloys in a ribbon form. The rapidly solidified alloys are then isothermally annealed to improve the stability of the material by partially devitrifying the ribbon samples, resulting in improved magnetic performance. The reason for the performance improvement has been linked to the grain size and volume fraction of crystallites in the optimized microstructure. As a result, the processing conditions have a significant impact on the performance of the alloy with the annealing time and temperature being important factors. To examine the crystallization kinetics, constant heating rate experiments were performed using a TA Instruments SDT 2960 Differential Thermal Analysis system. The heating rates were varied between 2 and 85°C/min within the temperature range 50 to 900°C. In this study, the crystallization kinetics of alloys with composition (Fe, Co, Ni)-Zr-B-(Cu) are determined by Kissinger analysis. The thermally activated primary and secondary crystallization temperatures were observed for each sample at numerous heating rates to provide accurate activation energies. The trends of the activation energy for primary crystallization as a function of magnetic transition metal composition were examined in this study and compared to values in the literature. Alloys rich in Fe show activation energies between 3 and 3.5 eV/atom while alloys rich in Ni have substantially lower activation energies, near 2.1 to 2.5 eV/atom. The reduced activation energy likely results from the more active diffusion in Ni-based alloys and may be a reason for the deteriorated nanocrystalline alloy formation at these compositions.

SESSION I4: Poster Session  
Monday Evening, November 26, 2007  
8:00 PM  
Exhibition Hall D (Hynes)

#### I4.1

**Nanoconductive and Magnetic Properties of Nanostructured Iron Thin Films Prepared by Sputtering at Very Low Temperatures.** Carmen Munuera<sup>1</sup>, Felix Jimenez-Villacorta<sup>2,1</sup>, Carmen Ocal<sup>3</sup> and Carlos Prieto<sup>1</sup>; <sup>1</sup>Instituto de Ciencia Materiales de Madrid, Consejo Superior de Investigaciones Científicas, Madrid, Spain; <sup>2</sup>Spline, ESRF, Grenoble, France; <sup>3</sup>Instituto de Ciencia de Materiales de Barcelona, Consejo Superior de Investigaciones Científicas, Cerdanyola del Valles, Spain.

Iron thin films prepared by sputtering on passivated Si (001) substrates at temperatures in the 300 to 200 K range show a change from typical magnetic thin film behavior (room temperature prepared samples) to weakly interacting granular magnetic system [1,2] (200K prepared samples) with characteristic sizes of several nanometers exhibiting exchange bias [3]. Scanning probe microscopy (SPM) has already proven its almost unique potential for characterization and surface manipulation down to the nanometer scale. Furthermore, the ability to measure different properties by combining diverse operation modes has made SPM a unique tool in the field of nanoscience and nanotechnology: not only surface topography, but frictional, elastic, magnetic or current maps can be acquired with unprecedented resolution [4]. In this work, and by means of Conductive Scanning Force Microscopy (CSFM), we have faced the combined study of the surface structure and the electrical characteristics of iron ultra-thin films grown on silicon in order to study the influence of the substrate temperature during film growth on both, the surface topography and the conductivity properties. Films of about 6 nm average thick have been prepared by DC magnetron sputtering at substrate temperatures of 300 and 200 K to study their magnetic and nanoconductive properties. Noticeable differences are found in the surface morphology in agreement with changes in the magnetic behavior. Samples prepared at room temperature present a uniform coverage over the entire surface. However, samples prepared at 200 K present a morphology composed by relatively big grains, which appear to be interconnected by chains of near 1D small grains with a total covered area of about 48 %. By exploiting the capability of CSFM to measure at specific locations on the surface, differences in the electrical nature of the different grains are revealed by the respective current versus voltage (I-V) curves. In particular, for films prepared at TS=200 K, two different conductive responses are obtained: larger grains show an ohmic behavior while smaller grains present I-V curves, exhibiting a typical insulator behavior. These curves can be compared with the I-V characteristics of the bare Si substrate and finally to identify the three observed behavior as corresponding to metallic iron, iron oxide and p-doped silicon, respectively. References: [1] F. Jiménez-Villacorta, Y. Huttel, A. Muñoz-Martín, C. Ballesteros, E. Román and C. Prieto, *J. Appl. Phys.*, 96, 113914 (2007). [2] J. Stankiewicz, F. Jiménez-Villacorta and C. Prieto, *Phys. Rev. B* 73, 014429 (2006). [3] A. Muñoz-Martín, C. Prieto, C. Ocal, J. L. Martínez, and J. Colino, *Surf. Sci.* 482-485, 1095 (2001). [4] J. Loos, *Adv. Mater.*, 17, 1821 (2005).

#### I4.2

**On the Microstate and Magnetism in Co:TiO<sub>2</sub> Films Grown at Low Temperature in Different Reducing Ambient.** Satish B. Ogale<sup>1,2</sup>, Darshan C. Kundaliya<sup>2</sup>, S. Mehraeen<sup>3</sup>, Lianfeng Fu<sup>3</sup>, Shixiong Zhang<sup>2</sup>, A. Lussier<sup>4</sup>, J. Dvorak<sup>4</sup>, N. B. Browning<sup>3</sup>, Y. Idzerda<sup>4</sup> and T. Venkatesan<sup>2,5</sup>; <sup>1</sup>National Chemical Laboratory, Pune, India; <sup>2</sup>Physics Department, University of Maryland, College Park, Maryland; <sup>3</sup>Department of Chemical Engineering and Materials Science, University of California, Davis, California; <sup>4</sup>Department of Physics, Montana State University, Bozeman, Montana; <sup>5</sup>Department of Physics, National University of Singapore, Singapore, Singapore.

In recent years, diluted magnetic semiconductors (DMS) are amongst the most intensely studied materials in view of their great application potential in the fields of spintronics. Yet, they have also proved to be the most controversial due to the possibility of extrinsic effects arising from dopant clustering, incorporation of unintentional impurities etc. Very recently interesting approaches are being considered wherein dopant clustering could be better understood by spatially highly resolved elemental analysis and controlled to yield effective spintronic materials. In this work we apply this approach to the most studied and yet highly controversial oxide based DMS system Co:TiO<sub>2</sub>. We have performed a characterization of epitaxial rutile Co<sub>x</sub>Ti<sub>1-x</sub>O<sub>2</sub> (x=0-0.06) films grown at 400 °C under different ambient, employing high resolution scanning transmission electron microscopy and electron energy loss spectrometry, x-ray absorption (XAS)/ x-ray magnetic circular dichroism (XMCD), and magnetization measurements. These together reveal a mixed state scenario involving intrinsic DMS and cluster ferromagnetism.

#### I4.3

**Properties of Fe/MgO(100) Nanometric Films Grown by dc Sputtering.** Claudionor Gomes Bezerra<sup>1</sup>, Carlos Chesman<sup>1</sup>, Thatyara Freire<sup>1</sup> and Charlie Salvador<sup>1</sup>; <sup>1</sup>Departamento de Física, UFRN, Natal, Rio Grande do Norte, Brazil; <sup>2</sup>Departamento de Física, UFMG, Belo Horizonte, Minas



Gerai, Brazil.

The deposition of magnetic materials on monocrystalline substrates in the 1980s has aroused a great interest in thin films structures. As a consequence, in the last decade a number of articles have been focused on the understanding of magnetic properties of layered films of ferromagnetic metals. A very simple and interesting situation occurs when the thickness of ferromagnetic films are in the nanometric regime. Despite its simplicity, such a system presents a very rich physical behavior, which is supported by the discovery of remarkable new physical properties, such as antiferromagnetic exchange coupling, giant magnetoresistance, oscillatory behavior of the exchange coupling and biquadratic exchange coupling. In particular, nanometric or ultrathin films in the monolayer regime can exhibit an out-of-plane uniaxial surface anisotropy which is sufficient to overcome the demagnetizing field. This feature is very useful for magnetic recording once data could be recorded at higher densities in such magnetic media. Because of all physical properties listed so far, these systems are excellent options for technological applications and attractive objects of research. In this work, structural and magneto-crystalline properties of Fe nanometric films, grown onto MgO (100) using dc magnetron sputtering, were studied by different experimental techniques. Surface roughness and thickness of the films were investigated by atomic force microscopy, while magneto-crystalline properties were investigated by magneto-optical Kerr effect and ferromagnetic resonance. Furthermore, the purity degree of the films was investigated with X-Ray photoelectron spectroscopy. Our results show that as we increase the deposition temperature, the magneto-crystalline anisotropy of the films also increases. The saturation value of the magneto-crystalline anisotropy (550 Oe corresponding to Fe bulk) is reached at deposition temperature of 300°C.

#### I4.4

Transferred to I6.9

#### I4.5

**Magnetic Properties of Iron Nano Particles Agglomerated in Self Assembled Chains.** Tim P. Huelser<sup>1,2</sup>, Mehmet Acet<sup>1</sup>, Hartmut Wiggers<sup>2</sup> and Axel Lorke<sup>1</sup>; <sup>1</sup>Department of physics and CeNIDE, Universität Duisburg-Essen, 47057 Duisburg, Germany; <sup>2</sup>Institute of combustion and gas dynamics, and CeNIDE, Universität Duisburg-Essen, 47057 Duisburg, Germany.

We report on the self-assembly of iron nanowires consisting of iron nanoparticle segments. The particles with a diameter of about 35 nm are synthesized by the thermal decomposition of iron pentacarbonyl  $\text{Fe}(\text{CO})_5$  in a hot wall reactor. The particles are single magnetic domain and ferromagnetic. The magnetic forces between the particles lead to an arrangement into iron nano chains of up to 300  $\mu\text{m}$  length. A network of iron nanowires can be collected in a filter system. The resulting powder specimen is characterized magnetically using superconducting quantum interference device (SQUID) magnetometry. Temperature dependent magnetization measurements reveal that iron nanowires are thermally stable. Measurements at 5 K give a saturation magnetization of 160 emu/g indicating a reduction of the bulk value caused by iron oxide on the surface. Morphological characterizations using high resolution transmission electron microscopy verify the observations and indicate an oxide shell with a thickness of 3-4nm. For a more detailed magnetic characterization, p-type Silicon substrates were placed in the particle stream during the synthesis using a pneumatic sampling device. With this system, iron nanowires were thermophoretically sampled, and after deposition they were orientated in a homogenous magnetic field. The magnetization of the orientated chains on silicon substrates was measured perpendicular and parallel to the applied field at 5 K and 293 K. In case of the perpendicular configuration the hysteresis loop in the range -1 T to 1 T shows shearing and a slower increase of magnetization at both temperatures than that for the parallel configuration. These results indicate the presence of anisotropy due to dipole coupling of adjacent particles.

#### I4.6

**Optimization of Coercivity Values in Cobalt Ferrite Nanocrystals.** Yarilyn Cedeno-Mattei<sup>1</sup>, Oscar Perales-Perez<sup>2</sup>, Maharaj S. Tomar<sup>3</sup> and Felix Roman<sup>1</sup>; <sup>1</sup>Chemistry, UPR - Mayaguez, Mayaguez, Puerto Rico; <sup>2</sup>Engineering Science & Materials, UPR - Mayaguez, Mayaguez, Puerto Rico; <sup>3</sup>Physics, UPR - Mayaguez, Mayaguez, Puerto Rico.

Among the various ferrite materials, cobalt ferrite ( $\text{CoFe}_2\text{O}_4$ ) is well known to possess excellent chemical stability and good mechanical hardness. The presence of a larger positive first order crystalline anisotropy constant ( $K_1$ ) has made this ferrite a promising candidate for magneto-optical recording media. In addition to the precise control on the composition and structure of  $\text{CoFe}_2\text{O}_4$ , the success of its practical application will depend on the capability of controlling particle size at the nanoscale. It is known that the crystal size is closely related to the relative interdependence between the nucleation and growth steps, which in turn can strongly be affected by the solution chemistry and precipitation conditions. On this basis, our research involves a modified co-precipitation approach that allows control of the growth of cobalt ferrite nanocrystals within the superparamagnetic and single domains limits and achieve high coercivity and moderate magnetization at room-temperature. This size-controlled synthesis approach became possible by controlling both the reaction time and the oversaturation conditions during ferrite formation. Optimum oversaturation was achieved by a precise monitoring of the feeding flow-rate of reactant solutions in aqueous phase. XRD analysis confirmed the formation of the ferrite structure for a reaction time as short as five minutes. The ferrite formation was very sensitive to the variation in flow-rate. Broad XRD peaks were observed in the pattern corresponding to the sample synthesized at 1 mL/min. This peak broadening suggested a poor crystallinity, which was attributed to the extremely low saturation conditions attained at that particular flow-rate. HRTEM analysis confirmed the growth of ferrite nanocrystals when the reaction time was increased from 5 to 60 minutes. Room-temperature M-H measurements verified the strong influence of synthesis conditions and crystal size on the magnetic properties of ferrite nanocrystals. The coercivity was increased abruptly when the ferrite was produced under controlled flow-rate conditions. The coercivity values varied from 460 Oe, (with no control on flow rate), up to 1597 Oe for an optimum flow rate of 5 mL/min for one hour of reaction. In order to enhance crystal growth, cobalt ferrite nanoparticles were annealed at 900°C for one hour. The non-annealed sample, produced at 10 mL/min of flow rate and one hour of reaction, exhibited a coercivity and maximum magnetization of 1219 Oe and 57 emu/g, respectively. After annealing, the coercivity went down to 670 Oe while the maximum magnetization increased up to 85 emu/g. Particle aggregation and crystal growth within the magnetic multi-domain region should be involved with the observed drop in coercivity. Based on our experimental results, a complete discussion of the optimization of the magnetic properties in ferrite nanocrystals will also be included.

#### I4.7

Abstract Withdrawn



**I4.8**

**Size Dependent Magnetic Anisotropy in 3d Elemental Nanomagnets Made From Laser-Induced Self-Organization.** Hare Krishna<sup>1,2</sup>, C. Miller<sup>3</sup>, C. Favazza<sup>1,2</sup>, A. Gangopadhyay<sup>1,2</sup>, E. Solarte<sup>4</sup>, E. Baca<sup>4</sup>, A. Devia<sup>5</sup>, H. Garcia<sup>6</sup> and R. Kalyanaraman<sup>1,2</sup>; <sup>1</sup>Department of Physics, Washington University in St. Louis, St. Louis, Missouri; <sup>2</sup>Center for Materials Innovation, Washington University in St. Louis, St. Louis, Missouri; <sup>3</sup>Department of Electrical Engineering, Washington University in St. Louis, St. Louis, Missouri; <sup>4</sup>Department of Physics, Universidad del Valle, Cali, Colombia; <sup>5</sup>Department of Physics, Universidad Nacional de Colombia, Sede Manizales, Colombia; <sup>6</sup>Department of Physics, Southern Illinois University, Edwardsville, Illinois.

Presently, there is a strong emphasis on the magnetic behavior, including anisotropy, switching dynamics and thermal stability of single-domain (SD) magnetic particles because of their importance in high-density magnetic data storage, processing and sensing applications. It is widely accepted that the stationary magnetic states of these magnets strongly depend on shape, size and the processing conditions. There have been several studies characterizing the magnetic states of disk-, dot- and ring-shaped nanomagnets, created primarily through lithographic processes. Here we present results detailing the unusual magnetic anisotropy in near hemispherical polycrystalline 3d (Co, Fe, Ni) elemental nanomagnets on SiO<sub>2</sub> substrates, produced through a fast (nanosecond) laser driven self-organization technique [1,2]. We found that particles with a diameter less than 180 nm are single domain [3] and have a size-dependent magnetization direction. Here we detail the role of laser processing conditions, post-assembled thermal annealing and the external magnetic field on the magnetization behavior of these particles. This reason for this anisotropy could be the fast laser processing leading to large thermal strains as well as the size-dependent polycrystalline microstructure of the nanomagnets. These results suggest simple routes to producing nanostructures with stable magnetization behavior from soft 3d elements and could be useful in a variety of applications. [1] J. Trice, D. Thomas, C. Favazza, R. Sureshkumar, and R. Kalyanaraman, Phys. Rev. B, v75, in press, 2007. [2] C. Favazza, R. Kalyanaraman and R. Sureshkumar, Nanotechnology 17, 4229, 2006. [3] R. M. H. New, R. F. W. Pease and R. L. White, IEEE Trans Mag., 31, 3805, 1995.

**I4.9**

**Synthesis and Characterization of Monodisperse Isotopic and Anisotropic Core/shell Magnetic Nanocomposites with Applications towards RF Antennas and Metamaterial Devices.** Max D. Alexander, Nicholas R Hendricks, Tricia L Meyer and Jennifer N. DeCervo; Polymer Branch, Air Force Research Laboratory, Dayton, Ohio.

The synthesis of magnetic nanomaterials is of much interest in the production of radio frequency (RF) antenna substrates and engineered index (positive & negative) metamaterial devices. While testing has been completed on single component samples, core/shell materials are believed to enhance these electromagnetic properties. Specifically, 4-12nm Fe<sub>3</sub>O<sub>4</sub>/CoFe<sub>2</sub>O<sub>4</sub> core/shell nanoparticles have been synthesized via seed-mediated growth as well as other metal oxides (M=Sm, Mn, Fe, Co) and metal oxide coated gold nanoparticles. The tunable size and shape of these materials is another factor that makes core/shell materials intriguing. In order to elucidate the structure-property relationships of nanocomposites based on these materials, reflectance, transmittance, permittivity, and permeability were investigated. Additionally, we will report on the intrinsic and frequency dependent magnetic and electric properties of these materials.

**I4.10**

**Enhanced Neel Temperature in Mn-ferrite Nanoparticles Linked to Growth Rate Induced Cation Inversion.** Aria Yang<sup>1</sup>, C. N Chinnasamy<sup>1</sup>, Soack D Yoon<sup>1</sup>, Jing Lou<sup>1</sup>, Zhuhua Cai<sup>4</sup>, Kailin Hsu<sup>1</sup>, Steve Oliver<sup>3</sup>, Shaheen Islam<sup>2</sup>, Carmine Vittoria<sup>1</sup> and Vincent G Harris<sup>1</sup>; <sup>1</sup>Electrical Engineering, Northeastern University, Boston, Massachusetts; <sup>2</sup>Virginia Union University, Richmond, Virginia; <sup>3</sup>Gilford High School, Gilford, New Hampshire; <sup>4</sup>Chemical Engineering, Northeastern University, Boston, Massachusetts.

The spinel ferrite is a big family of magnetic materials that is largely used in high frequency microwave devices due to their near insulating properties, high permeability, and moderate magnetization. Current interest has been to make nano sized ferrite particles to reduce their energy loss, and to study their size dependent electronic and magnetic properties. In the case of Mn-ferrite nanoparticles, size dependent magnetic properties have already been reported in detail a decade before. However, recently we found that the magnetic properties of MnFe<sub>2</sub>O<sub>4</sub> nanoparticles are not directly related to the finite size scaling effect and size dependent cation inversion.<sup>1</sup> We presented in this article the observed enhanced Néel temperature (T<sub>N</sub>) and quantitative inversion parameters results by fitting extended x-ray absorption fine structure analysis (EXAFS) data to theoretical standards following established EXAFS procedure with modified model exclusively for nanoparticles. Mn-ferrite (MnFe<sub>2</sub>O<sub>4</sub>) nanoparticles with diameters ranging from 4 nm to 50 nm were synthesized using a modified coprecipitation technique. The mixed metalchloride solutions were added to different concentrations of boiling NaOH solutions to control the particle growth rate and resulted in different particle sizes. Magnetization measurements indicated an increase in Néel temperature above the bulk equilibrium value (300°C) for larger particles having the higher growth rates. The ~4 nm MnFe<sub>2</sub>O<sub>4</sub> particles showed a Néel temperature (T<sub>N</sub>) of about 320°C whereas the ~50 nm particles had a TN of about 400°C.

Results of EXAFS indicated a corresponding systematic increase in cation inversion parameter,  $\delta$ , described by the formula, (Mn<sub>1- $\delta$</sub> Fe <sub>$\delta$</sub> )<sup>tet</sup>[Mn <sub>$\delta$</sub> Fe<sub>2- $\delta$</sub> O<sub>4</sub>]. The enhanced Néel temperature is attributed to changes in the exchange energy resulting from cation inversion and is unrelated to particle size. Similar relationship between Néel temperature and inversion parameters were observed for pulsed laser deposited manganese ferrite films studied earlier.<sup>2</sup> Low and high temperature magnetization were both measured from 5.5K to 723K for all the samples by the Lakeshore VSM system. Theoretical modeling based on the molecular field theory and the inversion parameters extracted from EXAFS analysis showed good agreement with the experimental magnetization (M) vs temperature (T) data sets. Reference: 1 N. Ponpandian, A. Narayanasamy, C. N. Chinnasamy, and N. Sivakumar, J. -M. Grenèche, K. Chattopadhyay, K. Shinoda, B. Jevadevan, and K. Tohji, Appl. Phys. Let., 86, 192510 (2005) 2 X. Zuo, F. Yang, R. Mafhoum, R. Karim, A. Tebano, G. Balestrino, V. G. Harris, and C. Vittoria, IEEE Trans. Magn., 40, 2811 (2004)

**I4.11**

**Synthesis and Functionalization of FeCo Alloy Nanoparticles for Magnetic and Electronic Applications.** Q. Nguyen<sup>1</sup>, Chins Chinnasamy<sup>1</sup>, Soack D Yoon<sup>1</sup>, Somu Sivasubramanian<sup>2</sup>, A. Baraskar<sup>1</sup>, Ahmed Busnanina<sup>2</sup>, Sanjeev Mukerjee<sup>3</sup>, Carmine Vittoria<sup>1</sup> and Vincent G Harris<sup>1</sup>; <sup>1</sup>Center for Microwave Magnetic Materials, Northeastern University, Boston, Massachusetts; <sup>2</sup>Center for High- Rate Nanomanufacturing, Northeastern



University, Boston, Massachusetts; <sup>3</sup>Dept. of Chemistry and Chemical Biology, Northeastern University, Boston, Massachusetts.

Iron-cobalt based alloys exhibit particularly interesting magnetic properties, with high Curie temperatures, the highest saturation magnetizations, high permeability and low losses. Preparing the FeCo alloy nanoparticles with surface functionalization makes possible applications from biomedical to electronic applications. Here, the  $\text{Fe}_{100-x}\text{Co}_x$  alloy nanoparticles have been prepared by using the modified low temperature chemical reduction technique. The X-ray diffraction pattern of the as-prepared particles clearly showed the formation of alloy nanoparticles and it was further confirmed by high resolution Transmission electron microscopic (TEM) analysis. The TEM analysis showed that the particle size was varied between 20 and 60 nm and nearly monodispersed (Fig. 1) The magnetic properties were measured using SQUID magnetometer at 300 K and as well as at 5 K. The maximum saturation magnetization of about 210 emu/g was achieved at room temperature for the 50 nm sized particles. The as-prepared nanoparticles were assembled and fixed on a substrate and aligned by using an external magnetic field. The microwave properties measured by in-plane ferromagnetic resonance at various frequencies indicate a minimum line width of  $\approx 4500$  Oe which is consistent with ferromagnetic nanoparticles (Fig. 2). For the surface functionalization, these  $\text{Fe}_{100-x}\text{Co}_x$  alloy nanoparticles were coated with various kinds of capping ligands and its magnetic properties were studied. On the other hand, a few nanometer thicknesses of high resistive oxide particles were passivated on the surface of  $\text{Fe}_{100-x}\text{Co}_x$  alloy nanoparticles to reduce the eddy current loss and its effect on the microwave properties were studied in detail.

#### 14.12

**FeCoPt Nanoparticles.** Gregory Poole, David Eugene Nikles, Jin Mei Dong and James Weston; Center for Materials for Information Technology, The University of Alabama, Tuscaloosa, Alabama.

FeCoPt nanoparticles were prepared by four different procedures, either 1) the simultaneous diol reduction of platinum(II) acetylacetonate, cobalt(II) acetylacetonate and thermal decomposition of iron pentacarbonyl, 2) the superhydride reduction of iron(III) acetylacetonate, cobalt(II) acetylacetonate and platinum(II) acetylacetonate, the diol reduction of iron(III) acetylacetonate, cobalt(II) acetylacetonate and platinum(II) acetylacetonate, or 4) the hydrazine reduction of hexachloroplatinic acid, cobalt(II) acetate and iron(II) chloride. In each case the particles were superparamagnetic with a face-centered cubic structure. Heating under 5% hydrogen in argon transformed the particles to the ferromagnetic tetragonal phase giving films with high coercivity. Fits of the time dependence of the remanent coercivity to Sharrock's law gave values of coercivity for FeCoPt ( $H_0 = 5$  to 7 kOe) films much lower than that for FePt films ( $H_0 > 12$  kOe). This indicates that substituting Co for Fe in FePt lowers the magnetic anisotropy.

#### 14.13

**Controlling Ruthenium Redox Chemistry: A Low Temperature Route to SrRuO<sub>3</sub> Nanocubes.** Yolonda Smith, Jennifer M. Noblitt and Amy Prieto; Chemistry Department, Colorado State University, Fort Collins, Colorado.

The strontium ruthenate family of compounds (including  $\text{Sr}_{n+1}\text{Ru}_n\text{O}_{3n+1}$  and  $\text{SrRuO}_3$ ) exhibit a wide range of interesting electronic properties. Of particular interest is  $\text{Sr}_2\text{RuO}_4$  ( $n=1$ ), which is the only non-copper containing oxide to exhibit superconducting properties. Members of this family have been synthesized hydrothermally previously using fairly high temperatures and pressures. We are interested in exploring the synthesis of nanoparticles of members of the strontium ruthenate family by controlling the redox chemistry of Ru in solution. We will show that by tuning the oxidation state of Ru in solution, we can synthesize members of this family at much lower temperatures and pressures. This should allow for more flexibility in tuning the size and shape of the resulting particles using organic capping ligands. We have recently synthesized nanoscale cubes of  $\text{SrRuO}_3$ , the parent compound of this family. Synthesis conditions such as pH, temperature, and reducing agents will be discussed, as well as preliminary magnetic measurements on these cubes.

#### 14.14

**Synthesis and Characterization of FePt/Fe<sub>3</sub>O<sub>4</sub> Bimagnetic Nanoparticles.** Vikas Nandwana, Kazuaki Yano and J. P. Liu; Physics, University of Texas at Arlington, Arlington, Texas.

Bimagnetic FePt/Fe<sub>3</sub>O<sub>4</sub> nanoparticles are synthesized by means of high-temperature solution method by growing soft magnetic Fe<sub>3</sub>O<sub>4</sub> phase on FePt nanoparticles. The soft phase can be coated or attached to the FePt phase in controlled manners. The size of the soft and hard phases can be tuned by changing reaction conditions. When the soft phases are coated on the hard phase particles, core/shell structured bimagnetic nanoparticles are formed; when the soft phases are attached to the hard phase, brick-like bimagnetic nanoparticles are formed. Magnetic properties of these nanoparticles are affected by dimensions of the soft and hard components due to the exchange coupling between them. Upon a reductive annealing, an assembly of the nanoparticles is transformed into a hard magnetic nanocomposite with enhanced energy product which is 36% higher than the FePt single phase.

#### 14.15

**Size and Property Control in the Synthesis of Magnetic Iron Nanoparticles.** Judith M. Lavin, Dale L. Huber, Todd C. Monson and Eugene L. Venturini; Sandia National Laboratories, Albuquerque, New Mexico.

We have synthesized a series of iron nanoparticles of varying sizes through the thermal decomposition of iron pentacarbonyl in dioctyl ether. The nanoparticles are stabilized by the presence of a weakly interacting  $\beta$ -diketone surfactant. This surfactant interacts strongly enough with iron to prevent agglomeration but does not induce oxidation. This allows us to synthesize very strongly magnetic iron nanoparticles, although they do display size-dependant magnetic moments. Iron nanoparticles with narrow polydispersity can be produced through this method only within a limited size range. Particles synthesized outside this size window tend to have high polydispersity and sometimes have bimodal distributions. The reasons for this limited range and the appearance of bimodal distributions will be discussed and hinge upon the issue of solubility. Evidence for the temporal separation of nucleation and growth in this relatively simple procedure will also be presented. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.



**I4.16**

**Size Dependence of Magnetic Properties of Fe<sub>3</sub>O<sub>4</sub> Particles in AC Magnetic Field.** Domingo Ferrer, Erik Taylor and Miguel Jose-Yacamán; Chemical Engineering Department, The University of Texas at Austin, Austin, Texas.

Magnetic nanoparticles are an attractive agent for tumor hyperthermia therapy due to the possibility for external activation via applied AC magnetic field. It has also been proposed that these particles could be targeted using a powerful magnetic field enhancing the importance of the magnetic aspect of the particle. Yet, recent results show the use of Fe<sub>3</sub>O<sub>4</sub> based magnetic heating is limited use for tumor lesions larger than 1 cm in diameter. It has been previously shown that other ferrite based magnetic nanoparticles may have a higher power loss than magnetite. One such material, MnFe<sub>2</sub>O<sub>4</sub>, is known but has been shown to be toxic to mammalian cells. Our proposed solution to this problem is to coat these particles with gold which is known to be biologically inert. Here, we present a consistent synthesis method for the production of XFe<sub>2</sub>O<sub>4</sub> ferrite nanoparticles where X includes Mn, Fe, and other 2+ oxidation state metals. We have succeeded in coating these magnetic nanostructures with gold in order to test the ability of these differing materials to cause localized heating with and without a gold coating.

**I4.17**

**Magnetic Field Assisted Fractionation of Non-Magnetic Colloids in Ferrofluid.** Derek S. Halverson and Gennady Friedman; ECE department, Drexel University, Philadelphia, Pennsylvania.

Creating monodisperse emulsions is an area of much interest with existing methods including drop break off [1] and entropic depletion forces [2]. A new method is proposed to create monodisperse colloidal systems, including emulsions, nearly irrespective of their composition, by using ferrofluid and an external magnetic field. In this method ferrofluid, which is fluid containing ten nanometer superparamagnetic iron oxide nanoparticles, is added to the continuous phase of a non-magnetic, stabilized, polydisperse emulsion. A uniform magnetic field is then applied across the media. This causes an attractive force to occur between the non-magnetic emulsion droplets due to negative magnetophoresis. The combination of dispersion, double layer or steric, depletion, and magnetic potentials results in an energy minima at a small displacement for particles larger than a certain size which causes them to flocculate and allows them to be removed as a cream. Smaller particles remain in the continuous phase. In order to create a monodisperse system the field can be increased slightly after the cream has been removed. Only the monodisperse set of particles, which were just too small to floc at the lower field, appear in the newly formed cream, which can then be collected. The ferrofluid can be removed from the continuous phase after the separation using a commercially available magnetic rack, or other known methods. In this work oil in water microemulsions stabilized by sodium dodecylsulfate and polydisperse sets of electrostatically stabilized polystyrene particles are investigated experimentally and theoretically. The advantages of this method over drop break off are that it works regardless of the interactions that the different phases may have with surfaces, requires less specialized equipment, and can be scaled to high throughput operations. Depletion force based methods, which are the existing process that is the most similar to the proposed method, use extremely short ranged forces, requiring the separation to take place over the course of days as particles must diffuse into each other. The magnetic force, however, is longer ranged resulting in separations occurring in hours or less. [1] P.B. Umbanhowar, V. Prasad, D.A. Weitz, "Monodisperse emulsion generation via drop break off in a coflowing stream," *Langmuir* 2000, 16, 347 [2] J. Bibette, "Depletion interactions and fractionated crystallisation for polydisperse emulsion purification." *J. Colloid Interface Sci.* 147, 474-478 (1991).

**I4.18**

**Mechanical and Magnetic Properties Characterization of Highly-aligned Nickel Nanowires / Elastomer Composites.** Heather Denver<sup>1</sup>, Timothy Heiman<sup>1</sup>, Elizabeth Martin<sup>2</sup>, Amit Gupta<sup>2</sup>, Xueti Tang<sup>3</sup>, Mutsuhiro Shima<sup>3</sup> and Diana-Andra Borca-Tasciuc<sup>1</sup>; <sup>1</sup>Mechanical, Aerospace and Nuclear Engineering, Rensselaer Polytechnic Institute, Troy, New York; <sup>2</sup>Chemical Engineering Department, Rensselaer Polytechnic Institute, Troy, New York; <sup>3</sup>Materials Science Department, Rensselaer Polytechnic Institute, Troy, New York.

Applications that utilize magnetic polymer nanocomposites are currently emerging at a high rate. Examples include magnetic actuation in microelectromechanical systems (MEMS) and medical devices, thermal actuation through electromagnetic power harvesting, and magnetically actuated morphing structures. This work pursues the fabrication and characterization of nanocomposites based on polydimethylsiloxane (PDMS) with nickel (Ni) nanowires as fillers. An electrochemical deposition process was employed to fabricate "in house" nickel nanowires 200nm in diameter with a length of a few micrometers. An anodic aluminum oxide (AAO) membrane is used as the template with gallium indium (Galn) as a seed layer. After fabrication, the nanowires are removed from the template by etching with a 6M sodium hydroxide (NaOH) solution and then dispersed in ethanol. Before mixing with PDMS the nanowires are coated with allyltrimethoxysilane surfactant to enhance dispersion. The polymer nanocomposite is left to cure in uniform magnetic field to facilitate the alignment of nickel nanowires. Afterward the glass transition temperature of the nanocomposite is measured employing a differential scanning calorimetry (DSC) machine. The quality of the dispersion is evaluated through scanning electron microscope (SEM) images. Magnetic properties measurement is done by vibrating sample magnetometer. Finally the stress-strain curves are collected by an instron.

**I4.19**

**Magnetometric Measurements of Ferrimagnetic Micro-particles Dispersed in Medium Approximating the Intracellular Environment.** Peter Jurdak<sup>1</sup>, Martin Kopani<sup>2</sup>, Ivan Simacek<sup>1</sup> and Jan Manka<sup>1</sup>; <sup>1</sup>Institute of Measurement Science, Slovak Academy of Sciences, Bratislava, Slovakia; <sup>2</sup>Department of Pathology, Comenius University, School of Medicine, Bratislava, Slovakia.

Using the one channel SQUID gradiometric system the time courses of the relaxation of the remanent magnetization depending on the intensity of the magnetizing field, the concentration of micro-particles, and the viscosity of carrier liquid have been investigated. Relaxation of the samples with magnetized ferrimagnetic micro-particles (Fe<sub>3</sub>O<sub>4</sub>, of the diameter ranging from 1 to 14 μm) dispersed in non-magnetic liquids approximating the intracellular environment, e.g. macrophages, was measured. This environment was simulated by liquids (epoxy and dimethylpolysiloxane) with two various viscosities. Since the relaxation is always present after the magnetizing process, for the realistic evaluation of the ferro- or ferrimagnetic contamination by retained dust in the lungs (magnetopneumography) and of the iron stores in the human liver and spleen, the time dependences of the relaxation have to be measured. The relaxation measurements can be also successfully applied in a magnetopneumographic investigation of alveolar clearance.



**14.20**

**Structural and Magnetic Properties of Melt-spun Fe-Co-Ni Ribbons and Powders for Inductor Applications.** Ashish Baraskar<sup>1</sup>, Soack D Yoon<sup>1</sup>, C. N. Chinnasamy<sup>1</sup>, Yajie Chen<sup>1</sup>, Nian Sun<sup>1</sup>, Carmine Vittoria<sup>1</sup>, Todd Heil<sup>2</sup>, Matthew Willard<sup>2</sup> and Vincent G. Harris<sup>1</sup>; <sup>1</sup>Center for Microwave Magnetic Materials and Integrated Circuits, Northeastern University, Boston, Massachusetts; <sup>2</sup>Naval Research Laboratory, Washington, District of Columbia.

The structural and magnetic properties of Ni<sub>11</sub>Co<sub>11</sub>Fe<sub>66</sub>Zr<sub>7</sub>B<sub>4</sub>Cu powders and ribbons were investigated. Ribbons of the above composition were prepared by rapid solidification then ball milled to obtain powder samples. The ribbons were annealed at temperatures from 300 °C to 550 °C to study the ductile to brittle transition as well as dc and rf magnetic properties. The ductile to brittle transition was measured in the sample annealed at 300 °C for 2 hours which was found to retain soft magnetic properties ( $4\pi M_s \sim 16$  kG,  $\Delta H \sim 100$  Oe and  $H_c \sim 0.5$  Oe). The brittle ribbons were ball milled using tungsten carbide vials in an inert atmosphere for various milling times. The sample milled for 10 hours was found to have a  $4\pi M_s$  of about 13 kG and coercivity of about 73 Oe with an average particle size of about 10  $\mu\text{m}$ . The sample, mixed with an epoxy and a binder, was then screen printed on Mylar. The as-prepared and aligned samples showed a linewidth ( $\Delta H$ ) of about 1000 Oe. Similar values were obtained for screen printed films annealed for 1 hour at 200 °C and 400 °C. Samples milled for more than 15 hours showed a considerable decrease in magnetization which was found to remain constant as the milling time was increased. A similar trend was observed with coercivity values.

**14.21**

**Fabrication of Co-Fe-B Nanowires as High Performance Biosensor Platform.** Kewei Zhang, Suiqiong Li, Liling Fu and Zhongyang Cheng; Auburn University, Auburn, Alabama.

Magnetostrictive Nanowires (MSNWs) as high performance biosensor platforms were introduced recently. As an acoustic wave device, the smaller the size of the MSNW, the higher the sensitivity of the sensor platform. At the same time, the smaller the size of the MSNWs, the higher the operating frequency of the platform. Therefore, MSNWs with high quality merit factor at high frequency (MHz - GHz) is required. Additionally, as biosensor platform, there is a great concern about the corrosion of the MSNW in water. Based on the properties of bulk materials, the Co-Fe-B amorphous alloy was selected as the magnetostrictive materials for fabricating MSNWs. In this article, the fabrication of amorphous Co-Fe-B MSNW in diameter from 50 nm to 200 nm is reported. The structure including microstructure and morphology were characterized. The magnetization of the NWs was measured. Based on the results, the optimized condition for preparing amorphous Co-Fe-B MSNWs was determined.

**14.22**

**Complex Nanoscale Magnetic Order in Manganite Superlattices.** Steven J. May<sup>1</sup>, S. G. E. te Velthuis<sup>1</sup>, X. Zhai<sup>2</sup>, M. R. Fitzsimmons<sup>3</sup>, J. N. Eckstein<sup>2</sup>, S. D. Bader<sup>1,4</sup> and A. Bhattacharya<sup>1,4</sup>; <sup>1</sup>Materials Science Division, Argonne National Laboratory, Argonne, Illinois; <sup>2</sup>Department of Physics, University of Illinois, Urbana-Champaign, Illinois; <sup>3</sup>Los Alamos National Laboratory, Los Alamos, New Mexico; <sup>4</sup>Center for Nanoscale Materials, Argonne National Laboratory, Argonne, Illinois.

Recently, the role of atomic disorder has been investigated in  $(\text{LaMnO}_3)_{2n}/(\text{SrMnO}_3)_n$  superlattices deposited by ozone-assisted molecular beam epitaxy (MBE), which are the ordered analogues of ferromagnetic  $\text{La}_{2/3}\text{Sr}_{1/3}\text{MnO}_3$ . While both  $\text{LaMnO}_3$  and  $\text{SrMnO}_3$  are antiferromagnetic in bulk form, the  $(\text{LaMnO}_3)_{2n}/(\text{SrMnO}_3)_n$  superlattices are ferromagnetic. However, little is known about their magnetic order on the nanoscale. In this work, we present evidence of a complex magnetic structure in  $(\text{LaMnO}_3)_{10+\delta}/(\text{SrMnO}_3)_{5-\Delta}$  superlattices. Polarized neutron reflectivity (PNR) measurements have been used to probe the magnetic order. Fits to the PNR data indicate the magnetic structure of the superlattices is modulated and repeats every bilayer. The PNR data cannot be fit to models in which the ferromagnetism is due to either a constant magnetization residing solely within the  $\text{LaMnO}_3$  layers or a large magnetization arising symmetrically at the LMO/SMO and SMO/LMO interfaces. A magnetic profile that is asymmetric about the interfaces will be presented as a possible structure. Additionally, a positive magnetoresistance is measured in the  $(\text{LaMnO}_3)_{10+\delta}/(\text{SrMnO}_3)_{5-\Delta}$  superlattices, persisting up to 25 kOe at 10 K. This positive magnetoresistance is not observed in magnetically homogeneous  $\text{La}_{2/3}\text{Sr}_{1/3}\text{MnO}_3$  films and  $(\text{LaMnO}_3)_2/(\text{SrMnO}_3)_1$  superlattices. Mechanisms in which the positive magnetoresistance arises as a consequence of the complex magnetic order will be discussed.

SESSION 15: Magnetic Recording Media  
Chairs: Eric Fullerton and Ichiro Takeuchi  
Tuesday Morning, November 27, 2007  
Commowalth (Sheraton)

**8:30 AM 15.1**

**L1<sub>0</sub> FePt for Ultrahigh Density Magnetic Recording Media: Phase Formation and Stability of the Ordered Intermetallics in the Fe-Pt**

**System.** David C. Berry<sup>1</sup>, Bincheng Wang<sup>1</sup>, Katayun Barmak<sup>1</sup> and Timothy J. Klemmer<sup>2</sup>; <sup>1</sup>Dept. of Materials Science and Engineering, Carnegie Mellon University, Pittsburgh, Pennsylvania; <sup>2</sup>Seagate Research, Pittsburgh, Pennsylvania.

L1<sub>0</sub> ordered FePt continues to be of interest for application in ultrahigh density ( $\geq 1\text{Tb}/\text{in}^2$ ) magnetic recording media. First principles calculations of phase stability and modeling of the A1 to L1<sub>0</sub> phase transformation are now viewed as important and necessary steps in alloy, process and recording system design. These calculations and modeling efforts will, in turn, benefit from the availability of experimentally-measured heat of formation data for the various intermetallic phases in the Fe-Pt system. Using non-isothermal differential scanning calorimetry (DSC) of sputter-deposited multilayer thin films of Fe/Pt, the heats of formation of the three ordered intermetallic phases in the Fe-Pt system, namely L1<sub>2</sub> Fe<sub>3</sub>Pt, L1<sub>0</sub> FePt, and L1<sub>2</sub> FePt<sub>3</sub>, are measured. These values are compared with the first principles calculations reported in the literature. The agreement between experimental values and calculated values is reasonable; however, all of the calculated values are found to underestimate the total heats of



formation. In addition to reporting the heats of formation for the intermetallic phases, the complex sequence of phases formed in the Fe/Pt multilayers determined using x-ray diffraction will be presented.

#### 8:45 AM I5.2

**Nanoscale Annular NiFe/Cu/Co Devices for Magneto-Logic Applications.** Bryan Gar-Wah Ng, Irene A Colin, Fernando J Castano and Caroline A Ross; Materials Science and Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts.

The magneto-transport response of patterned elements made from hard layer/non-magnetic spacer/soft layer structures is dominated by giant magnetoresistance (GMR), and results in distinct resistance levels depending on the relative alignment of the magnetization in the hard and soft layers. The ability to electrically discriminate these non-volatile magnetic states in elongated or elliptical elements has already been exploited in magnetic random access memories and proposed for logic devices. However, ring-shaped elements are much more interesting geometries due to the additional resistance levels from vortex-like magnetic configurations in the hard and soft layers, allowing the storage or processing of more than two bits per element. The present work explores annular NiFe/Cu/Co structures as logic gates and shows that these devices offer several advantages over traditional CMOS, including the ability to perform logic operations using a single structure, to change the logic operation with an applied field and to preserve the logic operation in a non-volatile magnetic state. Prototypical devices consisting of elliptical and rhomboidal NiFe/Cu/Co ring-shaped elements with Ta/Cu electrical contacts were fabricated using lift-off processing and a combination of optical and electron-beam lithographies. The rings studied had long axes ranging from 500 nm to 4 $\mu$ m, aspect ratios of 2, and line widths between 80nm and 150nm. The magneto-transport response was investigated using a 4-point technique with a 0.01mA probing current at 1kHz. The results from two different measurement configurations will be presented. In the first configuration, current is injected using two diametrically opposed leads and the voltage measured using two leads located on one side of the ring. These measurements result in GMR values of 1-3%, which are comparable with those of unpatterned NiFe/Cu/Co stacks. In the second configuration, both current and voltage leads are located at diametrically opposed sites on the ring but perpendicular to each other, as in a Wheatstone bridge. The latter method is especially sensitive since it measures the differential resistance in each branch. The symmetry of the ring-shaped elements results in low absolute resistance values. However, the asymmetric nucleation and movement of domain walls produce large GMR values typically around 40-100%, and as high as 200%. The rhomboidal devices are of particular interest due to numerous 360 degree domain walls that are present in micromagnetic simulations and are inferred from magneto-transport results. Characteristics of these annular elements for use as logic device will also be discussed, including the use of current to induce magnetic state changes, and the reproducibility of achieving desired remanent states through low frequency dynamics measurements.

#### 9:00 AM \*I5.3

**Domain Walls in Magnetic Nanowires for Digital Logic and Ultrahigh Density Data Storage.** Russell Cowburn, Department of Physics, Blackett Laboratory, Imperial College London, London, United Kingdom.

Nanometre scale planar magnetic nanowires can exhibit a special magnetic property known as domain wall conduit behaviour in which domain walls can be transmitted along the nanowire by the application of weak magnetic fields or electrical currents. This opens up the possibility of integrated circuits containing complex networks of nanowires in which information is carried, stored and processed by domain walls flowing along nanowire conduits. In this talk I show a complete Boolean logic system implemented using domain walls in nanowires and describe the outlook for ultrahigh density solid state data storage based on this approach.

#### 9:30 AM I5.4

**Application of Cylinder Forming Block Copolymers as Templates for Formation of Bit Patterned and Graded Media.** Vishal Warke<sup>1,2</sup>, Martin Gerard Bakker<sup>1,2</sup>, Kunlun Hong<sup>3</sup>, Phillip Britt<sup>3</sup> and Jimmy Mays<sup>3</sup>; <sup>1</sup>Center for Materials for Information Technology, The University of Alabama, Tuscaloosa, Alabama; <sup>2</sup>Department of Chemistry, The University of Alabama, Tuscaloosa, Alabama; <sup>3</sup>Center for Nanophase Materials Science, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

Bit patterned media, including media fabricated with a gradient in composition, is being developed as a potential path to higher information storage density. The formation of metal nanopillars with 20-30 nm repeat spacing and precisely controlled magnetic properties presents a significant challenge to current fabrication methods. We have been developing cylinder forming block copolymer phases as a method to generate the desired patterns coupled with the processing steps necessary to transfer the pattern into magnetic material. This involves spin coating of the polymer on an appropriate orienting layer, annealing to allow the pattern to form by self-organization of the block copolymer, solvent processing to remove the minority domain, electrodeposition to form a hard mask, followed by ion-milling to transfer the pattern to the magnetic material. We have demonstrated each step in this process and will report on the quality of the pattern transfer achieved.

#### 9:45 AM I5.5

**Magnetic Switching Behavior of Permalloy Thin Film, Disks, and Coupled Disk/film Structures.** Lei Huang and Yimei Zhu; Institute for Advanced Electron Microscopy, Brookhaven National Laboratory, Upton, New York.

Understanding magnetization reversal dynamics in patterned ferromagnetic elements is crucial to the development of modern magnetic storage media and spintronic devices. In this work, we choose three different types of polycrystalline permalloy structures: continuous thin film, patterned disk arrays, and coupled disk/film structures to systematically study how geometric confinements, magnetostatic interaction, and interlayer coupling can influence the switching behavior. All the samples are prepared by UHV electron beam deposition method. Dynamic switching process with changing field is recorded by in-situ Lorentz Microscopy with low magnification. Bulk magnetic moments and hysteresis curves of the same samples are then measured by SQUID and compared with TEM results. In this way, we can have a clear knowledge of the magnetic microstructure in various stages of the hysteresis curve, and analyze the underlying mechanism. Besides, micromagnetic simulation is also employed to help distinguish important details such as nucleation events, in case experimental capabilities are lacking. We find that, for the continuous film, when field is reduced from saturation, switching behavior consist of two mechanisms: magnetization rotation and domain wall propagation, and the transition of these two stages correspond to the jump position of hysteresis curve. For the patterned disk arrays, switching is caused by magnetic vortex nucleation, propagation and annihilation, confirming previous observations. Most interesting is the coupled structure, of which patterned permalloy disk arrays is deposit on top of continuous permalloy film and a nonmagnetic spacer layer (carbon). In this case, a new switching mechanism is discovered: magnetization is collectively rotated, but the domain walls are formed in the shape of sharp spikes, and are pinned under each disk at all times. We give our explanation based on interlayer magnetic dipole coupling, and the model is qualitatively confirmed by micromagnetic simulation.



**10:30 AM I5.6**

**Magnetic Behavior of Self-organized Nanomagnet Arrays Epitaxially Grown by LaserMBE.** Akifumi Matsuda<sup>1</sup>, Takahiro Watanabe<sup>1</sup>, Yasuyuki Akita<sup>1</sup>, Makoto Hosaka<sup>1</sup>, Kouji Koyama<sup>2</sup>, Yoshitaka Kitamoto<sup>1</sup> and Mamoru Yoshimoto<sup>1</sup>; <sup>1</sup>Department of Innovative and Engineered Materials, Tokyo Institute of Technology, Yokohama, Kanagawa, Japan; <sup>2</sup>Crystal Growth Laboratory, Namiki Precision Jewel Co., Ltd., Yokohama, Kanagawa, Japan.

The epitaxially grown magnetic nanostructures including nanodots, nanowires and nanorings have been attracting much scientific and engineering interests because of their expected unique physical characteristics due to quantum effects. These epitaxial nanomagnets and their array are undoubtedly thought to make major contribution to the development of future *SPINTRONICS* devices, ultra-high density magnetic random access memory (MRAM) and magnetic switching devices for examples, and other quantum devices. In this case, epitaxial growth of the nanomagnets and the resulting anisotropic properties are one of the largest interest as well as fine-nanostructuring. There have been some concerns such as throughput rate with conventional nanoprocessing techniques involving FIB lithography and e-beam lithography, and/or minimization-limit with photolithography due to the wavelength. On the other hand, self-assembly or self-organized methods could also be used for construction of nanopatterns, in which such nanostructures are directly built up from separate atoms. Here we report about formation and characterization of self-organized nanomagnet arrays made of metals and oxides. We have epitaxially grown ferrimagnetic Fe<sub>3</sub>O<sub>4</sub> (111), (Mn<sub>0.55</sub>Zn<sub>0.35</sub>Fe<sub>0.10</sub>)Fe<sub>2</sub>O<sub>4</sub> (111), ferromagnetic Ni (111) and antiferromagnetic NiO (111) nanodots, nanowires and nanogroove arrays on the atomically stepped ultra-smooth sapphire (0001) substrate by LaserMBE. The sapphire ( $\alpha$ -Al<sub>2</sub>O<sub>3</sub> single crystal) substrates have atomic steps of 0.2 nm in height and atomically flat terraces of 50-100 nm in width so that self-assembly processes of nanomagnet arrays were strongly induced by the energetic instability at the straight and periodic step-edges. In this study, NiO worked as a antiferromagnetic exchange bias layer. On the other hand, NiO was also reduced into ferromagnetic Ni metal by annealing in hydrogen atmosphere in some situations for further applications. Crystallographic and morphology analyses of the nanomagnets were made by *in-situ* reflection high-energy electron diffraction (RHEED), *ex-situ* X-ray diffraction (XRD), transmission electron microscope (TEM), and atomic force microscopy (AFM). Magnetic properties were characterized by superconducting quantum interference device (SQUID) magnetometer and magnetic force microscopy (MFM). Further experimentals are conducted for magneto-optical characterizations for above mentioned metal and/or oxide nanomagnet arrays.

**10:45 AM I5.7**

**Fabrication of Discrete Track Media with Patterned Servo-areas and Tracks on Disk Substrate.** Yuko Tsuchiya, Kenichi Ito, Chiseki Haginoya and Yoshiyuki Hirayama; Central Research Laboratory, Hitachi, Ltd., Kokubunji, Tokyo, Japan.

Patterned media recording is now situated as next-generation technology applied with perpendicular magnetic recording (PMR) to achieve higher magnetic recording densities. In the broad sense, there are two types of patterned media, one is bit patterned media (BPM) and the other is discrete track media (DTM). In patterned media fabrications, one of the important processes is a nano-pattern transfer from a resist layer to a substrate or a metal film by etching/milling. The resist patterns are fabricated by Photo lithography, EB lithography, and nano-imprinting lithography. In the stage of mass-production of patterned media, the efficient and the stable resist pattern transfer is required even though there are inhomogeneous property in resist thickness. The purpose of this study is to fabricate DTM by using inhomogeneous resist patterns as etching mask and to find a solution to the issue concerning the nano pattern transfer. We use resist patterns including servo and track patterns with about 240 nm in track pitch as etching mask, which are imprinted on a SiN layer with 100nm in thickness made on the surface of 2.5" glass disk. The resist patterns are translated to the SiN layer by two-step Reactive Ion Etching (RIE). The first step eliminates base layer of resist patterns in order to obtain homogeneous resist patterns in thickness, and the second step etches the SiN layer using the resist patterns without base layer. As a result, nano-patterns including servo and track patterns are translated to the SiN layer. We fabricate a DTM after PMR films deposition on the patterned surface followed by several post processes including tape-cleaning, head burnish, and lubricant coating. We also observe read-back signals from servo patterns on the DTM in spin-stand test. The fabrication process and the structure of the DTM will be discussed in detail. In conclusion, the resist patterns involving servo and track patterns are successfully translated to the SiN surface by two step RIE process with suitable etching conditions, which shows that inhomogeneous resist patterns in thickness, such as nano-imprinted resist patterns, can be applied to mass-production by optimizing the fabrication process. The fabricated DTM shows stable flying during read back signal detection, which suggests a practical use of the DTM as magnetic recording media.

**11:00 AM I5.8**

**Fabrication and Magnetic Behavior of Nano-Patterned Magnetic Media.** Sungho Jin, University of California-San Diego, La Jolla, California.

The magnetic properties and switching behavior of 10-20 nm regime magnetic islands are of immense interest to the field of ultra-high-density magnetic recording media, especially for patterned media applications. We have fabricated an array of vertically anisotropic (Co/Pd)<sub>n</sub> multilayered islands in the ~1 Tbit/in<sup>2</sup> recording density regime on a pre-patterned Si nanopillar template by e-beam lithography, RIE dry etching and magnetic multilayer sputter deposition. Both negative resist and positive resist were used for comparative patterning of nano-magnet islands with different size and shape. The processing parameters were modified to intentionally alter the shape of the Si nanopillar sidewall so as to minimize or maximize the undesirable deposition of magnetic recording media on the pillar sidewalls or corners, and to study the associated effects on switching field distribution of patterned media. Vertically straight, positive tapered, or negative tapered pillar sidewall configurations were utilized, and the M-H loop characteristics, coercivity and switching behavior of the patterned media on these pillars with different dimensions were evaluated. For comparison, structure and properties of patterned media based on anodized aluminum oxide (AAO) templates<sup>[1,2]</sup> with further tailored nano-magnet configurations will also be discussed. For evaluation of ultra small nano-magnets, high resolution MFM probes capable of resolving 10-20 nm regime features are highly desirable. Some progress toward fabricating such probes useful for patterned media analysis will also be described. 1. A. I. Gapin, X. R. Ye, J. F. Aubuchon, L. H. Chen, Y. J. Tang, and S. Jin, "CoPt patterned media in anodized aluminum oxide templates," J. Appl. Phys. 99, 08G902 (2006). 2. A. I. Gapin, X. R. Ye, L. H. Chen, D. Hong, and S. Jin, "Patterned media based on soft/hard composite nanowire array of Ni/CoPt," IEEE Trans. Magn., 43(6), 2151 (2007).

**11:30 AM I5.9**

**Fundamentals of Magnetism and Transport in 3d-/5d(4d) Materials: Nano-alloys, Nano-interfaces, Nano-composites.** Oleg N. Mryasov, Seagate Research, Pittsburgh, Pennsylvania.



The continuous demand for ever-higher storage density and faster data transfer prompts to reevaluate basic materials and device physics utilized so far in magnetic recording and magneto-electronic devices. Interdependence of fundamental material properties (uniaxial magnetic anisotropy ( $K_1$ ), striction, magnetization saturation ( $M$ ), conduction electron spin polarization ( $\eta$ ) and finite size effects often create constraints for design of magnetic nano scale device. In particular 3d-/5d(4d) magnetic material system plays prominent role in achieving controllable perpendicular  $K_1$ ,  $M$ , striction, Curie point, anomalous Hall effect(AHE),  $\eta$ . In this presentation we focus on fundamental aspect of 3d-5d(4d) electronic interactions being at the origin of many observed properties of these materials. These interactions are theoretically investigated for 3d-/5d(4d) material system both in the case of proximity interaction (like Co/Pt multi-layers), intermetallic nano scale alloys ( $L1_0$  FePt, B2 FeRh nano-particles) and exchange coupled composite (FePt/FeRh). We demonstrate microscopic mechanism responsible for the wealth of properties (expanded design space) which can be achieved in these nano-phase structures. First, we consider nano-particle (single grain) of  $L1_0$  FePt, FePd and B2 FeRh as a vivid examples of magnetic 3d-5d(4d) nano-alloys [1,2]. Then we investigate how magnetic performance and exchange coupling are affected by interfacial interaction for FePt/FeRh composite nano structures [3]. We discuss examples showing importance of atomic scale finite size effects and correspondingly a need to develop a quantitative model of magnetic interactions. The proposed microscopic model of magnetic interactions generally applicable for 3d-5d(4d) alloys [1,2] is tested against measurements of the temperature dependent magnetic [2] and switching properties of nano-particulate and granular FePt thin films. This model of isotropic and anisotropic magnetic inter-atomic interactions mediated by the Stoner intra-atomic interaction enhanced elements Pt, Pd and Rh is shown to be capable of explaining the interesting finite size and temperature dependent magnetic properties of these nano-alloys, conduction electron spin polarization and trends in AHE variation arising from the orbital polarization due to 3d-5d interaction in these alloys. References [1] O.N. Mryasov et al., EuroPhys. Lett., v.9, p.805, 2005 [2] G.Ju et al., Phys. Rev. Lett., v93, p.197403 (2004); O.N. Mryasov, Phase Transitions, v.78, N.1-3, p. 197-208, 2005 [3]F.Garcia-Sanchez et al.,Appl.Phys. Lett., v.87,p.122501, 2005

SESSION I6: Magnetic Thin Films, Processing and Applications  
Chairs: Julia Lyubina and John Prater  
Tuesday Afternoon, November 27, 2007  
Commowwealth (Sheraton)

#### 1:30 PM I6.1

**Fabrication and Real Time Characterization of Highly Anisotropic Nanostructures.** Jonathan R. Skuza<sup>1</sup>, Michelle N. Sestak<sup>1</sup>, Cesar Clavero<sup>1</sup>, Rosa Alejandra Lukaszew<sup>1</sup>, Donald A. Walko<sup>2</sup> and Roy Clarke<sup>3</sup>; <sup>1</sup>Department of Physics & Astronomy, The University of Toledo, Toledo, Ohio; <sup>2</sup>Advanced Photon Source, Argonne National Laboratory, Argonne, Illinois; <sup>3</sup>Department of Physics, University of Michigan, Ann Arbor, Michigan.

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 ( $\sim 10^7$  erg/cc), while the  $L1_2$  phase exhibits in-plane magnetic anisotropy.<sup>1</sup> Thus, suitable combinations of these chemically ordered phases have been proposed for the next generation of magnetic recording media with tilted magnetization.<sup>2</sup> 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<sup>+</sup> 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  $\sim 400^\circ$  C using x-ray diffraction (XRD), with further re-ordering and formation of the  $L1_0$  phase at  $\sim 500^\circ$  C. Further analysis of the isothermal annealing data shows that the activation energy of the  $L1_0$  phase in these nanocomposite samples is  $\sim 1.0$  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. <sup>1</sup> A. Cebollada, R. F. C. Farrow, and M. F. Toney, in *Magnetic Nanostructures*, edited by H. S. Nalwa (American Scientific, Stevenson Ranch, CA, 2002), pp. 93 - 122. <sup>2</sup> A. K. Singh, J. Yin, H. Y. Y. Ko, and T. Suzuki, J. Appl. Phys. **99**, 08E704 (2006).

#### 1:45 PM I6.2

**Hard Magnetic Films for MEMS Applications.** N. M. Dempsey<sup>1</sup>, A. Walther<sup>2,1</sup>, C. Ndao<sup>1</sup>, C. Marcoux<sup>2</sup>, B. Desloges<sup>2</sup>, R. Grechishkin<sup>3</sup>, M. S. Kustov<sup>3</sup>, K. Khlopov<sup>4</sup>, O. Gutfleisch<sup>4</sup> and D. Givord<sup>1</sup>; <sup>1</sup>Institut Neel, CNRS/UJF, Grenoble, France; <sup>2</sup>CEA Léti - MINATEC, Grenoble, France; <sup>3</sup>Laboratory of Magneto-electronics, Tver State University, Tver, Russian Federation; <sup>4</sup>Institute of Metallic Materials, IFW Dresden, Dresden, Germany.

Magnetic MEMS (Micro-Electro-Mechanical-Systems) hold much potential for applications in the fields of information technology, energy transformation/management and bio-medicine, because they may produce large actuation forces over long distances for relatively low voltage and power consumption [1]. However, their development has been limited by the poor quality of permanent magnets (low remanence and low coercivity) which have been produced at the right scale (i.e.  $\geq 5 \mu\text{m}$ ) using micro-fabrication processes which are compatible with MEMS technology. In this presentation we will discuss the preparation, structuring and characterisation of a variety of high performance hard magnetic materials destined for applications in Magnetic MEMS. Following a brief description of the state-of-the-art, we will present our recent results concerning two rare earth transition metal systems (NdFeB[2, 3] and SmCo) as well as the  $L1_0$  FePt system. We have used 100 mm Si wafers so as to be compatible with standard micro-fabrication processes. Thick films (5-50  $\mu\text{m}$ ) were deposited with a triode sputtering system at deposition rates of up to 20  $\mu\text{m/h}$ . The influence of deposition temperature on the magnetic and structural properties of films in the as-deposited and post-deposition annealed states will be presented. The lateral structuring of these films will be discussed. Patterned films have been locally characterised using both magnetic and magneto-optic methods and the results will be compared with calculated stray field patterns. Finally, the mechanical properties of the different materials will be discussed. [1] O. Cugat, J. Delamare and G. Reyne, IEEE Trans. Mag. **39** 3608 (2003) [2] N.M. Dempsey, A. Walther, F. May and



D. Givord, K. Khlopov and O. Gutfleisch, Appl. Phys. Lett. 90 092509 (2007) [3] A. Walther, K. Khlopov, O. Gutfleisch, D. Givord and N.M. Dempsey, J. Magn. Magn. Mat. 316 174 (2007)

### 2:15 PM I6.3

**Growth and Characterization of Cobalt Thin Films Grown on Nanoporous Alumina Membranes.** Chunming Jin<sup>2</sup>, Nori Sudhakar<sup>2</sup>, Wei Wei<sup>2</sup>, Ravi Aggarwal<sup>2</sup> and Roger Jagdish Narayan<sup>1,2</sup>, <sup>1</sup>Biomedical Engineering, University of North Carolina, Chapel Hill, North Carolina; <sup>2</sup>Materials Science and Engineering, North Carolina State University, Raleigh, North Carolina.

Unlike other nanoporous membranes, nanoporous alumina (also known as anodized aluminum oxide) exhibits high porosity, a uniform spatial distribution of pores, and a narrow range of pore sizes, which range between tens of nanometers and a few hundred nanometers. These unusual materials have previously been used to develop arrays of nanoparticles and nanorods. In this work, we report on the processing and characterization of magnetic cobalt thin films grown on nanoporous alumina substrates. The films were grown using pulsed laser deposition at room temperature using a KrF (wavelength=248 nm) laser. For comparison, cobalt thin films were also grown on silicon substrates. The cobalt films grown on nanoporous alumina have a network-like structure due to the porous nature of the substrate material. X-ray diffraction and transmission electron microscopy were used to examine the microstructure of this novel material. Surface morphology was determined using atomic force microscopy and scanning electron microscopy. The temperature- and field-dependent magnetization properties of these materials were measured using a superconducting quantum interference device (SQUID) and a vibrating sample magnetometer (VSM). Isothermal field dependent magnetization was measured at different temperatures, ranging from 10 K to 350 K. The magnetization started saturating at ~500 Oe, and the samples exhibited large hysteresis reminiscent of ferromagnetic materials. All the curves at different temperatures revealed hysteresis up to 350 K. The coercivity values for the films grown on nanoporous alumina substrates (order of 1000 Oe) was much higher than those for the films grown on flat silicon substrates (~100 Oe). The low temperature magnetization (at 10 K) did not saturate in fields as high as 20 kOe, which is suggestive of superparamagnetic behavior. These novel network-like cobalt thin films are expected to find several applications in magnetic recording and other related fields.

### 2:30 PM I6.4

**Magneto-transport Properties of Gd-doped In<sub>2</sub>O<sub>3</sub> Thin Films.** K. Ghosh<sup>1</sup>, Ram K Gupta<sup>1</sup>, D. Brown<sup>1</sup>, S. R Mishra<sup>2</sup> and P. K Kahol<sup>1</sup>; <sup>1</sup>Physics, Astronomy and Materials Science, Missouri State University, Springfield, Missouri; <sup>2</sup>Physics, university of memphis, memphis, Tennessee.

Dilute Magnetic Semiconductors (DMS) are a rare group of promising materials that utilize both electronic charge, a characteristic of semiconductor materials, and electronic spin, a characteristic of magnetic materials. Among all the DMS materials, oxide based DMS show promise of ferromagnetism (FM) at room temperature. It has been found that doping metal oxides such as (ZnO, TiO<sub>2</sub>, In<sub>2</sub>O<sub>3</sub>) with magnetic ions such as Fe, Co, Mn, Cr produces DMS and exhibit FM above room temperature. In<sub>2</sub>O<sub>3</sub>, a transparent opto-electronic material, is an interesting prospect for spintronics due to its unique combination of magnetic, electrical, and optical properties. High quality thin films of rare earth magnetic gadolinium (Gd) doped oxide-based DMS materials have been grown by pulsed laser deposition technique on various substrates such as single crystal of sapphire (001), silicon (100), and quartz under suitable growth conditions such as substrate temperature and oxygen pressure in the PLD chamber. The effect of rare earth magnetic doping on the structural and electro-magnetic properties of these films has been studied using various techniques such as Raman Spectroscopy, X-Ray Diffraction, Scanning Electron Microscopy, and Magneto-Transport. X-ray diffraction study reveals that these films are single phase and highly oriented. Characteristic Raman peaks corresponding to indium oxide appeared at 496 and 627 cm<sup>-1</sup>. Detailed temperature and magnetic field dependent resistivity, magnetoresistance, and Hall effect data will be presented. This work is supported by Research Corporation (award number CC6166).

### 2:45 PM I6.5

**L10 Ordered Epitaxial FePt Thin Films and Nanodots Integrated with Si (100).** Gopinath Trichy and Jagdish Narayan; North Carolina State University, Raleigh, North Carolina.

In magnetic systems size reduction to magnetic length scales like magnetic exchange length and domain-wall width can lead to favorable changes in coercivity, remanence and domain reversal mechanisms. Systems that have high magneto crystalline anisotropy like the L10 ordered FePt ( $K_u = 7 \times 10^7$  erg/cm<sup>3</sup>), permit the use of smaller particles before the onset of superparamagnetism. We present findings on the synthesis and processing of c-axis oriented FePt thin films and individual nanodots using pulsed laser deposition (PLD). Our approach has been to grow FePt on Si (100) using epitaxial TiN as a template buffer. The unique feature of this study stems from the use of Si (100) as the substrate. Usage of Si facilitates potential integration of our magnetic structures with the present day microelectronic devices. Insertion of TiN as the template buffer leads to FePt growth oriented along the magnetically hard [001] direction. The composition of the nanostructures, as determined by Rutherford backscattering, was varied from Fe<sub>40</sub>Pt<sub>60</sub> to Fe<sub>50</sub>Pt<sub>50</sub>. By using the Pt rich off-stoichiometric Fe<sub>41</sub>Pt<sub>59</sub> system and a high-energy processing technique like PLD, we show that we can induce considerable L10 order at a low processing temperature of 500 °C. XRD and TEM studies showed that the FePt thin film and nanodot systems are ordered and epitaxially oriented such that the c-axis is perpendicular to the sample surface. Selected area electron diffraction patterns along the <110> and <001> zones were analyzed to study the L10 order in these systems. From these studies the following epitaxial relationship was obtained; FePt(001)<001>||TiN (100)<001>||Si(100)<001>. The FePt thin film was 30 nm thick and average size of the nanodots was 18 nm. For the continuous thin film system perpendicular coercivity for a sample grown at 500 °C was 2250 Oe. When growth temperature was increased to 600 °C, the squareness of the perpendicular loop improved remarkably to 0.95. For the nanodot system grown at 500 °C, room temperature coercivity was 3200 Oe and squareness was 0.87. Improved coercivity for the nanodot system was attributed to the transition to single domain states. In this system, assuming one bit of information is stored in each nanodot, areal density can exceed 1 Tbit/inch<sup>2</sup>, corresponding to 250 million pages of information per chip. By changing the composition to near equiatomic (Fe<sub>50</sub>Pt<sub>50</sub>) we obtained perpendicular coercivity as high as 13500 Oe. Preliminary magnetoresistance (MR) studies on this system revealed 0.57% MR when the field was perpendicular to the current. The MR loops showed hysteresis behavior consistent with MH loops and maximum resistance was observed at coercive field. When field was kept parallel to the current, resistance values were consistently higher. Magnetic properties of these nanostructures can be tuned to the requirements of information storage and recording devices.

### 3:30 PM \*I6.6

**Magnetization Behavior in Epitaxially Grown FePt Films.** Toshiyuki Shima<sup>1</sup> and Koki Takashi<sup>2</sup>; <sup>1</sup>Electronics Engineering, Tohoku Gakuin University, Tagajo, Japan; <sup>2</sup>IMR, Tohoku University, Sendai, Japan.



Magnetization process in hard magnetic materials with a large magnetocrystalline anisotropy is conveniently classified as the nucleation-type and the pinning-type. For example, the former is typically observed for Nd-Fe-B magnets, and the latter, for Sm-Co magnets. However, in the both cases, a high magnetic field is necessary to saturate the magnetization completely for getting a high coercivity ( $H_c$ ); in other words, generally it is not easy to fully wipe out reversed domains at a low magnetic field. We reported that high  $H_c$  exceeding 70 kOe was achieved in highly ordered FePt (001) films with island structure, which were epitaxially grown on MgO (001) substrates [1]. In this paper, we will overview the recent results [2] on the magnetization behaviour in comparison with domain observation for the FePt(001) films, indicating that they are ideal nucleation-type nanomagnets. Samples were prepared by multiple dc-sputtering with co-deposition of Fe and Pt directly onto single crystalline MgO (001) substrates heated up to 780 C during the deposition. The structural analysis was performed by TEM and XRD. The magnetization was measured by SQUID and VSM with the maximum applied field of 140 kOe, and the domain observation was made by MFM. The FePt films with the nominal thicknesses from 20 to 50 nm consist of FePt islands with multiple domain structure in demagnetized state. The multiple domain structure is turned into single domain one at an applied field lower than 10 kOe, and the magnetization is saturated. When the applied field is reversed after the saturation,  $H_c$  reaches an almost full value more than a few tens kOe. This indicates that reversed domains are wiped out completely even at a low applied field, resulting in high  $H_c$ . [1] T. Shima et al. Appl. Phys. Lett. 81, 1050 (2002). [2] T. Shima et al. Appl. Phys. Lett. 85, 2571 (2004).

#### 4:00 PM I6.7

**Epitaxial Pr-Co films: Intrinsic and Extrinsic Properties.** Ajit Kumar Patra, Volker Neu, Sebastian Faehler and Ludwig Schultz; IFW Dresden, Dresden, Germany.

Permanent magnet thin films with a well-defined texture and high energy density are useful for today's applications in magnetic microelectromechanical systems (Mag-MEMS) and magnetic nanoelectromechanical systems (Mag-NEMS). Because of the excellent magnetic properties of the RE-Co magnets, they are one of the preferred materials in the family of permanent magnets. Pulsed laser deposited epitaxial  $\text{Pr}_x\text{Co}_{100-x}$  ( $x = 8.7 - 27.6$ ) have been prepared on Cr buffered MgO(110) single crystal substrates and systematically examined as a function of Pr content. Structural investigations reveal that films with  $x = 8.7 - 13$  crystallize in a disordered metastable  $\text{PrCo}_7$  structure (TbCu7 type), films for  $x = 15.4 - 20.4$  exhibit a mixed phase of  $\text{PrCo}_5$  (CaCu5 type) and  $\text{Pr}_2\text{Co}_7$  (Ce<sub>2</sub>Ni<sub>7</sub> type), and samples with  $x = 22.9 - 27.6$  crystallize in a hexagonal  $\text{Pr}_2\text{Co}_7$  phase. All films exhibit a (h00) texture with the c-axis of the Pr-Co grains uniquely aligned in the substrate plane along the MgO[001] directions. Uniaxial anisotropy at room temperature is observed for all cases. Saturation polarization (JS) decreases monotonically with the increase of Pr content. Remanent polarization (JR) follows the trend of JS with a remanence squareness (JR/JS) of  $> 0.9$ , due to the excellent epitaxial growth. Coercivity increases with the increase of Pr content and exhibits a broad maximum (see figure) around 16.5 - 23.5 at. % Pr. For the best combination of coercivity and polarization, the energy density reaches a value of 310 kJ/m<sup>3</sup>, which is the highest value reported for RE-Co magnets. References: A. K. Patra, V. Neu, S. Fähler, R. Groetzschel, S. Bedanta, W. Kleemann and L. Schultz, Crystal structure and its correlation to intrinsic and extrinsic magnetic properties of epitaxial hard magnetic Pr-Co films, Phys. Rev. B 75, 184417 (2007). A. K. Patra, V. Neu, S. Fähler, R. Groetzschel, and L. Schultz, Metastable, epitaxial  $\text{PrCo}_7$  films with high energy product, Appl. Phys. Lett. 89, 142512 (2006).

#### 4:15 PM I6.8

**Nanostructured NiFe<sub>2</sub>O<sub>4</sub> Ferrite Film Fabricated by Wet Chemical and Tape-Casting.** Heng Zhang and Danny T Xiao; Inframat Corporation, Farmington, Connecticut.

A nanostructured NiFe<sub>2</sub>O<sub>4</sub> ferrite has been synthesized using a combination of chemical synthesis, a tape casting and thermal sintering process. The NiFe<sub>2</sub>O<sub>4</sub> precursors were synthesized using a sol-gel process. Thin tapes were prepared from the nickel ferrite precursor powder through a tape casting process. The tapes were then shaped and heated under controlled conditions to obtain bulk components with nanostructure. The formation of the magnetic phase from precursors is a homogeneous nucleation process that can lead to ultrafine nanostructure. The structure, electronic behavior and magnetic properties of the material have been investigated by using x-ray diffraction, SQUID magnetometer, impedance spectroscopy and high precision multimeter measurements. The study indicated that the grain size, microstructure and density are determined by sintering temperature and heating rate. Slow heating can lead to a high density and nanostructure. The packing density increases significantly with temperature when a lower heating rate is used. Using an appropriate sintering consolidation process, an ultrafine nanostructured ferrite with high density, good insulating capability and high permeability can be achieved. In an optimal condition, a packing density over 93%, an electrical resistivity over 1.15x10<sup>8</sup> ohm.cm and a permeability over 25 at the frequency of 13 MHz can be achieved. Details of the study will be presented in this presentation.

#### 4:30 PM I6.9

**Structural and Magnetic Properties of Cobalt Nanodots Grown with Pulsed Laser Deposition.** Ravi Aggarwal<sup>2</sup>, Chunming Jin<sup>2</sup>, Nori Sudhakar<sup>2</sup>, Wei Wei<sup>2</sup>, Jagdish Narayan<sup>2</sup> and Roger Jagdish Narayan<sup>1</sup>; <sup>1</sup>Biomedical Engineering, University of North Carolina, Chapel Hill, North Carolina; <sup>2</sup>Materials Science and Engineering, North Carolina State University, Raleigh, North Carolina.

Nanodots of magnetic metals attracted considerable attention for scientific research as well as for magnetic device applications. The properties of these materials can be tailored by the size and the three-dimensional distribution of nanodots. In this work, we report on the growth and characterization of multilayered structures of cobalt nanodots grown in amorphous alumina matrices on silicon (001) substrates and amorphous silica substrates using pulsed laser deposition (PLD). Several films were deposited in a high vacuum chamber using a wavelength=248 nm KrF laser at various temperatures between room temperature to 600 degrees C. Film microstructure was examined using X-ray diffraction (XRD) and transmission electron microscopy (TEM). The morphology and the size distribution of nanodots was determined using atomic force microscopy (AFM). The size of the nanodots in these structures was ~10-20 nm. The optical properties of these films were examined using UV-visible spectrometry. The variation of magnetic properties of the nanodots was studied as a function of the growth parameters. The field- and temperature-dependent magnetization of the multilayered nanodot films were examined using a superconducting quantum interference device (SQUID) and a vibrating sample magnetometer (VSM). Isothermal field dependent magnetization measured in applied field strengths in the range  $\pm 20$  kOe showed high saturation moments, on the order of 10-4 emu. The saturating field was found to vary between 100-2000 Oe, depending on the growth parameters. The coercive fields were of the order of 100 Oe. These novel materials are expected to find several applications in magnetic recording and other related fields.

#### 4:45 PM I6.10



**The Early Stages of Manganese Nanostructure Growth on the Si(100)(2x1) Surface.** Hui Liu and Petra Reinke; Department of Materials Science and Engineering, University of Virginia, Charlottesville, Virginia.

The development of spintronics is a revolutionary approach to achieve faster, more efficient, and novel device structures. One of the great challenges is the use of group IV semiconductors in spintronics devices, which would enable a seamless combination of spintronics and charge-based electronics. However, the requisite doping of bulk Si with Mn has so far remained problematic. The selection of a surface-driven route promises to circumvent some of the limitations inherent to bulk doping, and is at the same time crucial for the development of complex heterostructures. We present here an experimental study in which we observe the growth of Mn on the Si(100)(2x1) with a focus on the sub-monolayer regime. Mn is deposited on a reconstructed Si(100)(2x1) surface and the evolution of the surface structure is observed with scanning tunneling microscopy. The substrate was for the majority of experiments held at room temperature to avoid the formation of silicide crystallites, which dominates at elevated temperatures. We observe the formation of monoatomic Mn-wires at coverages below about 0.3 ML, while at higher coverage isolated adatoms and ultrasmall clusters appear and compete with the wire growth. The Mn-wires are always oriented perpendicular to the Si-dimer rows and consequently switch orientation at each step edge. The mean length of the Mn-wires increases with coverage, albeit the maximum wire length appears to be limited to about 20 times the Si-dimer line distance with a nearly random spatial distribution. The local Si-reconstruction adopts a p(2x2) structure in the vicinity of the Mn-wires, and remains in the (2x1) phase around the clusters. The STM images indicate that the Mn-atoms within the wires are positioned in between the Si-dimers, while isolated Mn-atoms prefer to bond on top of a Si-dimer. Several possible interpretations of the experimental data with respect to the Mn-wire and adatom bonding position, and the consequence for electronic and direct or indirect exchange coupling of the magnetic moments will be discussed. The co-existence of wire and clusters is tentatively assigned to a competition between different adatom bonding sites, and the wire growth itself is promoted by an anisotropic attachment favouring bonding to the wire ends. If the deposition is performed at an elevated substrate temperature (above 500 degree C) the growth of needle-like silicide crystallites with a fixed orientation with respect to the Si-lattice occurs. The number of surface defects increases dramatically, and the step edge direction is modified due to migration of the edge atoms into the silicide material. The silicide formation is clearly driven by (and limited) by the Si-adatom supply and thus kinetically controlled. This study illustrates that Mn nanostructures, in the form of monoatomic wires, grow on a Si (100) surface and strongly indicates the feasibility to grow single-layer Mn structures and delta-doped Mn-layers embedded in a Si-matrix.

SESSION 17: Magnetic Nanoparticles and Novel Nanostructures  
Chairs: Valerie Browning and Dave Sellmyer  
Wednesday Morning, November 28, 2007  
Commowwealth (Sheraton)

#### 8:00 AM 17.1

**Synthesis and Characterization of Novel Magnetic Nanostructures.** Tae-Jin Park<sup>1</sup>, Fen Zhang<sup>1</sup> and Stanislaus Wong<sup>1,2</sup>; <sup>1</sup>SUNY Stony Brook, Stony Brook, New York; <sup>2</sup>Brookhaven National Laboratory, Upton, New York.

Our group has recently synthesized a number of magnetic nanostructures through various techniques. In one manifestation of our efforts, monodisperse nanocrystalline rhombohedral composites of Fe and magnetite magnetic materials have been obtained employing a reduction reaction, in a flowing gas mixture of hydrogen and nitrogen, of single-crystalline, submicron-sized hematite rhombohedral precursors. In turn, hematite rhombohedra of reproducible shape were successfully prepared using a facile, large-scale molten-salt reaction. Moreover, their predictive formation has been investigated through a systematic variation of experimental parameters. Extensive structural characterization of as-prepared samples has been performed using scanning electron microscopy (SEM), transmission electron microscopy (TEM), high-resolution TEM (HRTEM), energy-dispersive X-ray spectroscopy (EDS), selected area electron diffraction (SAED), X-ray diffraction (XRD) and superconducting quantum interference device (SQUID) magnetic measurements. In a second manifestation of our work, the generalized green synthesis of single-crystalline potassium manganese fluoride and ammonium manganese fluoride nanorods as well as of their rare-earth ion doped analogues, possessing reproducible shape and controllable size, has been achieved using a modified template-directed approach under ambient room-temperature conditions, with simple inorganic salts as functional precursors. Extensive characterization of the resulting nanorods has been performed using electron microscopy, optical spectroscopy, as well as magnetic techniques. We have studied the antiferromagnetism of as-prepared ternary metal fluoride nanorods as well as the luminescence of their as-doped counterparts. Our collective data suggest the possibility of the incorporation of these high-quality, purified materials into functional nanoscale devices with various potential applications that exploit the interesting optomagnetic properties of these systems.

#### 8:15 AM 17.2

**Multi-component Nanostructures Combining Magnetic, Plasmonic, and Semiconducting Functionalities.** Hao Zeng<sup>1</sup>, Shuli He<sup>1</sup>, Hongwang Zhang<sup>2</sup> and Mark Swihart<sup>2</sup>; <sup>1</sup>Physics, University at Buffalo, SUNY, Buffalo, New York; <sup>2</sup>Chemical and Biological Engineering, University at Buffalo, SUNY, Buffalo, New York.

We present a general synthetic strategy for multi-component hybrid nanostructures with paired combinations of plasmonic, semiconductor and magnetic functionalities. A rich combination of materials involving FePt or Fe<sub>3</sub>O<sub>4</sub> as the magnetic component, Au or Ag as the metallic component and II-VI (e.g. CdS) or IV-VI (e.g. PbS) as the semiconducting components have been fabricated. These nanostructures are realized by sequential growth of a second and/or third component on pre-synthesized nanoparticle seeds. By rationally tuning the synthetic parameters, such as heating rate, solvents, and ratio of precursors to seeds, a large variety of morphologies have been synthesized including core/shell, peanut-like and dumbbell-like structures. Different components grow on top of each other quasi-epitaxially with common interfaces, which facilitates the charge, spin and energy transfer between them. The optical properties and magnetic properties are appreciably affected by the presence of the conjugate material in the hybrids, as compared to their single component counterparts. These multi-component hybrid nanostructures may have a broad range of potential applications in heterogeneous catalysis, multifunctional bio-labels, and as building blocks for spintronic devices. The growth techniques can also be modified for the synthesis of semiconductor and magnetic semiconductor quantum rods.

#### 8:45 AM 17.3

**Synthesis of Novel Magnetic Nanoparticles: From Core-Shell Fe/Fe<sub>3</sub>O<sub>4</sub> to Hollow Fe<sub>3</sub>O<sub>4</sub>.** Sheng Peng<sup>1</sup>, Chao Wang<sup>2</sup>, Jin Xie<sup>1</sup> and Shouheng Sun<sup>1,2</sup>; <sup>1</sup>Department of Chemistry, Brown University, Providence, Rhode Island; <sup>2</sup>Division of Engineering, Brown University, Providence, Rhode Island.



Monodispersed iron-based nanoparticles (NPs) in the size range below 20 nm are important superparamagnetic materials with high magnetic moment. Their stable dispersions in various liquid media are predicted to have important applications in bio-separation, bio-sensing, drug delivery and MRI contrast enhancement. We have developed a simple one-pot synthesis to produce monodispersed Fe NPs with high moment density.[1] As-synthesized Fe NPs are quickly oxidized under ambient conditions during sample treatment, and a thin layer of amorphous Fe<sub>3</sub>O<sub>4</sub> is formed on the surface resulting in amorphous core-shell Fe/Fe<sub>3</sub>O<sub>4</sub> NPs. To stabilize the metallic cores, controlled oxidation is carried out to crystallize the amorphous shell. After oxidation, dramatic increase in chemical and dispersion stability of the NPs is achieved. By modifying controlled oxidation conditions, monodispersed 16nm hollow Fe<sub>3</sub>O<sub>4</sub> nanoparticles can be readily made by using core-shell Fe/Fe<sub>3</sub>O<sub>4</sub> NPs as seeds.[2] The morphology evolution has been studied and the Kirkendall diffusion is found to assist the formation of the hollow structure. The resulted hollow NPs show superparamagnetic behaviors. Various core-void-shell Fe/Fe<sub>3</sub>O<sub>4</sub> NPs with different crystalline nature have also been produced by controlling the reaction. Surface ligand exchange can be readily applied to both the core-shell Fe/Fe<sub>3</sub>O<sub>4</sub> and hollow Fe<sub>3</sub>O<sub>4</sub> NPs to transfer the NPs from hydrophobic to hydrophilic, forming stable aqueous dispersion of the NPs in PBS. The functionalized NPs are suitable for biomolecule attachment and biomedical applications. [1]: Peng, S.; Wang, C.; Xie, J.; Sun, S. J. Am. Chem. Soc. 2006, 128, 10676-10677. [2]: Peng, S.; Sun, S. Angew. Chem. Int. Ed. 2007, 46, 4155-4158.

#### 9:00 AM \*17.4

**Opportunities in Nanomagnetism.** Samuel D. Bader, Materials Science Division and Center for Nanoscale Materials, Argonne National Laboratory, Argonne, Illinois.

This talk discusses challenges and scientific problems in the emerging area of nanomagnetism. [1] Included are experiments that explore spin-related transport and dynamical behavior in metallic systems, as well as efforts to understand the observed phenomena. As a subfield of nanoscience, nanomagnetism shares many of the same basic organizing principles, such as geometric confinement, physical proximity, and chemical self-organization. These principles are illustrated by means of examples, including one that shows the synergetic relationship to other fields of science, the manipulation of viruses to fabricate magnetic nanoparticles. \* Work supported by U. S. Department of Energy, Office of Basic Energy Sciences - Materials Science, under Contract No. W-31-109-Eng-38. [1] S. D. Bader, Rev. Mod. Phys. 78, 1 (2006).

#### 9:30 AM 17.5

**Photo-switchable Magnetic Materials at Room Temperature.** Yasuaki Einaga and Masayuki Suda; Chemistry, Keio University, Yokohama, Japan.

We have reported several examples of novel photo-switching magnetic systems containing photochromic compounds and magnetic materials. That is, the magnetic properties can be controlled by photoisomerization of the photochromic compounds. In order to realize reversible photo-switching of magnetization at room temperature, we have focused on a surface modification of nano-scale magnetic particles and a combination of photochromic azobenzene-containing amphiphilic compounds and the magnetic nanoparticles as magnetic materials that can function at room temperature. The magnetic iron oxide nanoparticles, with an estimated average size of 5 nm, were encapsulated with an azobenzene-containing amphiphilic compound. Photoisomerization of the azo moiety (trans/cis) affected the electrostatic field around the magnetic nanoparticles. As a result, we were able to reversibly control the magnetic properties of this composite material by photo-illumination in the solid state at room temperature. However, the examples reported so far did not show ferromagnetic behavior at room temperature. From the viewpoint of their practical application to the magnetic recording systems, the ability to fix their magnetic moments such that they still exhibit room temperature ferromagnetism is an absolute requirement. Here we have designed reversible photo-switchable ferromagnetic FePt nanoparticles whose surfaces were coated with azobenzene derivatized ligands. These composite nanoparticles showed ferromagnetic behavior even at room temperature. On the surfaces of core particles, reversible photoisomerization of azobenzene in the solid state was realized by using spacer ligands which provide sufficient free volume between azo-ligands. These photoisomerization brought changes in the electrostatic field around the core-FePt nanoparticles. As a result, we have succeeded in controlling the magnetic properties of these ferromagnetic composite nanoparticles by alternating photoillumination in the solid state at room temperature. References Einaga, Y., et al. J. Am. Chem. Soc. 1999, 121, 3745., J. Am. Chem. Soc. 2003, 125, 12396., Angew. Chem. Int. Ed. 2004, 43, 6135., J. Am. Chem. Soc. 2004, 126, 13177., J. Am. Chem. Soc. 2005, 127, 16065., J. Am. Chem. Soc. 2006, 128, 10978., J. Am. Chem. Soc., 2007, 129, 5538.

#### 9:45 AM 17.6

**Photoinduced Magnetism of Rubidium Cobalt Hexacyanoferrate Nanoparticles.** Daniel M Pajerowski<sup>1</sup>, Franz A Frye<sup>2</sup>, Daniel R Talham<sup>2</sup> and Mark W Meisel<sup>1</sup>; <sup>1</sup>Department of Physics, University of Florida, Gainesville, Florida; <sup>2</sup>Department of Chemistry, University of Florida, Gainesville, Florida.

The possibility of a device using a photoinducible magnetic material functionalized as nanoparticles is an interesting prospect that has sparked recent and ongoing work in the field. We have synthesized nanoparticles of the photomagnetic Rb<sub>3</sub>Co<sub>k</sub>[Fe(CN)<sub>6</sub>] · nH<sub>2</sub>O Prussian blue analog. Nanoparticle size, as measured by Transmission Electron Microscopy (TEM) and Dynamic Light Scattering (DLS), is controlled by the introduction of varying concentrations of protective encapsulants or their precursors during the synthesis procedure; different encapsulating materials and synthesis procedures have been investigated. Temperature, magnetic field, and photo-irradiation dependence of the magnetization indicates evolution of ordering temperature, coercivity, and photoinducibility with particle size<sup>a</sup>. In the small particle limit, i.e. particles less than approximately 10 nm, ordering is suppressed. In some of the larger particles, i.e. a batch with a characteristic diameter of approximately 13 nm, we observe ordering temperatures (T<sub>c</sub> ~ 17 K in 100 G) and coercive fields (H<sub>c</sub> ~ 250 G at 2 K). AC-susceptibility data is consistent with glassy ordering in the samples. [a] D. M. Pajerowski, M. W. Meisel, F. A. Frye, D. R. Talham, to be published in New Journal of Physics; preprint arXiv:cond-mat/0701027v2. Supported by the NSF via DMR-0305371 (MWM), DMR-0543362 (DRT), and DMR-0701400.

#### 10:30 AM 17.7

**Controlled Synthesis of Highly Water-Soluble Magnetite Nanostructures.** Jianping Ge, Yongxing Hu and Yadong Yin; Department of Chemistry, University of California, Riverside, Riverside, California.

A high-temperature solution-phase hydrolysis approach has been developed for the synthesis of colloidal magnetite nanostructures with well-



controlled size and size distribution, high crystallinity, and high water solubility. Monodisperse nanodots with size from ~3 nm to 20 nm and clusters of nanodots with size from ~20 nm to 200 nm can be controllably synthesized using this method by simply varying the reaction parameters. Each nanocrystal cluster is composed of many single magnetite crystallites of ~10 nm, thus retaining the superparamagnetic properties at room temperature. The use of polyelectrolyte as surfactant in synthesis provides the magnetite nanostructures high water solubility and high surface charges. The CNCs show strong responses to external magnetic field due to their much higher magnetization per particle than that of individual magnetite nanodots. The combination of superparamagnetic property, monodispersity, and highly charged surfaces makes the nanostructures ideal candidates for various important applications. For example, the colloidal nanocrystal clusters can self-assemble into three-dimensional colloidal photonic crystals with magnetically tunable bandgaps covering the whole visible region. Their optical response to the external magnetic field is rapid and fully reversible.

#### 10:45 AM \*I7.8

**Effect of Metal Additives and Composition Distribution on Chemical Ordering of Isolated FePt Nanoparticles.** James W Harrell<sup>1,4</sup>, Greg Thompson<sup>2,4</sup>, David E Nikles<sup>3,4</sup>, Shishou Kang<sup>4</sup>, Shifan Shi<sup>1,4</sup> and Chandan Srivistava<sup>2,4</sup>; <sup>1</sup>Dept. of Physics & Astronomy, The University of Alabama, Tuscaloosa, Alabama; <sup>2</sup>Dept. of Metallurgical & Materials Engineering, The University of Alabama, Tuscaloosa, Alabama; <sup>3</sup>Dept. of Chemistry, The University of Alabama, Tuscaloosa, Alabama; <sup>4</sup>MINT Center, The University of Alabama, Tuscaloosa, Alabama.

Previous studies of the effect of metal additives on chemical ordering of chemically synthesized FePt nanoparticles have been obscured by sintered grain growth during thermal annealing [1]. Additive Au and Ag, for example, significantly lower the ordering temperature, but also lower the temperature for sintered grain growth. Hence, the intrinsic effect of additives on ordering in FePt nanoparticles has not been determined. Recently Liu and co-workers have shown that annealing in a salt matrix is a very effective method of obtaining chemical ordering with essentially no grain growth [2]. We have employed this method to study the intrinsic effect of additives such as Ag, Cu, and Mn on ordering. Preliminary results show that additive Ag reduces the ordering temperature of isolated nanoparticles, although the reduction is significantly less than when sintered grain growth occurs. The effect of additive Cu and Mn on ordering is weak. Chemical ordering of nanoparticle powders depends not only on average composition but on particle-to-particle composition distributions. When sintered grain growth is allowed to occur during annealing, the effect of these distributions is reduced and greater ordering occurs than when grain growth is inhibited by salt annealing. High resolution TEM and nano-EDX shows that individual salt-annealed FePt particles that have nearly equiatomic composition have a single fct phase while those particles whose composition is far away from equiatomic stoichiometry may have both fcc and fct phases. We have used nano-EDX to study the effect of the type of synthesis on the particle-to-particle composition distribution of FePt nanoparticles. Significant differences have been found between two common methods of synthesizing FePt nanoparticles. [1] J.W. Harrell et al., Scripta Mater. 53, 411 (2005). [2] K. Elkins et al., J. Phys. D - Appl. Phys. 38, 2306 (2005).

#### 11:15 AM I7.9

**Nitrogen-Assisted Diffusion Enhancement in FePt Nanoparticles.** Mehmet Acet, Olga Dmitrieva, Guenter Dumpich, Jochen Kaestner and Marina Spasova; Experimental Physics, Duisburg-Essen University, Duisburg, Germany.

Fe-Pt nanoparticles prepared by vapor condensation in a high pressure sputtering unit are guided through a furnace where they are in-flight sintered at 1000 °C. They are subsequently collected on a substrate. The particles have a 6 nm diameter with a multiply twinned icosahedral structure. The equilibrium L10 structure does not form at these sizes presumably because of the lack of dislocations and vacancies, which are required for the diffusion in the ordering process. With the aim of inducing imperfections, we introduce nitrogen into FePt interstitially by partially substituting the argon sputtering gas with nitrogen. Nitrogen later migrates out of the particle during in flight sintering at 1000 °C while enhancing diffusion and thereby facilitating the stabilization of the L10 phase. Particles prepared under such conditions are observed to be a mixture of fcc crystalline and L10. We show results on the study of the influence of nitrogenation on the structural and compositional properties of FePt using high resolution electron microscopy, electron energy loss spectroscopy, and X-ray absorption studies.

#### 11:30 AM I7.10

**Ordering of Nanocrystalline Fe-Pt Alloys Studied by *in-situ* Neutron Powder Diffraction.** Julia Lyubina<sup>1</sup>, Olivier Isnard<sup>2</sup>, Oliver Gutfleisch<sup>1</sup> and Ludwig Schultz<sup>1</sup>; <sup>1</sup>IFW Dresden, Institute for Metallic Materials, P.O. Box 270016, D-01171, Dresden, Germany; <sup>2</sup>Laboratoire de Cristallographie, CNRS and Institut Laue-Langevin, 38042, Grenoble, France.

Phase transformations and ordering in Fe-Pt alloys prepared by mechanical ball milling [1] have been studied by a combination of *in-situ* neutron powder diffraction and thermal analysis. The influence of stoichiometry and initial microstructure (A1 or multilayer-type) on the transformation to the L10 phase as well as the dependence of the L10 phase magnetic moments on the compositional order have been investigated [2,3]. Independent of milling time and stoichiometry the onset of ordering is at around 300 °C. Heating of the Fe<sub>100-x</sub>Pt<sub>x</sub> (x = 40; 45; 50; 55) alloys with the initial A1 structure induces the A1 → L10 transformation, whereas in the Fe<sub>50</sub>Pt<sub>50</sub> powders with the multilayer-type microstructure, the L10 formation proceeds via a metastable state according to the sequence: Fe/Pt precursor → L10 + L12 → L10. For the equiatomic composition the A1 → L10 transformation rate is fastest and a deviation from the equiatomic concentration significantly decelerates the ordering. For alloys with a multilayer-type microstructure an enhanced kinetics of ordering is observed, characterised by an activation energy of 1.03 ± 0.08 eV. [1] J. Lyubina, O. Gutfleisch, R. Skomski, K.-H. Müller, L. Schultz, Scr. Mater. 53 (2005) 469. [2] J. Lyubina, O. Isnard, O. Gutfleisch, K.-H. Müller, L. Schultz, J. Appl. Phys. 100 (2006) 094308. [3] J. Lyubina, O. Isnard, I. Opahle, M. Richter, O. Gutfleisch, K.-H. Müller, L. Schultz, Appl. Phys. Lett. 89 (2006) 032506.

#### 11:45 AM I7.11

**Rapid Thermal Annealing of Monodisperse FePt Nanoparticles.** Kazuaki Yano, Vikas Nandwana, Narayan Poudyal, Chuan-bing Rong and J. Ping Liu; Department of Physics, University of Texas at Arlington, Arlington, Texas.

In this paper, we report a systematic study on rapid thermal processing (RTP) of monodisperse FePt nanoparticles [1, 2]. FePt particles with average size of 8 nm were synthesized by chemical synthesis, and annealed by using RTP and conventional furnace annealing (FA). It was observed that the FePt nanoparticles can be transformed from disordered A1 phase to ordered L10 phase at 650 C in 10s by using RTP, which is much shorter than the time needed for FA. The transmission electronic microscopy and X-ray diffraction studies have revealed that the average particle size of RTP annealed FePt is smaller than that of the furnace annealed samples and no obvious particle sintering and agglomeration was observed in the



RTP treated samples. In addition, correlation between the coercivity of RTP treated samples to the square root of treatment time was observed, which implies that the phase transition may be related to atomic diffusion of Fe atoms from Fe-rich shells into the Pt-rich cores. 1.H. Zeng, S. Sun, R.L. Sandstrom and C.B. Murray, *J. Magn. Magn. Mater.*, 266, 227 (2003). 2.Z.Q. Jin and J.P. Liu, *J. Phys. D: Appl. Phys.* 39, R227 (2006)

SESSION I8: Spintronic Materials and Devices  
Chair: Yvan Bruynseraede  
Wednesday Afternoon, November 28, 2007  
Commowwealth (Sheraton)

#### 1:30 PM I8.1

**Room Temperature Ferromagnetism of FeCo-codoped ZnO Nanorods Prepared by Chemical Vapor Deposition.** Jiajun Chen<sup>1</sup>, Yanfa Yan<sup>2</sup>, Jingjing Liu<sup>1</sup>, Amber West<sup>1</sup>, Minghui Yu<sup>1</sup> and Weilie Zhou<sup>1</sup>; <sup>1</sup>Advanced Materials Research Institute, New Orleans, Louisiana, <sup>2</sup>National Renewable Energy Laboratory, Golden, Colorado.

Diluted Magnetic Semiconductors (DMS) are among the most promising candidates for spintronics, since they provide much better lattice and conductivity match compared with ferromagnetic metals as used for spin-polarized carrier sources. Transitional-metal-doped ZnO nanowires or nanorods with room temperature ferromagnetism have been fabricated via various methods. Doping ZnO nanostructures by two or more types of dopants is a feasible strategy to achieve room-temperature ferromagnetic ordering or optimize the magnetic properties. FeCo-codoped ZnO nanorods with room temperature ferromagnetic ordering have been synthesized by chemical vapor deposition. Detailed nanostructures were investigated by field emission scanning electron microscopy (FESEM), transmission electron microscopy (TEM) and nanoprobe X-ray energy dispersive spectroscopy (EDS). The ZnO nanorods were grown along c-axis of wurtzite nanocrystals. EDS spectra indicated that Co and Fe were successfully doped into the ZnO lattice with concentrations about 0.6 ~ 1.0 at%. Magnetic measurement shows that a ferromagnetic ordering with Curie temperature higher than 300K presents in the ZnO nanorods, which is useful for spintronic nanodevice fabrication.

#### 1:45 PM I8.2

**Room Temperature Ferromagnetism in Nonmagnetic Cu Doped GaN Nanowires.** Han-Kyu Seong<sup>1</sup>, Jae-Young Kim<sup>2</sup>, Ju-Jin Kim<sup>3</sup>, Seung-Chul Lee<sup>4</sup>, So-Ra Kim<sup>3</sup>, Ungkil Kim<sup>1</sup>, Tae-Eon Park<sup>1</sup> and Heon-Jin Choi<sup>1</sup>; <sup>1</sup>School of Advanced Materials Science and Engineering, Yonsei University, Seoul, South Korea; <sup>2</sup>Pohang Accelerator Laboratory, Pohang University of Science and Technology, Pohang, South Korea; <sup>3</sup>Department of Physics, Chon-buk National University, Chon-ju, South Korea; <sup>4</sup>Future Technology Research Division, Korea Institute of Science and Technology, Seoul, South Korea.

The concept of simultaneously manipulating both charge and spin in a single semiconductor medium leads to the exciting area of spintronics. Semiconductors doped with transition metal, so called diluted magnetic semiconductors (DMSs), are the most promising candidates for such applications. According to the principle of mean field theory, transition metals such as Sc, Ti, V, Cr, Mn, Fe, Co, and Ni that have partially filled d states can be doped for transforming spin-frustrated semiconductors to ferromagnets. It has also been predicted that room temperature ferromagnetism, which would be advantageous in many applications, could be achieved in magnetic doped wide band-gap semiconductors. Indeed, room temperature ferromagnetism has been reported from Cr, Mn, Fe and Co doped GaN, ZnO, and TiO<sub>2</sub>. However, these transition metals with local magnetic moments may not be the best choice for the doping elements. Magnetic secondary clusters have been shown to be ferromagnetic, arguing the motivation that the ferromagnetism of the DMSs arises from magnetic secondary clusters. Namely, the origin of ferromagnetism in these DMSs is still controversial, due to the possibility of magnetic secondary phases and uncertainty of magnetic interactions. Herein, we report magnetism in nonmagnetic Cu doped single crystalline GaN nanowires. The Ga<sub>1-x</sub>Cu<sub>x</sub>N nanowires (x = 0.01, 0.024) were grown by transporting gallium (Ga) and copper chloride (CuCl) onto a nickel coated sapphire substrate under flow of ammonia (NH<sub>3</sub>) at 800 °C. The diameter and length of these nanowires were from 10 nm to 100 nm and tens of micrometers, respectively, and they had a triangular structure. The Ga<sub>1-x</sub>Cu<sub>x</sub>N nanowires (x = 0.01, 0.024) with Curie point above room temperature indicate that Cu atoms substitute the Ga sites and they largely take part in the wurtzite network of host GaN. X-ray absorption and x-ray magnetic circular dichroism spectra showed that doped Cu have local magnetic moment and the electronic configuration of doped Cu is mainly 3d<sup>9</sup> with a small portion of 3d<sup>8</sup> component. The room temperature ferromagnetic Ga<sub>1-x</sub>Cu<sub>x</sub>N system is expected to open a pathway toward a new class of nonmagnetic doped diluted magnetic semiconductors.

#### 2:00 PM \*I8.3

**Spin Torque Transfer Devices with New Nanostructures.** Jian-Ping Wang, Xiaofeng Yao, Hao Meng and Yuanpeng Li; Department of Electrical and Computer Engineering & The Center for Micromagnetics and Information Technologies (MINT), University of Minnesota, Minneapolis, Minnesota.

Spin torque transfer effects in nanomagnets attract lots of attention recently. The discovery of spin torque transfer not only provides a base for "current-driven" spintronic devices and but also a new platform to study the spin flipping and precession. The mechanism of the spin torque transfer has been studied in giant magnetoresistive (GMR) or magnetic tunnel junction (MTJ) nanostructures, fixed layer/space layer/free layer, in which the magnetization switching in the free layer has been proved and treated as the single-domain uniform switching. However, the critical switching current density in such typical sandwich structure is around 10e7 A/cm<sup>2</sup>, which results in poor compatibilities with other integrated electronics components, which will be a challenge for any practical application. Furthermore, if there were no further change of the existing spin transfer structures that are based on the single-domain switching, from the engineering viewpoint, we would soon face the famous dilemma on the thermal stability and switching capability for high density spin transfer devices, which need a tremendous size reduction, such as MRAM and magnetic logic. Spin torque transfer structures with new spin switching configurations are proposed, fabricated and investigated to address this challenge in this talk [1-3]. The non-uniform current-induced magnetization switching is implemented based on both GMR and MTJ nano devices. The proposed new spin transfer structure has a hybrid free layer that consists of a layer with conductive channels (magnetic) and non-conductive matrix (non-magnetic) and traditional free layer(s). Two mechanisms, a higher local current density by nano-current-channels and a non-uniform magnetization switching (reversal domain nucleation and growth) by a magnetic nanocomposite structure, contribute in reducing the switching current density. The critical switching current density for the new spin transfer structure is reduced to one third of the typical value for the normal structure. It can be expected to have one order of magnitude or more reduction for the critical current density if the optimization of materials and fabrication processes could be done further. Meanwhile, the thermal stability of this new spin transfer structure is not degraded, which may solve the long-standing scaling problem for magnetic random access memory (MRAM). This spin transfer structure, with the proposed and demonstrated new spin switching configurations, not



only provides a solid approach for the practical application of spin transfer devices but also forms a unique platform for researchers to explore the non-uniform current-induced switching process. 1) H. Meng and J. P. Wang, IEEE Trans. Magn., 41, 2612 (2005); Appl. Phys. Lett. 89, 152509 (2006); 2) H. Meng and J. P. Wang, Appl. Phys. Lett., 88, 172506 (2006); 3) H. Meng, J. Wang, and J. P. Wang, Appl. Phys. Lett. 88, 082504 (2006)

#### 2:30 PM 18.4

**Correlation between Photoluminescence and Magnetic Properties of GaMnN.** Neeraj Nepal<sup>1</sup>, Amr M. Mahros<sup>1</sup>, S. M. Bedair<sup>1</sup>, N. A. El-Masry<sup>2</sup> and J. M. Zavada<sup>3</sup>, <sup>1</sup>Electrical and Computer Engineering, North Carolina State University, Raleigh, North Carolina; <sup>2</sup>Materials Science and Engineering, North Carolina State University, Raleigh, North Carolina; <sup>3</sup>U.S. Army Research Office, Durham, North Carolina.

Dilute magnetic semiconductor (DMS) materials offer outstanding potential for integration of photonic, electronic, and magnetic devices on a single substrate. GaMnAs material system with a cryogenic Curie temperature has been widely studied as a DMS. However, GaMnN attracted great interest because of its high Curie temperature allows room temperature spintronic devices. In this work metal-organic chemical vapor deposition grown GaMnN samples were studied by photoluminescence (PL) spectroscopy and hysteresis measurements. Depending on growth conditions of GaMnN, hysteresis measurements along the easy axis show transformation from magnetic to non-magnetic behavior. The PL spectra of both magnetic and non-magnetic GaMnN exhibited GaN bandedge transition at about 3.4 eV and deep level impurity peak at about 1.3 eV. The PL emission intensity of 1.3 eV emission peak is considerably stronger for magnetic GaMnN samples and is assigned to the transitions of an electron bound to Mn<sup>2+</sup> level and a hole bound to Mn<sup>3+</sup> level. At optimum growth temperature and Mn concentration, the Fermi level is in the Mn<sup>2+</sup> band, which increases the PL intensity of 1.3 eV emission peak. Deviation from the optimum growth conditions lowers the Fermi level leaving the Mn<sup>2+</sup> band empty thereby decreasing the PL emission intensity. The PL intensity of about 1.3 eV emission peak appears to be directly correlated with ferromagnetic behavior in GaMnN films. \* NRC Post-doctoral Fellow

#### 2:45 PM 18.5

**Magnetic Properties of Ni Doped MgO System.** N. Sudhakar, Deepayan Chakraborti, S. Ramachandran and J. Narayan; Materials Science & Engineering Department, North Carolina State University, Raleigh, North Carolina.

Diluted magnetic semiconductor (DMS) materials such as ZnO, TiO<sub>2</sub> and MgO have been envisaged as potential candidates for use in spintronics applications owing to the fact that they exhibit ferromagnetic properties at room temperature. Several mechanisms are being considered to explain the role of free carriers and intrinsic defects like oxygen vacancies and interstitials. Therefore, from a fundamental perspective, the role of defects and carriers in stabilizing the ferromagnetic properties in oxide based DMS systems needs to be addressed properly. MgO has been chosen as a host system for the present study as it is electrically insulating and also can be synthesized as high quality crystals devoid of defects like vacancies and interstitials. In the present work Ni doped MgO crystals have been synthesized using an arc fusion technique in two forms. (i) in which the Ni ions occupy substitutional sites and (ii) in which Ni is present in the form of metal precipitates. The magnetic properties of the Ni precipitates can be used to compare the results when a DMS material is not fully devoid of nanoclusters or secondary phases. Detailed structural characterization was done using transmission electron microscopy. The size distribution of the precipitates ranged from 10 to 100 nm with an average size of 50 nm. Magnetic properties of both the systems were carried out in the temperature range of 10-350 K and in magnetic fields up to 2 T. While the crystals with substitutional Ni displayed perfect paramagnetic properties in the entire temperature range<sup>1</sup>, the crystals with Ni precipitates displayed interesting ferromagnetic properties up to temperatures as high as 350 K. The coercive field (H<sub>c</sub>) and saturating field (H<sub>s</sub>) have decreased as the temperature is raised from 10 to 350K. The field cooled (FC) and the zero field cooled (ZFC) temperature dependent magnetization in the range 10-350 K measured at three different fields (500, 2000 and 10000 Oe) show a bifurcation and the bifurcation temperature has decreased with the increase in the applied field. The blocking temperatures observed from the ZFC measurements also show a similar variation. This is one of the characteristic features of the superparamagnetic behavior that arises due to the presence of Ni nanoclusters. Thus from a detailed magnetic characterization of both types of crystals we can infer that the crystals having substitutional Ni show perfect paramagnetism because of the absence of defects like vacancies to couple the moments of the unpaired d electrons in Ni. But in case of the crystals with Ni precipitates the ferromagnetic properties arise due to the Ni clusters and not as an intrinsic property of the MgO DMS itself. Therefore it is concluded that substitutionally doped oxide based DMS materials exhibit paramagnetism in the absence of defects and ferromagnetism only in the presence of Ni clusters or precipitates.

<sup>1</sup>S. Ramachandran et al., Appl. Phys. Lett. 90, 132511 (2007)

SESSION 19: Magnetic Oxides and Multiferroics  
Chair: Jianping Wang  
Wednesday Afternoon, November 28, 2007  
Commowwealth (Sheraton)

#### 3:30 PM \*19.1

**Multifunctional Double Perovskite Thin Films and Heterostructures.** Arunava Gupta, MINT Center, University of Alabama, Tuscaloosa, Alabama.

A double perovskite is a perovskite with the general formula of A<sub>2</sub>BB'O<sub>6</sub>, where A is a divalent alkaline earth cation and B and B' are transition-metal ions. Depending on the relative size and oxidation state, the B and B' ions can be crystallographically completely ordered, making up a rocksalt-type lattice. La<sub>2</sub>NiMnO<sub>6</sub> is an ordered double perovskite that is a ferromagnetic semiconductor with a T<sub>CM</sub> of 280 K. Recent studies of La<sub>2</sub>NiMnO<sub>6</sub> in the bulk have revealed large magnetic-field induced changes in the resistivity and dielectric properties at temperatures as high as 280 K [1]. This is a much higher temperature than previously observed for such a coupling between the magnetic, electric, and dielectric properties in a ferromagnetic semiconductor. Substitution at the A site can also lead to multiferroic behavior in the double perovskites. Azuma *et al.* have recently succeeded in synthesizing the 'designed' compound Bi<sub>2</sub>NiMnO<sub>6</sub> in the bulk under high pressure and established its multiferroic properties, with ferroelectric and ferromagnetic transition temperatures of 485 K and 140 K, respectively [2]. Since the above reports of multiferroic and magnetoelectric behavior in the bulk, we have been synthesized epitaxial thin films of La<sub>2</sub>NiMnO<sub>6</sub> [3] and Bi<sub>2</sub>NiMnO<sub>6</sub>. A related ferromagnetic semiconductor, La<sub>2</sub>CoMnO<sub>6</sub>, has also been grown epitaxially [4]. High quality epitaxial films of these double perovskites are grown on lattice-matched substrates such as SrTiO<sub>3</sub>, NdGaO<sub>3</sub> and LaAlO<sub>3</sub> using the technique of pulsed laser deposition (PLD). Preliminary measurements have shown the expected magnetic and



electric behavior in these films. Efforts are underway to produce heterostructures by artificially layering these multifunctional materials with other related oxides in order to tailor their properties. [1] N. S. Rogardo, J. Li, A. W. Sleight, and M. A. Subramanian, *Adv. Mater.* **17**, 2225 (2005). [2] M. Azuma, K. Tanaka, T. Saito, S. Ishiwata, Y. Shimakawa, and M. Takano, *J. Am. Chem. Soc.* **127**, 8889 (2005). [3] H. Guo, J. Burgess, S. Street, A. Gupta, T. G. Calvarese, and M. A. Subramanian, *Appl. Phys. Lett.* **89**, 022509 (2006). [4] H. Z. Guo, A. Gupta, T. G. Calvarese, and M. A. Subramanian, *Appl. Phys. Lett.* **89**, 262503 (2006).

#### 4:00 PM 19.2

**Superconductivity and Ferromagnetism in Epitaxial Thin Film Heterostructures.** R. C. Budhani, Dept. of Physics, Indian Institute of Technology - Kanpur, Kanpur, India.

The antagonism between superconductivity and ferromagnetism has generated a considerable degree of interest in recent years. Thin film heterostructures of a variety of superconducting (SC) and ferromagnetic (FM) materials permit experimental verification of such diverse phenomena as p-phase shift, triplet pairing, field enhanced superconductivity, domain wall superconductivity, and enhanced flux pinning by magnetic inhomogeneities. We have been working on FM-SC-FM and SC-FM-SC trilayers of conventional materials such as NbN and CoPt, and the exotic systems comprising of YBa<sub>2</sub>Cu<sub>3</sub>O<sub>7</sub> (YBCO) and La<sub>1-x</sub>Sr<sub>x</sub>MnO<sub>3</sub> (LSMO) deposited on lattice matched substrates. Transport measurements on LSMO-YBCO-LSMO system show clear oscillations in critical current (*I<sub>c</sub>*) as the thickness of the LSMO layers is scanned from ~ 50 Å to ~ 1100 Å. In the light of existing theories of FM-SC heterostructures, this observation suggests a long range proximity effect in the manganite, modulated by its weak exchange energy (~2 meV). We have also addressed the nature of exchange coupling between two LSMO films separated by a thin c-axis oriented YBCO layer as a function of its thickness (*d<sub>s</sub>*). Magnetic hysteresis measurements show a clear antiferromagnetic coupling whose strength decays exponentially with *d<sub>s</sub>* and its monotonic growth on decreasing the temperature is truncated as the YBCO becomes superconducting. Currently, experiments are being carried out on LSMO-YBCO-LSMO trilayers where the YBCO layer is a-axis oriented. In this configuration, spin polarized quasiparticles are injected directly into CuO<sub>2</sub> superconducting planes. Further details of these measurements and the observation of field-induced superconductivity in CoPt-NbN heterostructures will be presented during the symposium. This research has been supported by grants from the Defence Research and Development Organization (DRDO), Department of Science and Technology (DST) and the Board for Research on Nuclear Sciences (BRNS).

#### 4:15 PM 19.3

**Transport and Magnetic Effects in Nanoscale Junctions Based on Perovskites.** Thomas Fix, Nadia Stelmashenko, Rantej Bali and Mark Blamire, Materials Science and Metallurgy, University of Cambridge, Cambridge, United Kingdom.

After the discovery of (i) reproducible switching effects for memory applications in Cr(0.2%) : SrZrO<sub>3</sub> [1], (ii) rectifying effects in La<sub>0.7</sub>Ca<sub>0.3</sub>MnO<sub>3</sub> / SrTiO<sub>3</sub> / La<sub>0.7</sub>Ce<sub>0.3</sub>MnO<sub>3</sub> trilayers [2], (iii) the role of dislocations and oxygen in switching behaviour of undoped single-crystal of SrTiO<sub>3</sub> [3] (iv) intrinsic spin filtering in La<sub>2/3</sub>Ca<sub>1/3</sub>MnO<sub>3</sub> / Nb(1%) : SrTiO<sub>3</sub> [4], it seems that oxides in general—and perovskites in particular—provide a huge potential for both fundamental and applied research. We focus on perovskite thin films such as Nb(2%) : SrTiO<sub>3</sub>, In(x%) : SrTiO<sub>3</sub>, SrRuO<sub>3</sub> and La<sub>0.67</sub>Sr<sub>0.33</sub>MnO<sub>3</sub>, deposited by pulsed laser deposition on NdGaO<sub>3</sub> (001). The structural, surface, magnetic and transport properties of the films are investigated by in-situ reflective high energy electron diffraction, atomic force microscopy, x ray diffraction, transmission electron microscopy, vibrating sample magnetometry, four point transport measurements. Hall effect is used to investigate the p or n properties, and resistivity measurements as a function of the temperature in order to investigate the semiconducting, metallic or insulating behaviour of the films, depending on the deposition conditions. The samples are patterned at different scales (macroscopic and nanometric) to investigate the effect of the patterning on the transport properties. The films are processed by ultraviolet lithography and focused ion beam, so that a perpendicular to plane current can be injected [5,6]. The total thickness of the layers is in the order of 400 nm and the lateral dimensions are around 300x300 nm<sup>2</sup>. We investigate the presence of reproducible switching behaviour, and of rectifying effect. [1] A. Beck, J.G. Bednorz, Ch. Gerber, C. Rossel, and D. Widmer, *Appl. Phys. Lett.* **77** 139 (2000) [2] C. Mitra, P. Raychaudhuri, G. Koebernik, K. Do rr, K.-H. Mueller, L. Schultz, R. Pinto, *Appl. Phys. Lett.*, **79** 2408 (2001) [3] K. Szot, W. Speier, G. Bihlmayer, and R. Waser, *Nature Mater* **5**, 312 (2006) [4] Y.F. Chen and M. Ziese, *Eur. Phys. Lett.* **77**, 47001 (2007) [5] S.-J. Kim, T. Yamashita, *Jpn. J. Appl. Phys.* **38**, 5069 (1999) [6] J.W.A. Robinson, S. Piano, G. Burnell, C. Bell, and M.G. Blamire, *Phys. Rev. Lett.* **97**, 177003 (2006).

#### 4:30 PM 19.4

**Size Induced Change From First To Second Order Magnetic Phase Transition In La<sub>0.67</sub>Ca<sub>0.33</sub>MnO<sub>3</sub> Nanoparticles.** Tapati Sarkar and Arup Kumar Raychaudhuri, Department of Material Science, S.N.Bose National Centre for Basic Sciences, Kolkata, West Bengal, India.

The doped perovskite oxide manganites (with ABO<sub>3</sub> structure) are fascinating because they can readily be tuned between different electronic phases by proper substitution of cations. Broadly speaking, the ground state can be either a ferromagnetic metal, a charge-ordered insulator or a paramagnetic polaron liquid. Recently we have shown that size reduction can tune the ground state of the manganites by destabilizing the charge ordered insulating state. In this report we show that for manganites like La<sub>0.67</sub>Ca<sub>0.33</sub>MnO<sub>3</sub> (LCMO) even the nature of the ferromagnetic transition is affected by size reduction to nanometric sizes. The size reduction can change the nature of the phase transition from first order (for bulk) to second order (for the nanoparticles). The specific system of La<sub>0.67</sub>Ca<sub>0.33</sub>MnO<sub>3</sub> shows a paramagnetic to ferromagnetic phase transition at 270K. We have prepared nanoparticles of La<sub>0.67</sub>Ca<sub>0.33</sub>MnO<sub>3</sub> using a sol gel based polymeric precursor (polyol) route which allows synthesis at a significantly lower sintering temperature compared to the conventional solid state procedure, and ensures homogeneity, phase purity and a good control over the stoichiometry of the end product. The nanoparticles were characterized using X-Ray Diffraction (XRD) and Transmission Electron Microscopy (TEM) techniques and checked for oxygen stoichiometry using iodometric titration. The ferromagnetic to paramagnetic phase transition near 270K in bulk LCMO is known to be of the first order, as established by using standard criterion (Banerjee, 1964). It consists of the observation of the slope of isotherm plots of H/M vs. M<sup>2</sup>, M being the experimentally observed magnetization and H the magnetic field. A positive or negative slope indicates a second order or first order transition respectively. We have applied this criterion to La<sub>0.67</sub>Ca<sub>0.33</sub>MnO<sub>3</sub> and found that the first order phase transition changes to second order when the particle size is brought down from a few μm to ~ 15nm. To our knowledge, this is the first report of tuning the nature (order) of a magnetic phase transition by tuning the size. The Curie temperature undergoes a slight decrease from the bulk value of 270K. This change in the order of the phase transition is explained from a reduced value of dT<sub>C</sub>/dP arising due to a combined effect of disorder and



increased surface pressure in the nanoparticles. We have also extracted the critical coefficients,  $\beta$ ,  $\gamma$  and  $\delta$ , of the nanoparticle sample from modified Arrott plots and found that the critical coefficients are close to the mean field value of  $\beta = 0.5$ ,  $\gamma = 1$  and  $\delta = 3$ .

#### 4:45 PM I9.5

**Inhomogeneous Magnetism in Anatase Nanorods with Low Fe Content.** Laura H. Lewis<sup>1</sup>, Yi Ding<sup>3</sup> and Wei-Qiang Han<sup>2</sup>; <sup>1</sup>Chemical Engineering Department, Northeastern University, Boston, Massachusetts; <sup>2</sup>Center for Functional Nanomaterials, Brookhaven National Laboratory, Upton, New York; <sup>3</sup>Condensed Matter Physics & Materials Science Department, Brookhaven National Laboratory, Upton, New York.

Ferromagnetism in transition-metal-doped  $d^0$  oxides is of fundamental interest in understanding the nature of the interaction between magnetic impurities in insulating systems. Applications of such materials include transparent magnetic semiconductors for spintronics purposes and photocatalysis for solar production of hydrogen. We report here simultaneous high-Curie temperature ( $T_C$ ) ferromagnetism and enhanced temperature-independent paramagnetism ( $\chi_{TIP}$ ) in  $\text{TiO}_2$  anatase nanorods doped with nominal 0.5 at% Fe. The Fe content of the nanorods is sufficiently low to preclude formation of ferromagnetic metallic Fe particles or clusters. The nanorods were synthesized by a hydrothermal route followed by low-temperature heating in air; they possess widths of 8-35 nm and are several hundreds nanometers in length. Transmission electron microscopy (TEM) reveals that the Fe concentration ranges from 0.3 at% - 0.8 at% within the nanorods. No evidence of pure iron nanoparticles in the sample is detected with TEM or with advanced synchrotron diffraction techniques. SQUID magnetometry performed in the temperature range  $10 \text{ K} \leq T \leq 775 \text{ K}$  in fields up to 1 T shows dominance of ferromagnetism at low fields that transitions to paramagnetic behavior at higher fields. Decomposition of demagnetization curves reveals that the nanorods possess an enhanced temperature-independent susceptibility  $\chi_{TIP}$  that is 100 times larger than that of pure bulk anatase  $\text{TiO}_2$  as well as ferromagnetism that persists to temperatures near 800 K. The inhomogeneous magnetism is attributed to the variation in Fe content within the nanostructures, and the large measured values of  $T_C$  and  $\chi_{TIP}$  are hypothesized to arise from an interaction between Fe cations exchange-coupled by large-orbit hydrogenic electrons originating from oxygen lattice and surface defects of the anatase nanorods [1]. [1]. J. M. D. Coey, M. Venkatesan, C. B. Fitzgerald, Nature Materials 4 173 (2005) Research performed under the auspices of the U.S. DOE, Office of Basic Energy Sciences under contract No. DE-AC02-98CH1-886.

SESSION I10: Poster Session  
Wednesday Evening, November 28, 2007  
8:00 PM  
Exhibition Hall D (Hynes)

#### I10.1

**Magneto-transport Properties of Cobalt doped Indium Oxide Dilute Magnetic Semiconductors.** K. Ghosh<sup>1</sup>, N. Mamidi<sup>1</sup>, Ram K Gupta<sup>1</sup>, S. R. Mishra<sup>2</sup> and P. K Kahol<sup>1</sup>; <sup>1</sup>Physics, Astronomy and Materials Science, Missouri State University, Springfield, Missouri; <sup>2</sup>Physics, university of memphis, memphis, Tennessee.

Recently, oxide-based dilute magnetic semiconductors (DMS) have attracted an immense research interest to the scientists due to the possibility of inducing room temperature ferromagnetism and potential uses in novel spintronic devices.  $\text{In}_2\text{O}_3$ , a transparent opto-electronic material, is an interesting prospect for spintronics due to its unique combination of magnetic, electrical, and optical properties. High quality thin films of Co-doped  $\text{In}_2\text{O}_3$  DMS were grown on quartz substrates using pulsed laser deposition technique. All the films have been characterized using different techniques such as x-ray diffraction, Raman spectroscopy, optical transmission spectroscopy, electrical resistivity, and Hall Effect measurement. The effect of growth temperature and oxygen pressure on the electrical, magnetic, and optical properties of these films have been studied in detail. The optical transparency in all the films is high. It has been observed that the optical transparency depends on growth temperature and oxygen pressure. The electrical parameters such as resistivity, carrier concentration, and mobility strongly depend on both oxygen pressure and growth temperature. The films grown at low temperature are semiconducting in nature while the films grown at high temperature are metallic. Detailed temperature and magnetic field dependent resistivity, magnetoresistance, and Hall effect data will be presented. This work is supported by Research Corporation (award number CC6166).

#### I10.2

**Nano Magnetic Composite Materials With Polymer Matrix Obtained Using Nano-Magnetic Fluids.** Nicolae Crainic<sup>1</sup>, Doina Bica<sup>2</sup>, Antonio Torres Marques<sup>3</sup>, Nicolae Calin Popa<sup>2</sup>, Paulo J. Novoa<sup>4</sup>, Nuno Correia<sup>4</sup>, Oana Marinica<sup>1</sup>, Carlos Pinto Moreira de Sa<sup>5</sup> and Ladislau Vekas<sup>2</sup>; <sup>1</sup>NCESCF, Politehnica University of Timisoara, Timisoara, Romania; <sup>2</sup>Romanian Academy, Timisoara, Romania; <sup>3</sup>FEUP, Universidade do Porto, Porto, Portugal; <sup>4</sup>CEMACOM, INEGI, Porto, Portugal; <sup>5</sup>CEMUP, Universidade do Porto, Porto, Portugal.

The paper presents the possibility to create a new category of nano-magnetizable composite materials, using nano-magnetic fluids (ferrofluids) and resins [1]. We prepared samples of different mixtures of resins, carrier liquids (of nano-magnetic fluids), and concentration of magnetic nano-particles. We used nano-magnetic fluids with cyclo-hexane, ethyl ether, pentanol and methyl-ethyl-ketone, as carrier liquids. In the cyclo-hexane carrier liquid, the  $\text{Fe}_3\text{O}_4$  nano-particles are monolayer sterically stabilized (with oleic acid). In the methyl-ethyl-cetone carrier liquid, the magnetite nano-particles have double sterical stabilization (chemisorbed oleic acid and physically absorbed dodecyle benzene sulphonic acid). In the case of the polar carriers, such as methyl-ethyl-ketone, the magnetite nano-particles have double sterical stabilization (chemisorbed oleic acid and physically absorbed dodecyle benzene sulphonic acid). As magnetic suspensions, we used iron particles in high vacuum oil (as carrier liquid), Methyl-ethyl ketone (MEK), ethyl ether (EE), and pentanol (Pent), were selected as resin compatible polar carriers. Especially MEK and EE are highly volatile and strongly polar liquids. Details of the preparation procedure are presented in [2] for MEK and EE, and, in [3] for Pent based MNF. Non-polar organic solvents, in particular styrene and cyclohexane were also used, the main steps of preparation of these type of MNF being described in [4]. The polymerization process took place with and without magnetic field. We investigated the magnetic properties of these solid samples with the measurement of magnetic field parallel and perpendicular to the polymerization magnetic field [5], the microstructure of the samples, and, the mechanical properties (three points bending test, elastic properties, gel time determination, etc.) corresponding to different preparation methods [6]. The target of these investigations is to obtain new materials having magnetically controllable mechanical properties. [1] N. Crainic, Doina Bica, A.



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### I10.3

#### Simultaneous Shock Compaction and Severe Plastic Deformation of Micron and Nano Sized Powders for Fabrication of Bulk Magnets.

Christopher Wehrenberg<sup>1</sup>, Chengda Dai<sup>1</sup>, Kevin Chasse<sup>1</sup>, Naresh Thadhani<sup>1</sup>, Chuanbing Rong<sup>2</sup> and Yanglong Hou<sup>3</sup>; <sup>1</sup>Material Science and Engineering, Georgia Institute of Technology, Atlanta, Georgia; <sup>2</sup>Physics, University of Texas at Arlington, Arlington, Texas; <sup>3</sup>Chemistry, Brown University, Providence, Rhode Island.

Shock compaction offers unique advantages for the fabrication of bulk magnets by allowing full density consolidation with retention of the nanostructure of powder precursors. Development of anisotropy through shock compaction holds promise for production of permanent magnets with very high energy products. In the present work, novel techniques are employed to simultaneously densify and severely deform powders during compaction. Numerical 2D simulations were used to test various impact geometries and explore compaction and deformation behavior. Micron and nano sized SmCo5 and Pr2Fe14B powders were compacted. Density measurements and SEM micrographs illustrate the consolidation behavior. XRD analysis was employed to determine the presence of anisotropy. Magnetic properties were measured with a SQUID magnetometer. The response of the magnetic behavior of SmCo5 and Pr2Fe14B powders to simultaneous shock compaction and severe plastic deformation was ascertained. This work is supported by ONR/MURI under Grant No. N00014-05-1-0497.

### I10.4

#### Silica Encapsulation and Magnetic Properties of Hard Magnetic Sm2Co17 Nanoparticles Obtained by Mechanical Ball-milling Process.

Girija Shankar Chaubey, Yiping Wang, Chaung-bin Rong, Narayan Poudyal, Vikas Nandwana, Kevin E. Elkin and J. Ping Liu; Physics, University of Texas at Arlington, Arlington, Texas.

Sm2Co17 nanoparticles obtained by mechanical ball milling are highly sensitive to air and prone to oxidation. Air-stability of the nanoparticles is desired for many applications. In order to make these particles air-stable, we have encapsulated these particles in a non-magnetic SiO2 layer. The coating experiments were carried out inside an inert glove box. Sm2Co17@SiO2 nanoparticles were taken out of the box and exposed to air. XRD patterns of the Sm2Co17@SiO2 sample after exposing for 24 hours in air, match well with the XRD patterns of the Sm2Co17 sample not exposed to air. No oxide peak was seen in the XRD patterns, which shows that SiO2 coating over Sm2Co17 particles prevents the particles from oxidation. The fact that SiO2 coating prevents Sm2Co17 nanoparticles from oxidation was further confirmed from their magnetic properties. Magnetic measurements on the Sm2Co17@SiO2 nanoparticles exposed to air for several days showed magnetic loops similar to their as-milled Sm2Co17 nanoparticle counterpart which were not exposed to air. Transmission electron microscopy image confirmed silica coating over ball-milled Sm2Co17 nanoparticles. The silica shell provides a chemically inert surface and greatly improves the hydrophilicity of the magnetic nanoparticles.

### I10.5

#### Strain-Induced Ferromagnetism in Fe-based B2 and L21 Intermetallic Compounds. Ian Baker, Q. Zeng and Y. Liao; Thayer School of Engineering, Dartmouth College, Hanover, New Hampshire.

A strain-induced paramagnetic to ferromagnetic transition has been observed in several intermetallic compounds that containing magnetic moment-bearing elements. The phenomenon arises from the generation of anti-phase boundary tubes (APB) during deformation. The magnetic behavior has been shown to be reversible on annealing out of the APB tubes. The saturation magnetization,  $M_S$ , resulting from deformation has been modeled in FeAl, using the *local environment* theory applied to APB tubes, where Fe atoms can have  $\geq 3$  like nearest neighbors. It is shown that the  $M_S$  depends on both the Fe:Al ratio, the ternary atoms present and on the degree of deformation. The FeAl-based derivative compound Fe2AlMn, which adopts the L21 structure, shows similar behavior strain-induced ferromagnetism to FeAl, but to a much greater and surprising extent. In addition to describing the phenomenon and the model, TEM observations of APB tubes in lightly-strained single crystals of FeAl and Fe2AlMn will be presented. Research sponsored by NSF grant DMR 05774 and NIST grant 60NANB2D0120.

### I10.6

#### A Series of New Transition Metal Borates with Magnetic Porous Frameworks. Jing Ju<sup>1,2</sup>, Juns Sasaki<sup>1</sup>, Tao Yang<sup>2</sup>, Katsumi Tanigaki<sup>1</sup>, Naoki Toyota<sup>1</sup> and Jianhua Lin<sup>2</sup>; <sup>1</sup>Department of Physics, Tohoku University, Sendai, Japan; <sup>2</sup>State Key Laboratory for Rare Earth Materials Chemistry and Applications, College of Chemistry and Molecular Engineering, Peking University, Beijing, China.

A series of new transition metal borates materials possessing 3D porous structures ([a]-[d]) have been recently synthesized using a boric acid flux method. [a] H2NaCuB7O13 contains oval 1D cavities formed by a set of (-B-O-)n infinite helices. The cavities have been cast around the rows of sodium ions. The structural framework of H2NaCuB7O13 is composed of octahedra (CuO6), tetrahedral (BO4) and triangles (BO3). The CuO6 octahedra share edges forming an octahedral dimer that further shares all oxygen atoms with borate groups. The borate groups (12BO3 and 2BO4), on the other hand, share all corners forming 14-ring one-dimensional channels along the b-axis. Na+ cations and water molecules are located within the 14-ring channels. The Na+ ions in the channel are mobile and can be completely replaced by Li+ or K+ ions. [b] In KCoB7O12 structure, parallel CoO6 octahedral layers are supported by (-B-O-)n chains, forming long and narrow void cavities. Mobile K+ ions occupy the cavities near the borate chains. [c] H3.5Na2.5[Cr2B6P5O27.5].3H2O is a borophosphate with open framework structure. It contains large cages composed of eight CrO6 octahedrons and eight PO4 tetrahedrons linked alternately with a P2O7 pair sealed at the center. [d] HNa2MB3P2O12.nH2O (M = Mn, Co, Ni or Cu)



are a series of transition metal borophosphates containing 12-MRs and 6-MRs pores, the centers of which are occupied by  $H_2O$  and  $Na^+$ , respectively. The magnetic porous solids are of scientific and technological interests because of their ability to interact with atoms, ions and molecules not only at their surfaces, but throughout the bulk of the materials. This has resulted in materials with unusual properties and broadened their application range beyond the traditional use as catalysts and adsorbents. In fact, porous materials now seem to contribute to the developments in areas ranging from microelectronics to medical diagnosis. The transition metal borates mentioned above contain regulated and continuous void-cavities to confine guest cations, where the cations communicate with other species via ion-exchange interactions. These borates contain both exchangeable cations among their channels and magnetic metal sites over their frameworks. We expect excellent and/or novel magnetic/electronic properties, as well as exotic properties via chemical manipulations of these series of porous borates. The interplay among localized magnetic spins, itinerant conduction carriers and polyhedral-network phonons shall be very advantageous in making perspective devices in the future. References [1] Yang T., Ju J., et al, *Inorganic Chemistry* (46): 2342-2344, 2007. [2] Ju J., Sasaki J., et al, *DALTON TRANSACTIONS* (13): 1597-1601, 2006. [3] Yang T., Li G., Ju J., et al, *JOURNAL OF SOLID STATE CHEMISTRY* 179 (8): 2534-2540, 2006. [4] Yang T., Li G., You L., Ju J., et al, *CHEMICAL COMMUNICATIONS* (33): 4225-4227, 2005.

### I10.7

**Structural Stability and Ordering Kinetics of FePt Nanoparticles.** Michael Mueller and Karsten Albe; Materials Modeling Division, Institute of Materials Science, Darmstadt, Germany.

The structural stability and ordering kinetics of FePt nanoparticles is studied by means of atomic scale computer simulations. Particles in multiply twinned and single crystalline morphologies are investigated by means of molecular statics calculations based on a recently developed analytic bond-order potential. A continuum model is parametrized which allows to assess the contributions of elastic strain, surface and and twin boundary energies, separately. The static model calculations predict a strong energetic preference for single crystalline morphologies in the ordered L1<sub>0</sub> and disordered A1 phases, if the particle size exceeds 2.6 nm, while smaller particles tend to form icosahedral structures. Kinetic Monte Carlo simulations are then employed to investigate the ordering kinetics of single-crystalline FePt nanoparticles. In non-supported particles, the A1 to L1<sub>0</sub> transition proceeds with a higher rate in layers at the surface than in the volume of the particles. Because of the statistical nucleation of the ordered phase, however, no single domain particles are obtained and an elimination of the antiphase boundaries can not be observed within the time scales accessible by the simulations.

### I10.8

**Switching the Electrical Resistance and Finite-Size Effects of Magnetite Nanoparticles.** Eung Young Jang<sup>1</sup>, Deung Jang Choi<sup>1</sup>, Tae Hee Kim<sup>1</sup>, Jung-Tak Jang<sup>2</sup>, Jin-Sil Choi<sup>2</sup> and Jinwoo Cheon<sup>2</sup>; <sup>1</sup>Department of Physics, Ewha Womans University, Seoul, South Korea; <sup>2</sup>Department of Chemistry, Yonsei University, Seoul, South Korea.

Understanding size effect in ferromagnetism and ferroelectricity, combined with the size reduction constraints imposed by the semiconductor industry, raises a lot of interests to researchers. For the last decade, many studies of magnetic and electric properties have been carried out on small magnetic particles because a different degree of ordering is expected to near surface or interfaces, leading to an intrinsic magnetic and electric dependence on sample size. However the understanding of the correlation between magnetic properties and particle size is incomplete. Magnetite (Fe<sub>3</sub>O<sub>4</sub>) is currently one of key materials for applications in magnetic storage devices due to its nearly full spin polarization at room temperature[1]. In this work, Fe<sub>3</sub>O<sub>4</sub> nanoparticles with different sizes ranging from 9 to 17 nm were prepared in a well-controlled manner by a nonhydrolytic synthetic method. The size dependence in magnetoelectric effect was investigated in Fe<sub>3</sub>O<sub>4</sub> nanoparticle pellets. Superparamagnetic behavior was clearly shown for the particles of size 9 nm. As the particle size decreases, the variability in the electrical properties of the nanoparticles, ranging from semiconducting to insulating behavior, was observed. We observed also the resistive switching behavior by the application of an appropriate electric field. From our results, we will discuss the size dependence of magnetoelectric effect linking the magnetic and electric effect for composite oxide materials, such as Fe<sub>3</sub>O<sub>4</sub> nanoparticles. This work is supported by the Basic Research Program of the Korea Science & Engineering Foundation (No.R01-2006-000-11227-0) and a Korea Research Foundation (KRF-2006-531-C00026). [1] J. M. D. Coey et al., (1998) *Appl. Phys. Lett.* 72, 734. Correspondence should be addressed to T.H.K.(taehee@ewha.ac.kr).

### I10.9

**Magnetic Dynamics of SiO<sub>2</sub> Coated Fe<sub>3</sub>O<sub>4</sub> Nanospheres.** K. Mohan Kant<sup>1,2</sup>, K. Sethupathi<sup>1</sup> and Mamidanna S.Ramachandra Rao<sup>1,2</sup>; <sup>1</sup>Physics, Indian Institute of Technology, Chennai, TamilNadu, India; <sup>2</sup>Materials Science Research Centre, Indian Institute of Technology Madras, Chennai, Tamilnadu, India.

Magnetite nanoparticles have many important applications in the fields of biotechnology and biomedicine. Biomedical applications require the use of magnetic nanoparticles (MNP) that present a superparamagnetic (SPM) behavior at room temperature. A particularly interesting physics occurs when superparamagnetic nanoparticles are dispersed/coated with non-magnetic matrix. The magnetic behavior of these systems can vary widely depending on the size of the nanocrystalline magnetic particles as well as interaction between individual and well separated MNPs. In this work, we demonstrated the formation of non-crystalline silica (SiO<sub>2</sub>) coating on the surfaces of crystalline iron oxide (Fe<sub>3</sub>O<sub>4</sub>) nanospheres to help prevent aggregation of MNPs and to realize tenability of relaxation time scales. Thickness of SiO<sub>2</sub> shell is varied from 3 nm to 65 nm by varying tetraethyl orthosilicate during synthesis. FTIR spectroscopy, EDS, HRTEM confirmed the presence of SiO<sub>2</sub> coating on Fe<sub>3</sub>O<sub>4</sub> nanoparticles. Magnetic properties of SiO<sub>2</sub> coated and uncoated Fe<sub>3</sub>O<sub>4</sub> particles were investigated by vibration scanning magnetometry and low field a.c.susceptibility. The mean magnetic moment per particle  $\langle \mu_B \rangle$  of sample S1 is calculated to be  $1.5 \times 10^4 \mu_B$  and the nanosphere diameter is obtained as 8.4 nm. The saturation magnetization scaled down as per SiO<sub>2</sub> wt% in the core-shell particles. The coercivity of pure (S1) and SiO<sub>2</sub> (S2, S3, S4 and S5) coated magnetite nanoparticles is nearly observed to be 0 Oe at room temperature, as compared to Fe<sub>3</sub>O<sub>4</sub> bulk value of 115-400 Oe. Frequency variation in ac-susceptibility measurements showed clear shift in the peak temperature, termed as blocking temperature. We used empirical parameter " $\Phi$ ", which represents relative shift of the maximum temperature  $T_m$  per one order increase in frequency.  $\Phi = \Delta T_m / T_m \Delta \log(f)$ , Where  $\Delta T_m$  is the difference between  $T_m$  measured in the frequency interval. The smaller values of  $\Phi < 0.07$  results in spin glass/cluster glass like surface behavior or due to interparticle interactions. For (S1, S2, S3, S4 and S5) we observed  $\Phi = 0.035$  (S1), 0.039 (S2), 0.063 (S3), 0.967 (S4) and 0.982 (S5). This lead us to



the conclusion that S1, S2 and S3 samples can be treated as interacting particle systems, S4 and S5 can be treated by non-interacting particle systems. Data of S1, S2 and S3 samples fit to critical slowing down behavior model and yielded relaxation time values of  $\tau_0$  in the order of  $10^{-10}$ s and  $\nu$  varies from 6.32 to 6.26. Core-shell particles with higher shell thickness yielded relaxation time values of the order of  $10^{-13}$ s. All the coated particles exhibit superparamagnetism below 200K. The structural, functionalization and magnetic properties will be discussed in detail.

#### I10.10

**Ferromagnetic Characteristics of Self-Assembled Gold (Au) Nanoparticles.** Jeremiah T Abiade, Mechanical Engineering & Chemical Engineering, North Carolina A&T State University, Greensboro, North Carolina.

Generally, ferromagnetism in metals is attributed to unpaired spins in 3d or 4f electron energy levels. In the bulk, gold (Au) is diamagnetic because the 4f and 5d electron energy levels are completely filled. However, recent reports suggest that Au nanoparticles and ultrathin films may possess ferromagnetic characteristics like room temperature coercivity and remanence. In this talk, we will discuss our recent investigation of the magnetic properties of Au nanoparticles embedded in nonmagnetic thin films. Both the nanoparticles (~1.8 nm - 20 nm) and thin film matrix were deposited by pulsed laser deposition (PLD). The particle size was obtained via scanning transmission electron microscopy (STEM). The nanoparticles evolve as three dimensional clusters (i.e. Volmer Weber growth) because of the respective surface and interface energies. Room temperature coercivity (~70 Oe) is observed up to 10 nm but disappears in bulk samples. Gold thin films (~175 nm) show the typical diamagnetic response. Unlike classical ferromagnetic nanoparticles, our Au samples show: weak dependence of the coercivity on particle size and temperature, rapid decrease in the magnetic moment with increasing particle size, and relatively constant magnetization from 300 K to 10 K.

#### I10.11

**Second Order Ferromagnetic Resonance in Magnetic Nanoparticles.** Derek Walton, Physics & Astronomy Department, McMaster University, Hamilton, Ontario, Canada.

Ferromagnetic resonance is almost exclusively explored experimentally in 1st order where one photon decays into a single magnon, necessarily of the uniform or magnetostatic modes. In 2d order where the photon creates two magnons of equal and opposite wave-vector, it is well known that details of the magnon spectrum become significant. An important consideration is the cut-off in the dispersion relations for magnons whose wavelength exceeds twice the scale of the particle. I will discuss the use of this property to selectively magnetize or demagnetize assemblies of single domain grains. This permits rather sensitive dating of ancient ceramics, and accurate determination of grain size distributions. I will show that microwave absorption is extremely efficient in ferrimagnetic nanoparticles, and that at low concentrations they can reach their magnetic transition temperature in tens of milliseconds.

#### I10.12

**Measuring the Order Parameter of Individual L10 FePt Nanoparticles.** Richard Vanfleet<sup>1</sup>, Romyana Petrova<sup>2</sup>, Bo Yao<sup>2</sup> and Kevin Coffey<sup>2</sup>; <sup>1</sup>Physics and Astronomy, Brigham Young University, Provo, Utah; <sup>2</sup>University of Central Florida, Orlando, Florida.

Nanoparticles of FePt and similar L10 family ordered alloys are candidate materials for high-density magnetic recording media. However, to be useful the particles must be highly chemically ordered. The order parameter (S) can be quantitatively measured by x-ray diffraction for sufficiently thick layers but signal to noise problems hamper studies on thin films and layers of nanoparticles. Additionally, X-rays measure large numbers of particles at once giving results for an "average" particle but no information about particle to particle variation. High Resolution Electron imaging techniques can show ordered spacings to identify individual chemically ordered particles but do not give a quantitative measure of the degree of ordering (S). We will present our work on using CBED based electron diffraction on FePt nanoparticles in conjunction with multislice simulations to extract order parameter values from individual particles. The important computational and experimental parameters and processes will be discussed.

#### I10.13

**Compositional Evolution of FePt Nanoparticles Prepared by Different Organometallic Synthesis Routes.** Chandan Srivastava<sup>1,6</sup>, Jayendra Balasubramanian<sup>2,6</sup>, Hitesh Bagaria<sup>3</sup>, Gregory B Thompson<sup>1,6</sup>, C. Heath Turner<sup>2,6</sup>, John Wiest<sup>2,6</sup>, David E Nikles<sup>4,6</sup> and James W. Harrell<sup>5,6</sup>; <sup>1</sup>Metallurgical & Materials Engineering, University of Alabama, Tuscaloosa, Alabama; <sup>2</sup>Chemical and Biological Engineering, University of Alabama, Tuscaloosa, Alabama; <sup>3</sup>Chemical and Biomolecular Engineering, Rice University, Houston, Texas; <sup>4</sup>Department of Chemistry, University of Alabama, Tuscaloosa, Alabama; <sup>5</sup>Department of Physics and Astronomy, University of Alabama, Tuscaloosa, Alabama; <sup>6</sup>Center for Materials for Information Technology, University of Alabama, Tuscaloosa, Alabama.

Self-assembled FePt nanoparticle arrays are candidate structures for ultrahigh density magnetic storage media. One of the factors limiting their application to this technology is particle-to-particle compositional variation. This variation will affect the A1 to L10 transformation as well as the magnetic properties of the nanoparticles. In the present study, an analysis is provided for the formation mechanism of FePt nanoparticles synthesized by the thermal decomposition of Fe(CO)5 and the reduction of FeCl2 by superhydride (LiBEt3H). The particle formation mechanism has been studied by extracting particles at different stages of the synthesis and individually determining particle-to-particle composition by STEM-EDS. In both processes, Pt rich seeds initially form from the reduction of Pt acetylacetonate. In the case of Fe(CO)5, the Fe is gradually incorporated into the Pt seeds and produces a wide variation in compositional distribution about the mean value. In contrast, the FeCl2 has a nearly instantaneous shift in composition to the average value with the introduction of the superhydride reducing agent. The discrepancies in compositional uniformity between the two processes will be discussed in terms of the intrinsic differences between the two synthetic methods induced by the different Fe precursors. Refluxing the reaction mixture in the superhydride-FeCl2 synthesis for extended periods of time resulted in a continual narrowing of the composition to the average value. The narrow composition distribution is presented with a thermodynamic analysis of the mechanism described in terms of free energy perturbation Monte Carlo simulations.

#### I10.14

**Nonstoichiometric Zinc-Ferrite Spinel Nanoparticles.** Darko Makovec<sup>1</sup>, Alojz Kodre<sup>1,2</sup>, Iztok Arcon<sup>1,3</sup> and Miha Drofenik<sup>1,4</sup>; <sup>1</sup>"Jozef Stefan" Institute, Ljubljana, Slovenia; <sup>2</sup>Faculty of Mathematics and Physics, University of Ljubljana, Ljubljana, Slovenia; <sup>3</sup>University of Nova Gorica, Nova



Gorica, Slovenia; <sup>4</sup>Faculty for Chemistry and Chemical Engineering, University of Maribor, Maribor, Slovenia.

The unique properties of nanoparticles in general are related to the adaptation of the materials' crystal structure to the small (nano) size, and the large surface-to-volume ratio. The flexibility of the chemical composition and the crystal structure is particularly pronounced in ferrite spinel nanoparticles. The possibility of occupying two different lattice sites existing in the spinel structure (tetrahedrally coordinated A sites and octahedrally coordinated B sites) with the same metal ion makes possible the formation of spinel nanoparticles, which display chemical compositions, crystallite structures and consequently magnetic properties, not observed in the bulk. When prepared as a bulk material ZnFe<sub>2</sub>O<sub>4</sub> has a normal spinel structure with Zn<sup>2+</sup> incorporated almost exclusively at the tetrahedral lattice sites and Fe<sup>3+</sup> at the octahedral sites ( (Zn)[Fe<sub>2</sub>]O<sub>4</sub> ) and is paramagnetic. Due to its "rigid" structure, its composition is also closely defined at Zn<sup>2+</sup>/Fe<sup>3+</sup> ~ 0.5. However, when prepared as nanoparticles, it shows a fairly large flexibility in its structure. A significant proportion of Zn can enter the zinc-ferrite structure at the octahedral sites, resulting in its ferrimagnetism. Due to the flexibility in the nanoparticles' structure also their composition is highly flexible. In this work the nonstoichiometry of zinc-ferrite nanoparticles has been studied as a function of the particle size. Nanoparticles with a narrow size distribution were synthesized using co-precipitation in water-in-oil microemulsions. For their characterization, the X-ray diffractometry, analytical electron microscopy, and extended X-ray absorption fine structure (EXAFS) were used in the combination with magnetic measurements. The zinc-ferrite nanoparticles with a size of ~ 9 nm retained the single-phase spinel structure when the Zn/Fe was between 0 and ~ 0.9. With a decrease in the particle size the compositional range of the zinc-ferrite spinel broadened. A special attention was given to study of structural mechanisms that are involved in compensation of this nonstoichiometry of the nanoparticles. The process of the structural rearrangement during the heating of the nanoparticles was also studied.

#### I10.15

**Geometric Frustration on Novel Nanomagnetic Lattices.** Yi Qi<sup>1</sup>, Todd Brintlinger<sup>1,2</sup> and John Cumings<sup>1,2</sup>; <sup>1</sup>Materials Science and Engineering, University of Maryland, College Park, College Park, Maryland; <sup>2</sup>Center for Nanophysics and Advanced Materials, University of Maryland, College Park, Maryland.

We demonstrate a realization of a two dimensional "kagome spin ice" using a nanomagnetic array based on a honeycomb lattice. Here single domain ferromagnetic line elements on the honeycomb lattice act as Ising spins that interact by dipolar and exchange forces. The array is lithographically patterned, with permalloy elements ~23nm thick, ~100nm wide, and ~500nm long. Lorentz TEM is used for real-time, in-situ measurements of local spins. By a statistical analysis of spin direction, we show a kagome ice state with both short-range order and long-range disorder, but also ice-like correlations. This system displays a 100% compliance with the "kagome ice rule," which forbids 3-in/3-out configurations, and correlations that decay consistently in sign and magnitude with two-dimensional spin-ice simulations. The ground state entropy, magnetic-field induced ordering and boundary effects are also measured and will be presented. Our study establishes a model system with many analogous features to other geometrically-frustrated systems, such as pyrochlore spin ice and water ice, and points toward future studies of frustration with defects, boundary conditions, and geometries that are designed rather than discovered.

#### I10.16

Transferred to I6.10

#### I10.17

**On the Nature of Magnetism and Hall Effect in Transition Metal (TM) Doped SrTiO<sub>3</sub> Thin Films.** Shixiong Zhang<sup>1</sup>, Satish B. Ogale<sup>1</sup>, Weiqiang Yu<sup>1</sup>, Lianfeng Fu<sup>2</sup>, Darshan C. Kundaliya<sup>1</sup>, Wang-Kong Tse<sup>1</sup>, Sheng-yu Young<sup>3</sup>, Lourdes Salamanca-Riba<sup>3</sup>, Nigel D. Browning<sup>2</sup>, Richard L. Greene<sup>1</sup> and T. Venky Venkatesan<sup>1</sup>; <sup>1</sup>Physics Department, University of Maryland, College Park, Maryland; <sup>2</sup>Department of Chemical Engineering and Materials Science, University of California at Davis, Davis, California; <sup>3</sup>Department of Materials Science and Engineering, University of Maryland, College Park, Maryland.

In the field of spintronics, considerable interest is being focused on the search for intrinsic diluted magnetic semiconductors (DMS). Transition metal (TM) doped SrTiO<sub>3</sub> (STO) is proposed to be one of the carrier mediated DMS with high spin polarization. In this work, we investigated the nature of magnetism and anomalous Hall effect (AHE) in TM doped Nb: SrTiO<sub>3</sub> and (La, Sr)TiO<sub>3</sub>. We found that carefully prepared TM doped Nb: SrTiO<sub>3</sub> thin films with excellent crystalline quality, i.e. epitaxial structure and uniform distribution of each element did not show ferromagnetism (FM), though theoretically the system falls into an RKKY type of long range ferromagnetic ordered state. Meanwhile, cobalt doped (La, Sr)TiO<sub>3</sub> (Co-LSTO) films show clear superparamagnetic (SPM) behavior instead of intrinsic FM, due to the segregation of nano-sized cobalt metal. These results raise a question: is TM doped STO a true carrier mediated DMS? Furthermore, AHE is clearly observed in the superparamagnetic Co-LSTO system, which questions the AHE as a tool to test intrinsic DMS. By a systematic study of the correlation of Hall resistivity and magnetization, we proposed the origin of AHE in this system and a new criterion for testing intrinsic or extrinsic DMS materials.

#### I10.18

Abstract Withdrawn

#### I10.19

**Nanofabrication and Characterization of Magneto-plasmonic Materials.** Michelle Nicole Sestak<sup>1</sup>, Jonathan R. Skuza<sup>1</sup>, Cesar Clavero<sup>1</sup>, Natalia M. Dushkina<sup>2</sup> and Rosa Alejandra Lukaszew<sup>1</sup>; <sup>1</sup>Physics and Astronomy, University of Toledo, Toledo, Ohio; <sup>2</sup>Physics, Millersville University, Millersville, Pennsylvania.

Magnetic nanoparticles embedded in noble metal thin films exhibit interesting properties that are a function of the microstructure and that can be used in relevant applications. These materials may exhibit plasmonic enhancement of their optical properties (magneto-plasmonic materials) and can be used in a variety of sensing applications, in particular, for biosensing. The optical, magnetic, and magneto-optical properties of these nanocomposite materials depend on the materials used, the nanoparticle size and distribution, the inter-particle distance, etc. We will present our studies on such composite materials in thin film form. In particular, we will show that ion-implantation of ferromagnetic metal ions onto noble metal thin films is a powerful tool for nanofabrication of embedded nanoclusters with controlled geometry (i.e. size and distribution). We are particularly interested in the enhancement of the surface plasmon resonance (SPR) of the noble metal (e.g. Au) when combined with a ferromagnetic metal (e.g.



Co), i.e. a magneto-plasmonic material. We will compare the SPR response of a Au/Co/Au trilayer, in which the optical response can be tailored by varying the thickness of the Co layer, with a nanocomposite material made with Co nanoclusters embedded on a Au thin film matrix. In this latter case, the Co clusters are ion-implanted onto the Au matrix and their size and penetration depth can be tailored by choosing the ion-implantation conditions. We will show our field dependent SPR data on these nanocomposite materials.

#### I10.20

**Experimental Tests of Possible Mechanisms for the Organic Magnetoresistive Effect.** Tho Duc Nguyen, Yugang Sheng, James Rybicki and Markus Wohlgemant; Department of Physics and Astronomy and Optical Science and Technology Center, The University of Iowa, Iowa city, Iowa.

Organic magnetoresistance (OMAR) is a recently discovered, large room-temperature magnetoresistive (MR) effect in sandwich devices comprised of nonmagnetic electrodes and thin films made of pi-conjugated organic semiconductors. It was previously found that the OMAR effect is often only weakly temperature dependent and it does not depend on the direction of the applied magnetic field (B). In some materials, the effect reaches up to 15% in an applied B of 10 mT at room temperature. We expand on our previous work and report also on the new discovery of OMAR effect in sandwich devices made from the doped polymer PEDOT:PSS. In this particular case, the effect must be assigned to interface resistance, distinct from the case of intrinsic, semiconducting devices where OMAR is related to the bulk resistance. To the best of our knowledge, the mechanism causing OMAR has not yet been established with certainty. However, three distinct classes of models of OMAR have been proposed: (i) Electron-hole pair mechanism (EHP) models; (ii) The triplet-exciton polaron quenching (TPQ) model. (iii) The bipolaron (BP) mechanism. They are all based on spin-dynamics induced by the hyperfine interaction. We prove the hypothesis that OMAR is related to hyperfine coupling in the hydrogen nuclei, and perform experiments that test the validity of these models. For the former, we study OMAR in fullerenes (C60) sandwich devices. We are unable to detect OMAR in this material but observe it in its derivative [C60]PCBM which contains hydrogen atoms in its side group. Therefore, hydrogen atoms are necessary for observing OMAR, confirming the hyperfine hypothesis. For the latter, we study OMAR in bipolar devices with varying concentration of minority carriers, some of which are almost unipolar. Whereas a significant dependence of the magnitude of OMAR on the minority carrier density was found, this dependence is much weaker than the linear dependence that would be expected from EHP. We perform charge-induced absorption (CIA) and electroluminescence spectroscopy in a polyfluorene (PFO) organic magnetoresistive device. Our experiments allow us to measure the singlet and triplet exciton densities in the live device under an applied B. We find that both the singlet exciton density as well as the triplet exciton density simultaneously increases with B together with the device current. Analyzing these results, we find they are in clear contradiction to EHP models and TPQ model, but are consistent with the bipolaron mechanism.

#### I10.21

**Magnetoresistance of Conduction Channels Formed in Magnetic Tunnel Junctions through Nanometer-Scale Local Ablation of the Aluminum Oxide Barrier.** Holger Grube and Joshua M Pomeroy; National Institute of Standards and Technology, Gaithersburg, Maryland.

We have previously shown that the resistance of tunnel junction devices can be reduced by exposing the thin oxide barrier in a metal-insulator-metal stack to highly charged ions (HCI), such as Xe<sup>44+</sup> [1]. Ballistic Electron Emission Microscopy reveals formation of nanometer-sized regions of enhanced current transport through the barrier, whose areal density is consistent with the dose of HCIs. This can be explained with local ablation or damage of the barrier by single HCIs, each carrying 51 keV of neutralization energy, resulting in dramatically changed electrical properties. HCIs have previously been shown to cause high sputter yields on insulators [2]. An HCI-induced reduction of the resistance-area (RA) product by three orders of magnitude has been accomplished for several process recipes for nonmagnetic and magnetic tunnel junctions (MTJ) with 1 to 1.4 nm aluminum oxide barriers. Magnetic and electrical measurements show that the HCI-created conduction channels are magnetoresistive themselves and have electrical transport properties consistent with tunnel junctions or metallic connections, depending on process recipe. While HCI modification of magnetic tunnel junctions reduces the zero-bias magnetoresistance (MR) from 20% to several percent, the final MR is more than can be attributed to the MR of the unmodified parts of the device alone. MR of all devices reduces with increasing bias voltage across the junction, but the MR of modified MTJs drops slower with bias. Significantly, at higher applied bias the MR of exposed devices exceeds that of unexposed MTJs, indicating that a different physical mechanism is involved. This strategy could be useful for current perpendicular to the plane (CPP) magnetic read heads with suitable impedance and signal level for high-density hard drives. [1] J.M. Pomeroy, A.C. Perrella, and H. Grube: Adjustable Resistance-Area Product by Highly-Charged Ion Irradiation, submitted to Applied Physics Letters. [2] G. Hayderer, S. Cernusca, M. Schmid, P. Varga, HP. Winter, F. Aumayr, D. Niemann, V. Hoffmann, N. Stolterfoht, C. Lemell, L. Wirtz, and J. Burgdörfer, "Kinetically Assisted Potential Sputtering of Insulators by Highly Charged Ions", Phys. Rev. Lett. 86, 3530 (2001).

#### I10.22

**Exchange-coupled Fe<sub>3</sub>O<sub>4</sub>/L<sub>10</sub>-FePt Bilayer Via Oxidation.** Xuerang Hu<sup>1,2</sup>, Peiwen Wu<sup>1,2</sup> and Jun Yuan<sup>1,2</sup>, <sup>1</sup>Department of Materials Science and Engineering, Tsinghua University, Beijing, China; <sup>2</sup>National Centre for Electron Microscopy (Beijing), Tsinghua University, Beijing, China.

L<sub>10</sub>-FePt has attracted much attention because it has good chemical stability and large magnetocrystalline anisotropy. It has great potential in applications such as high density magnetic recording and high performance permanent magnet. The application in magnetic recording industry of this material is currently hampered by its high coercive field which exceeds far beyond the write field of existing recording heads. Heat assisted magnetic recording (HAMR), which employs a focused high energy laser to heat the writing bit to elevated temperature, has been proposed to overcome this problem. Exchange spring magnet made of L<sub>10</sub>-FePt and a soft magnet has also been suggested as an alternative way to lower the coercive field while maintaining the thermal stability of the media. Conventionally exchange-coupled bilayer film was fabricated using sequential thin film deposition procedure. However, it not only complicates the whole fabricating process but also the post-annealing will cause element diffusion. We have introduced oxidation during the post-annealing of FePt thin film to fabricate Fe<sub>3</sub>O<sub>4</sub>/L<sub>10</sub>-FePt exchange-coupled bilayer to solve these difficulties. (Fe 1nm/Pt 1nm)<sub>10</sub> multilayer was fabricated using electron beam evaporation on Si and NaCl crystal. The multilayer was annealed for 10 minutes at 550 degrees using rapid thermal annealing technique. In order to introduce selective oxidation, the multilayer was annealed in N<sub>2</sub>. Selected-area electron diffraction (SAED) pattern shows not only the ordering of the multilayer to L<sub>10</sub>-FePt but also the appearance of magnetite Fe<sub>3</sub>O<sub>4</sub> while cross-sectional transmission electron microscope (TEM) bright field image clearly shows the formation of a bilayer structure with the upper bright layer identified as mainly the Fe<sub>3</sub>O<sub>4</sub> oxide and the lower dark layer the L<sub>10</sub>-FePt alloy. Magnetic hysteresis loops show a smooth single phase behavior which indicating the occurrence of exchange-coupling. The oxidation behavior of the FePt film strongly depends on the oxygen content in the annealing atmosphere and the annealing temperature which enable the manipulating of the magnetic properties to make it more



suitable for the application purpose.

### I10.23

**Magnetic and Optical Properties of Transparent Fe-doped SnO<sub>2</sub> Films.** Hyun-Suk Kim<sup>1</sup>, Lei Bi<sup>1</sup>, Gerald F Dionne<sup>1,2</sup> and Caroline A Ross<sup>1</sup>; <sup>1</sup>Materials Science and Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts; <sup>2</sup>Lincoln Laboratory, Massachusetts Institute of Technology, Lexington, Massachusetts.

Dilute magnetic semiconductors (DMS) and wide gap oxide semiconductors are appealing materials for magneto-optical devices such as optical isolators. (1,2) The strong sp-d exchange interactions in DMS leads to a sizeable Zeeman split of the optical transitions and a large Faraday rotation is expected. (2) Recently, above room-temperature ferromagnetism has been reported in Co- and Fe-doped SnO<sub>2</sub>. (3,4) Because SnO<sub>2</sub> is an attractive optical material with a large optical band gap (~3.6 eV), (5) DMS based on SnO<sub>2</sub> could be useful for a variety of applications requiring combined magnetic and optical functionality. In this study, we report on the structural and magneto-optical properties of high quality Sn<sub>1-x</sub>Fe<sub>x</sub>O<sub>2</sub> films fabricated by pulsed-laser deposition on sapphire substrates. The films had a (101) oriented rutile structure without any detectable impurity phase up to x = 0.30 as confirmed by x-ray diffraction measurements. Detailed study of the SnO<sub>2</sub> (101) peaks in Sn<sub>1-x</sub>Fe<sub>x</sub>O<sub>2</sub> films reveals that the lattice constant follows Vegard's law, indicating solubility up to 30% Fe concentration. Vibrating sample magnetometer hysteresis loops show that the films are ferromagnetic at room temperature. There is a clear evolution of magnetic properties with increasing Fe concentration. The saturation magnetization at 10 kOe ranges from 1.5 emu/cm<sup>3</sup> for Sn<sub>0.95</sub>Fe<sub>0.05</sub>O<sub>2</sub> to 64.7 emu/cm<sup>3</sup> for Sn<sub>0.7</sub>Fe<sub>0.3</sub>O<sub>2</sub>. The magneto-optical properties of Sn<sub>1-x</sub>Fe<sub>x</sub>O<sub>2</sub> films were characterized using Faraday rotation and optical absorption at 1.55- $\mu$ m wavelength and compared with those of Bi-substituted magnetic garnets, which are typically used as bulk optical isolators. The origin of the correlated magnetic, optical and magneto-optical properties will be discussed, and compared with those of Co-doped SnO<sub>2</sub> prepared under similar conditions. These studies suggest that Sn<sub>1-x</sub>Fe<sub>x</sub>O<sub>2</sub> has a high Faraday rotation accompanied by reasonably low optical losses, which makes it an interesting candidate for integrated thin-film optical isolator applications. 1. W. Zaets and K. Ando, Appl. Phys. Letts. 77, 1593 (2000). 2. K. Ando, K. Takahashi, T. Okuda, and M. Umehara, Phys. Rev. B 46, 289 (1992). 3. J. M. D. Coey, A. P. Douvalis, C.B. Fitzgerald, and M. Venkatesan, Appl. Phys. Letts. 84, 1332 (2004). 4. S. B. Ogale et al, Phys. Rev. Letts. 91, 077205 (2003). 5. M. Nagasawa and S. Shionoya, Jpn. J. Appl. Phys., Part 1 10, 472 (1971).

SESSION I11: Bulk Magnets, Processing and Applications  
Chairs: Oliver Gutfleisch and Naresh Thadhani  
Thursday Morning, November 29, 2007  
Commowwealth (Sheraton)

### 8:00 AM \*I11.1

**Solidification and Microstructure of Gas-Atomized and Melt-Spun MRE-Fe-Co-M-B (MRE=Y+Dy+Nd, M=Zr+TiC, Zr+ZrC).** Ralph William McCallum<sup>1,2</sup>, W. Tang<sup>1</sup>, Y. Q. Wu<sup>1</sup>, K. W. Dennis<sup>1</sup>, P. K. Sokolowski<sup>1</sup>, M. J. Kramer<sup>1,2</sup> and I. E. Anderson<sup>1,2</sup>; <sup>1</sup>Ames Laboratory, Iowa State University, Ames, Iowa; <sup>2</sup>Materials Science and Engineering, Iowa State University, Ames, Iowa.

To meet performance and cost goals for advanced electric drive motors, it is essential to improve the alloy design and processing of permanent magnet powders. From the standpoint of high volume manufacturing, an interior permanent magnet motor where the magnets are direct injection molded into the laminate stack is very appealing. This requires magnet particulate which can operate at 200 °C. This operating temperature requires the used of high temperature polymers with processing temperatures of 300 °C so the magnet powder must be chemically stable in this environment. In addition, in order to obtain high fill factors at low injection pressures, spherical powders are highly desirable. The production of spherical powders by high pressure gas atomization of RE-Fe-B based alloys requires the control of the solidification microstructure on the scale of 10's of nanometers at quench rates considerably below those typically used in melt spinning. We will discuss the development of such an alloy. The solidification pathway and the development of the microstructure during annealing will be discussed. Finally an in situ coating process for surface passivation of spherical powder during atomization will be presented.

### 8:30 AM I11.2

**Magnetic Properties of Nd-Fe-B-M (M=Si, C) Bulk Nanocomposite Magnets Prepared by the Spark Plasma Sintering Method.** Tomokazu Fukuzaki<sup>1</sup>, Keisuke Tanaka<sup>2</sup>, Kazue Nishimoto<sup>2</sup>, Yuji Muro<sup>3</sup>, Keishi Nishio<sup>2</sup> and Ryuji Tamura<sup>1,2</sup>; <sup>1</sup>Polyscal Technology Research Center, Tokyo University of Science, Noda-shi, Chiba-ken, Japan; <sup>2</sup>Department of Materials Science and Technology, Tokyo University of Science, Noda-shi, Chiba-ken, Japan; <sup>3</sup>Department of Physics, Tokyo University of Science, Noda-shi, Chiba-ken, Japan.

The Nd<sub>2</sub>Fe<sub>14</sub>B magnet is an excellent permanent magnet with extraordinary high coercivity and remanence. However, one of the main drawbacks of its usage is the high production cost since the magnet contains a rare earth metal, i.e., neodymium, of about 12 atomic percent. Therefore, in view of the reduction of the cost, Nd-Fe-B nanocomposite magnets are very attractive because of its low neodymium content. Nanocomposite magnets composed of soft and hard magnetic phases on nano scale can yield a high performance with reduced neodymium content by virtue of exchange coupling effect between the soft and the hard phases. In the present study, we have prepared a number of bulk nanocomposite magnets of nominal compositions Nd<sub>4</sub>Fe<sub>77.5</sub>B<sub>18.5</sub>-xM<sub>x</sub> using the Spark Plasma Sintering method, which enables us to produce a sintered bulk from powder samples at low temperature in a short sintering time, and investigated the substitution effect of other elements such as Si, C, etc. in the phase constitution of the bulk nanocomposites. In the case of the Si substitution, we observed that the coercivity of the Nd-Fe-B nanocomposite magnet is slightly increased by the substitution of 1 at.%Si, i.e., 221 kA/m. On the other hand, the sample substituted with more than 5 at.%Si exhibits a soft magnetic behavior, which suggests that the further substitution of B reduces the content of Nd<sub>2</sub>Fe<sub>14</sub>B phase.

### 8:45 AM I11.3

**Bulk SmCo<sub>5</sub>/ $\alpha$ -Fe Nanocomposite Magnets Prepared by Warm Compaction of Mechanically Milled Powders.** Chuanbing Rong, Yiping Wang, Vikas Nandwana and J.Ping Liu; Department of Physics, University of Texas at Arlington, Arlington, Texas.

Nanocomposite permanent magnets consisting of hard and soft magnetic phases have potential energy product (BH)<sub>max</sub> higher than conventional single-phase hard magnets.[1,2] However, it is challenging to fabricate bulk nanocomposite materials for engineering applications without losing the



nanoscale morphology of the magnets. In this work, we prepared fully dense bulk SmCo<sub>5</sub>/α-Fe nanocomposite magnets by high pressure (up to 4GPa) at a moderate temperature (<600 C). The amorphous was obtained by mechanical milling of powder mixtures of SmCo<sub>5</sub>+x wt% α-Fe (x=0~30). The milled powders were then compacted under 2.5 GPa at different temperatures. It was found the full density can be obtained at 400 C and 600 C for the crystallized and amorphous powders, respectively. The higher compaction temperature requested for the amorphous may be due to the higher concentration of defects in the powders. It was very interesting to find the compaction led to a low degree texture in the compacts. By adjust the fraction of SmCo<sub>5</sub> and post-annealing parameters, (BH)<sub>max</sub> about 16 MGOe can be obtained for the bulk SmCo<sub>5</sub>/α-Fe nanocomposite magnets. [1].R. Skomski and J. M. D. Coey, Phys. Rev. B, 48, 15812 (1993).[2].C.B. Rong, H.W. Zhang, R.J. Chen, et al., J. Magn. Mater. 302, 126 (2006)

#### 9:00 AM I11.4

**Shock Densification of Micron- and Nano-sized SmCo<sub>5</sub> Powders.** Chengda Dai<sup>1</sup>, Christopher Wehrenberg<sup>1</sup>, Naresh Thadhani<sup>1</sup>, Chuanbing Rong<sup>2</sup> and Yanglong Hou<sup>3</sup>; <sup>1</sup>Materials Sci. & Eng., Georgia Tech, Atlanta, Georgia; <sup>2</sup>Physics, University of Texas at Arlington, Arlington, Texas; <sup>3</sup>Chemistry, Brown University, Providence, Rhode Island.

Samarium cobalt (SmCo<sub>5</sub>) magnets have an excellent combination of extremely high magnetic properties, outstanding thermal stability and good corrosion resistance. These characteristics make SmCo<sub>5</sub> the ideal material in applications such as servo-motors, pump couplings, and sensors, particularly where the magnet is required to operate at high temperatures, across a broad range, or in a corrosive environment. Forming bulk magnets from SmCo<sub>5</sub> magnetic powders is needed for device fabrication. In the present work, we have applied the shock compaction technique to fabricate SmCo<sub>5</sub> bulk compacts. Micron- and nano-sized SmCo<sub>5</sub> powders are shock densified using light-gas-gun- or explosive-driven flyer plate impact experiments. The shock densification behavior was described using shock compaction dynamics and post-shock compact characterization. Model calculations were employed to outline shock compaction dynamics based on the measured impact velocity, known Hugoniot of flyer-plate, and the evaluated Hugoniot of SmCo<sub>5</sub> powder compacts. Density measurements, Vickers microhardness test, XRD analyses, SEM inspections, and magnetic measurements were performed on post-shock compacts of SmCo<sub>5</sub> powders to probe their shock densification behavior and magnetic properties. Results of the different dynamic densification responses of micron- and nano-sized SmCo<sub>5</sub> powders will be presented. This work is supported by ONR/MURI under Grant No. N00014-05-1-0497.

#### 9:15 AM I11.5

**Melt-spinning as a Novel Processing Route for (Mn,Fe)<sub>2</sub>(P,Ge,Si) and La(Fe,Si)<sub>13</sub>.** Oliver Gutfleisch, Julia Lyubina and Ludwig Schultz; IFW Dresden, Institute of Metallic Materials, P.O. Box 270016, D-01171, Dresden, Germany.

The magnetocaloric effect was studied in (Mn,Fe)<sub>2</sub>(P,Ge,Si) and La(Fe,Si)<sub>13</sub> melt-spun ribbons (wheel speed 20-40 m/s and subsequent short time annealing for 1 h at 1000 °C). Thermal, structural and magnetic properties were investigated by PPMS (c<sub>p</sub>), SQUID, XRD and SEM. The dependence of Curie temperature, thermal and magnetic hysteresis, crystal lattice parameters and magnetic entropy changes on composition and interstitial modification are described. It is demonstrated that melt-spinning [1,2] is an efficient and very simple processing route for (Mn,Fe)<sub>2</sub>(P,Ge,Si) and La(Fe,Si)<sub>13</sub>-type materials. For example, As free Fe<sub>2</sub>P-type alloys [3], exhibiting large values of magnetic entropy change (|ΔS<sub>M</sub>|=45 J/kgK) with very small magnetic hysteresis near room temperature can be prepared. [1] O. Gutfleisch, J. Appl. Phys. 97 (2005) 10M305\_1-3. [2] A. Yan, et al., J. Appl. Phys. 99 (2006) 08K903\_1-4. [3] D.T. Cam Thanh et al., J. Appl. Phys. 99 (2006) 08Q107\_1-3.

#### 10:00 AM \*I11.6

**Two-phase Nanoclusters for High-energy Exchange-spring Permanent Magnets.** Jeffrey Shield<sup>1,3</sup>, Xiangxin Rui<sup>1,3</sup>, David J. Sellmyer<sup>2,3</sup> and Matthew J. Kramer<sup>4</sup>; <sup>1</sup>Mechanical Engineering, University of Nebraska, Lincoln, Nebraska; <sup>2</sup>Physics and Astronomy, University of Nebraska, Lincoln, Nebraska; <sup>3</sup>Nebraska Center for Materials and Nanoscience, University of Nebraska, Lincoln, Nebraska; <sup>4</sup>Ames Laboratory, Iowa State University, Ames, Iowa.

For the past fifteen years or so, nanocomposite permanent magnets have captured the imagination of magneticians. These materials take advantage of the high magnetization of the soft magnetic phase, the extreme magnetic hardness of the hard magnetic phase, and exchange-coupling that occurs at the nanoscale to produce remarkably improved magnetic properties compared to single-phase materials. Nanocomposite permanent magnets hold the promise as the Next Great Material for increasing the energy product of permanent magnets. However, in practice we have yet to achieve the remarkably high energy products predicted for these materials. Difficulties include an inability to uniformly achieve the sub-10 nm grain size necessary for strong exchange coupling, rapid decrease of magnetic properties as the soft magnetic phase fraction increases, and an unclear understanding of the magnetic reversal processes. Our group has concentrated recent efforts in these areas. With a better understanding of the magnetic reversal process, it is possible to better tailor the nanostructure to resist demagnetization. In particular, cluster-assembly using inert gas condensation is an ideal technique to construct "ideal" nanostructures with uniform nanostructures below 10 nm. By tailoring the composition of the initial clusters, two-phase Fe<sub>3</sub>Pt+FePt clusters can be developed. Since each of the phases are confined to individual clusters, the scale of the phases is typically on the order of 2-4 nm, well below the exchange length of ~twice the domain wall width. This fine scale of the soft phase enables virtually complete exchange coupling, as indicated by recoil curves. These finely structured clusters are imbedded in a non-magnetic matrix, making them largely de-coupled from one another so that reversal of each cluster is mostly independent. This has allowed extremely large soft magnetic phase fractions of greater than 0.5, nearly twice what is routinely achieved in nanocomposite permanent magnets, while maintaining a coercivity of 6.5 kOe. The resulting energy products are among the highest achieved for any isotropic system. Micromagnetic modeling results indicate that the experimentally achieved energy products are near the theoretical maximum for these Fe<sub>3</sub>Pt/FePt nanocomposite permanent magnets. This talk will summarize these findings, as well as discuss the future of nanocomposite permanent magnets and the renewed hope of the Next Great Material.

#### 10:30 AM I11.7

**Nanostructured Mn-Al-C Permanent Magnets.** Q. Zeng<sup>1</sup>, Ian Baker<sup>1</sup>, J. Hanna<sup>1</sup>, Z. C. Yan<sup>2</sup> and J. Grosek<sup>3</sup>; <sup>1</sup>Thayer School of Engineering, Dartmouth College, Hanover, New Hampshire; <sup>2</sup>Department of Physics and Astronomy, University of Delaware, Delaware, Delaware; <sup>3</sup>University of Utah, Salt Lake City, Utah.



Pre-alloyed Mn-Al and Mn-Al-C powders were mechanically milled under argon, and the as-milled powders subsequently annealed at temperatures from 350-600°C to produce the ferromagnetic metastable L1<sub>0</sub>-structured  $\tau$  phase. Some bulk specimens were annealed under the similar conditions for comparison. By comparing the bulk and milled alloys, it is shown that there is a strong influence of microstructural refinement on the kinetics of formation and subsequent decomposition of the magnetic  $\tau$  phase. Nano-grained  $\epsilon$  phase begins to transform to the metastable  $\tau$  phase at lower temperature than coarse-grained  $\epsilon$  phase, and the  $\tau$  phase formed by nano-sized  $\epsilon$  phase reveals a very low thermal stability. The best magnetic properties, of  $H_C = 4.8$  kOe and  $M_r = 45$  emu/g, were obtained for Mn<sub>54</sub>Al<sub>46</sub> powders annealed at 400°C for 600s. It was found that although the  $\tau$ -phase is stabilized by C doping, C doping couldn't prevent the formation of the equilibrium  $\gamma_2$  and  $\beta$  phases from the metastable  $\epsilon$  phase during annealing. Due to the nanostructure and C precipitates, a very high coercivity, up to 5.2 kOe, was obtained in Mn<sub>51</sub>Al<sub>46</sub>C<sub>3</sub> powders annealed at 500°C for 30 min. Decreasing the Mn content, disorder in the  $\tau$  phase grains, and C doping lead to a lower Curie temperature. Attempts at consolidating the powders, while retaining the excellent hard magnetic properties will be described. Research sponsored by NIST grant 60NANB2D0120.

#### 10:45 AM \*I11.8

**Magnetocaloric Refrigeration at Ambient Temperature.** Ekkes Bruck, University of Amsterdam, Amsterdam, Netherlands.

Modern society relies on readily available refrigeration. Magnetic refrigeration has three prominent advantages compared to compressor-based refrigeration. First there are no harmful gasses involved, second it may be built more compact as the working material is a solid and third magnetic refrigerators generate much less noise. Recently a new class of magnetic refrigerant-materials for room-temperature applications was discovered. These new materials have important advantages over existing magnetic coolants: They exhibit a large magnetocaloric effect (MCE) in conjunction with a magnetic phase-transition of first order. This MCE is, larger than that of Gd metal, which is used in the demonstration refrigerators built to explore the potential of this evolving technology. In the present paper we compare the different materials concentrating on transition metal containing compounds. As we expect that the limited availability of Rare-earth elements will hamper the industrial applicability. Because fundamental aspects of MCE are not so widely discussed we also give some theoretical considerations.

#### 11:15 AM I11.9

**The Effect of Processing Route and Fe Substitutions on the Microstructure of Gd<sub>5</sub>Si<sub>2</sub>Ge<sub>2</sub>.** Benjamin Podmiljsak, Paul John McGuinness and Spomenka Kobe; Department for nanostructured materials, Jozef Stefan Institute, Ljubljana, Slovenia.

Gd<sub>5</sub>Si<sub>2</sub>Ge<sub>2</sub> exhibits the so-called giant magnetocaloric effect, making it a potential material for next-generation near-room-temperature permanent-magnet-based refrigeration devices. In the as-cast form this material is relatively complicated in terms of its structure and its metallurgy. We found that small cast ingots exhibit an extremely unusual macrostructure that varies from a sinew-like surface structure at very fast cooling rates through to an almost Fullerene-like structure at slower cooling rates. These unusual formations are linked to the microstructural picture near the surfaces of the cast ingots. Recent reports have suggested that small additions of iron can substantially improve the problems associated with hysteresis losses, so enhancing the material's potential for real-world applications. We have looked at iron substitutions in the range X=0 to X=1 for Gd<sub>5</sub>Si<sub>2</sub>-XGe<sub>2</sub> to investigate the macrostructures and microstructures of cast and homogenized materials, with particular emphasis on the amount of iron substituting for silicon in the Gd<sub>5</sub>(SiGe)<sub>4</sub> phase and the effect of the substituting iron on the Ge/Si ratio. The larger iron substitutions were found to eliminate the unusual macrostructures, and conventional ingots with smooth surfaces were the result. The iron was also found to dissolve at levels of 1-3% in the Gd<sub>5</sub>(SiGe)<sub>4</sub> phase and encourage the formation of the Gd<sub>5</sub>(SiGe)<sub>3</sub> phase at the expense of the magnetocaloric Gd<sub>5</sub>(SiGe)<sub>4</sub> phase. A substitution of X=1 was found to be sufficient to produce as-cast microstructures consisting almost entirely of the Gd<sub>5</sub>(SiGe)<sub>3</sub> phase. Melt-spinning provides an excellent route for producing high-surface-area materials with a very homogenous distribution of phases, and in some cases single-phase materials. Using high-temperature boron-nitride crucibles and an inert-gas melt spinner we have produced ribbons in the range X=0 to X=0.25 for Gd<sub>5</sub>(SiXGe<sub>1-X</sub>)<sub>4</sub>. The material was melted at approximately 1800°C and rapidly cooled using wheel speeds of between 10 and 50 m/s. The ribbon thickness exhibited a characteristic exponential decrease in thickness with wheel speed, varying from about 120 microns down to approximately 40 microns. The ribbon lengths were observed to vary from a few millimeters to a few centimeters, with the longer ribbons being formed at the slower speeds. With a scanning electron microscope (Jeol 840A) and an analytical transmission electron microscope (Jeol 2010 F with a field-emission gun) and an EDXS system from Oxford Instruments (Link Isis 300) we performed a detailed microstructural investigation of the processed materials. Special emphasis was placed on the intergrain regions and an assessment of the amount of Fe substituting in the main magnetocaloric phase.

#### 11:30 AM \*I11.10

**The R<sub>5</sub>(Si,Ge)<sub>4</sub> Systems - A Gold Mine of Magnetic, Thermal and Structural Phenomena.** Karl A Gschneidner<sup>1,2</sup> and Vitalij K Pecharsky<sup>1,2</sup>; <sup>1</sup>Ames Laboratory, Iowa State University, Ames, Iowa; <sup>2</sup>Materials Science and Engineering, Iowa State University, Ames, Iowa.

The rare earth (R)-silicon-germanium 5:4 intermetallic compounds, R<sub>5</sub>(Si<sub>1-x</sub>Ge<sub>x</sub>)<sub>4</sub>, exhibit three closely related, unique, self-assembled, nanolayer structures. There is a large (~0.05 nm) shift in the a-direction of the layers with respect to their neighboring layers as the compounds transform from one structure to another when the temperature, magnetic field, pressure, and/or composition is varied. This large shift as the phases transform to one another leads to a giant magnetocaloric effect, a giant magnetoresistance, a colossal magnetostriction, and other interesting phenomena in many of the R<sub>5</sub>(Si,Ge)<sub>4</sub> phases. In some of these compounds the magnetic structures change simultaneously with the crystallographic change, i.e. via a coupled magnetostructural transformation. But most of the transformations at ambient pressure and field are uncoupled, sometimes just a few Kelvin and in others by as much as 200 K. The behaviors exhibited by the R<sub>5</sub>(Si,Ge)<sub>4</sub> phases for a given R are significantly different for each R, other than the expected magnetic ordering temperatures which, with one exception - trivalent Sm, vary with the de Gennes factor of the R element. The unique features for each of the R 5:4 series will be discussed. Recently, we showed, both theoretically and experimentally, that the magnetism and other unique behaviors are governed by Gd 5d - Ge 4p - Ge 4p - Gd 5d exchange interactions. Presumably this is also true for some of the other magnetic lanthanide 5:4 compounds.

SESSION I12: Magnetic Nanowires  
Chair: Shouheng Sun  
Thursday Afternoon, November 29, 2007  
Commowwealth (Sheraton)



**1:30 PM \*I12.1**

**One-Dimensional Magnetic Iron Oxide Nanostructures.** Jenny Ruth Morber, Yong Ding, Melanie Kirkham, Jung-Il Hong, Zhong Lin Wang and Robert Snyder; Materials Science and Engineering, Georgia Institute of Technology, Atlanta, Georgia.

We have previously reported successful synthesis of both Fe<sub>3</sub>O<sub>4</sub> and epsilon-Fe<sub>2</sub>O<sub>3</sub> nanowires and nanobelts through a pulsed laser deposition (PLD) synthesis technique, and presented initial magnetic properties results based on these structures. [1-3] Although our technique yielded dense, high quality nanowires, imperfect knowledge of ideal synthesis conditions specific to each phase prevented consistent production of uniform samples, making extraction of only epsilon-Fe<sub>2</sub>O<sub>3</sub> nanostructures difficult. While heat treatment was found to be useful for conversion of some samples, we sought to better understand the conditions necessary for phase formation so that nanowires could be more precisely engineered, both in synthesis and in our post-treatments. To overcome this obstacle we have employed environmental XRD characterization techniques to precisely determine phase-specific reaction parameters. Temperature, pressure, and oxygen concentrations are systematically varied, while scans are performed to test for presence of the desired phases. These insights should allow production of completely uniform iron oxide nanowire samples, tailored not only to morphology and location, but also to chemical and crystallographic composition. Additionally, further studies of these materials have produced interesting new insights into their magnetic properties. MFM experiments coupled with SQUID allow novel comparisons between the specific and averaged magnetic signatures in these structures, enabling a greater understanding of both distinct and coupled behaviors in our samples. [1] "PLD-Assisted VLS Growth of Aligned Ferrite Nanorods, Nanowires, and Nanobelts-Synthesis, and Properties", J.R. Morber, Y. Ding, M.S. Haluska, Y. Li, J.P. Liu, Z.L. Wang and R.L. Snyder *J. Phys. Chem. B*, 110 (2006) 21672-21679. [2] "Nanowire Structural Evolution from Fe<sub>3</sub>O<sub>4</sub> to epsilon-Fe<sub>2</sub>O<sub>3</sub>", Y. Ding, J.R. Morber, R.L. Snyder and Z.L. Wang, *Adv. Funct. Mater.*, 17 (2007) 1172-1178. [3] for more details: <http://www.nanoscience.gatech.edu/zlwang/>

**2:00 PM \*I12.2**

**The Magnetic Racetrack Memory: A Shift Register Memory based on Current Induced Precessional Motion of Domain Walls.** Stuart Parkin, IBM Almaden Research Center, San Jose, California.

The current induced motion of magnetic domain walls confined to nanostructures is of interest for applications in magnetoelectronic devices in which the domain wall serves as the logic gate or memory element. A proposal for a novel storage-class memory is described in which magnetic domains are used to store information in a "magnetic race-track" [1]. The magnetic race-track promises a solid state memory with storage capacities and cost rivaling that of magnetic disk drives but with much improved performance and reliability: a "hard disk on a chip". The magnetic race track is comprised of tall columns of magnetic material arranged perpendicularly to the surface of a silicon wafer. The domains are shifted up and down the race-track by nanosecond long pulses of spin polarized current using the phenomenon of spin momentum transfer. We discuss the current induced resonant excitation and motion of domain walls in permalloy nanowires [2,3]. The injection of spin polarized current below a threshold value through a domain wall confined to a pinning potential results in its precessional motion within the potential well [4]. We show that, by using a short train of current pulses, whose length and spacing are tuned to this precession frequency, the domain wall's oscillations can be resonantly amplified [5]. This makes possible the motion of domain walls with much reduced spin polarized currents, more than five times smaller than in the absence of resonant amplification. [1] S. S. P. Parkin, US Patent # 6,834,005, 6,898,132, 6,920,062, 7,031,178, and 7,236,386 (2004-2007). [2] M. Hayashi, L. Thomas, C. Rettner, R. Moriya, and S. S. P. Parkin, *Nat. Phys.* 3, 21 (2007). [3] M. Hayashi, L. Thomas, C. Rettner, R. Moriya, Y. B. Bazaliy, & S. S. P. Parkin, *Phys. Rev. Lett.* 98, 037204 (2007). [4] L. Thomas, M. Hayashi, X. Jiang, C. Rettner and S.S.P. Parkin, *Nature* 443, 197 (2006) [5] L. Thomas, M. Hayashi, X. Jiang, R. Moriya, C. Rettner, and S. Parkin, *Science* 315, 1553 (2007).

**2:30 PM I12.3**

**Synthesis and Magnetic Properties of In<sub>2-x</sub>Ni<sub>x</sub>O<sub>3</sub> Nanowires.** Kai Wang, Jiajun Chen and Weilie Zhou; Advanced Materials Research Institute, New Orleans, Louisiana.

One-dimensional oxide semiconducting nanostructures doped with transition-metal elements are believed to be ideal candidates for a high Curie temperature ferromagnetic semiconductor to realize semiconductor spintronics, especially at room temperature. Transitional metal doped indium oxide in the form of thin films behaves ferromagnetic at room temperature were reported. In this work, diluted magnetic semiconducting In<sub>2-x</sub>Ni<sub>x</sub>O<sub>3</sub> nanowires were successfully synthesized by catalyst-assisted carbon thermal decomposition method. Field emission scanning electron microscopy (FESEM) showed that most nanowires are about 70 nm in diameter and have a length of several tens micrometer. Transmission electron microscopy (TEM) equipped with energy dispersive x-ray spectroscopy (EDS) analysis confirmed that the synthesized nanowires were single-crystalline cubic structure and the dopants were homogeneously distributed in the lattice of indium oxide nanowires. X-ray diffraction spectroscopy was used to investigate the crystal structure. No second phase or other precipitates were detected. Ferromagnetism was observed in the In<sub>2-x</sub>Ni<sub>x</sub>O<sub>3</sub> nanowires by superconducting quantum interference device (SQUID) measurement, which demonstrates potentially useful building blocks for spintronics.

**2:45 PM I12.4**

**Synthesis of Pt-based Nanowires and Nanorods.** Yanglong Hou, Chao Wang, Jaemin Kim and Shouheng Sun; Department of Chemistry, Brown University, Providence, Rhode Island.

Controlled reduction of Pt(acac)<sub>2</sub> and decomposition of Fe(CO)<sub>5</sub>/Co<sub>2</sub>(CO)<sub>8</sub> in oleylamine and octadecene leads to a facile synthesis of FePt/CoPt nanowires and nanorods with diameters in 2-3 nm. The length of the nanowires/ nanorods is tunable from over 200 nm down to 20 nm by simply controlling the volume ratio of oleylamine and octadecene. These nanowires and nanorods are promising building blocks for fabrication of single particle recording media, high performance permanent nanocomposites and highly sensitive magneto-resistive devices.

SESSION I13: Magnetic Imaging  
Chair: Yimei Zhu  
Thursday Afternoon, November 29, 2007  
Commowwealth (Sheraton)



**3:30 PM \*I13.1**

**Magnetic Domain Dynamics in Nanocomposite Materials Revealed by Real-Time Images.** Robert D Shull, National Institute of Standards & Technology, Gaithersburg, Maryland.

As the size of a ferromagnet decreases to the nanometer-scale, the mechanism whereby it reverses its magnetization upon application of a reversed external magnetic field may change dramatically. This is especially true when in the form of a composite. In this morphology, the boundary magnetism between the dissimilar magnetic materials becomes most important in determining the bulk magnetic behavior. As the reversal behavior dictates the application of that material, the applications of nanoscale ferromagnets may be quite different from those originally intended for it as a conventional material. Conversely, quite new applications may be found possible for ferromagnets due to their nanoscale morphology. In a conventional material, the easiest way to reverse its magnetization when subjected to a reversed field is to nucleate domains with reversed magnetization that subsequently grow throughout the material at the expense of those domains oriented in opposing directions. In this presentation, pictures of these domain dynamics are shown (using the magneto-optic indicator film, MOIF, technique developed in our laboratory). Specifically, magnetic domain structure and its dynamics will be shown in a bilayer of an antiferromagnet (AF)-ferromagnet (FM) possessing unidirectional magnetic anisotropy and also in a bilayer of a "hard" ferromagnet (h-FM)-"soft" ferromagnet (s-FM) possessing exchange anisotropy as the material undergoes a reversal process. In the AF/FM composite, for the first time different domain nucleation sites are observed for the remagnetization processes in opposite directions during cycling the field as in the measurement of a magnetic hysteresis loop. For the h-FM/s-FM, definitive visual proof is given for the first time which proves reversal is accomplished primarily by spin rotation rather than by domain nucleation and growth. Lastly, in ultrathin films of Co and in ultrathin alternating Co/Pt layers, direction-dependent nucleation is discovered in a "normal" ferromagnet for the first time. These findings indicate the physics of magnetization reversal are not so well understood after all in nanoscale materials. This has important ramifications for magnetic sensors, recording devices, and transformer materials.

**4:00 PM I13.2**

**EMCD: A New Analytical Technique for Nanoscale Magnetism.** Stefano Rubino<sup>1</sup>, Michael Stoeger-Pollach<sup>2</sup>, Peter Schattschneider<sup>1,2</sup>, Cecile Hebert<sup>5</sup>, Florent Houdellier<sup>4</sup>, Christian Hurm<sup>3</sup> and Josef Zweck<sup>3</sup>; <sup>1</sup>Inst. of Solid State Physics, Vienna Univ. of Technology, Vienna, Austria; <sup>2</sup>Univ. Service Centre for TEM, Vienna Univ. of Technology, Vienna, Austria; <sup>3</sup>Fakultaet f. Physik, Univ. Regensburg, Regensburg, Germany; <sup>4</sup>Nanomateriaux, CEMES-CNRS, Toulouse, France; <sup>5</sup>SB-CIME Station 12, EPFL, Lausanne, Switzerland.

Within the CHIRALTEM project we have established and developed a new method to detect and measure Circular Dichroism (CD) in the Transmission Electron Microscope (TEM) with a spatial resolution of 10 nm. This novel technique has been named Energy loss Magnetic Chiral Dichroism (EMCD). It is the TEM counterpart of XMCD, a widely used synchrotron technique for the characterization of magnetic materials and the study of magnetism in general. The purpose of the CHIRALTEM project (to observe CD in the TEM) has been fully reached [1] and has moreover generated several experimental methods to measure EMCD [1,2], that have been already adopted by several TEM group worldwide. The particular attraction of EMCD rests in the possibility to detect atom specific magnetic moments in combination with spin and orbital sum rules and the realistic perspective to reach a resolution of 2 - 3 nm. A review of the most important results achieved so far in the improvement of this new investigation tool will be presented. The dependence of the EMCD on several experimental conditions (such as thickness, relative orientation of beam and sample, collection and convergence angle) is investigated in the transition metals Iron, Cobalt and Nickel. Different scattering geometries are illustrated; their advantages and disadvantages are detailed, together with current limitations and proposals for improvement. This research was supported by the European Commission, contract nr. 508971 (CHIRALTEM). 1. P. Schattschneider et al., Nature 441 (2006) pp. 486-488 2. P. Schattschneider, C. Hébert, S. Rubino, Encyclopedia of Materials: Science and Technology (edited by K.H.J. Buschow, R.W. Cahn, M.C. Flemings, P. Veysiere, E.J. Kramer and S. Mahajan), in print.

**4:15 PM I13.3**

**Abstract Withdrawn**

**4:30 PM \*I13.4**

**Magnetic Imaging and Reversal Mechanism of Patterned Ferromagnetic Elements.** Yimei Zhu<sup>1</sup>, Lei Huang<sup>1</sup>, June Lau<sup>2</sup>, Marvin Schofield<sup>1</sup> and Marco Beleggia<sup>1</sup>; <sup>1</sup>Brookhaven National Laboratory, Upton, New York, <sup>2</sup>NIST, Gaithersburg, Maryland.

Understanding of magnetization reversal dynamics and switching behavior in patterned ferromagnetic elements, or building blocks of magnetic storage media and spintronic devices are crucial to the advancement of materials science and the development of modern technology. Using dedicated electron microscopy instruments for high performance in-situ magnetization and magnetic imaging, including electron holography, we develop various structural characterization techniques to quantitatively measure local magnetization of model systems and to link magnetic structure to its properties. We study the reversal mechanism and hysteresis behavior of patterned array of rings, squares, ellipses, and tear-drop shaped elements of Permalloy and Co thin-films. By quantitative analysis of the local magnetization, we examine the shape and edge effect of individual elements and their coupling across non-magnetic film-layers. By comparing experimental observations with theoretical calculations based on LLG micromagnetic simulation we explain why a parent state of the elements, isolated or in an array environment, can result in different low-energy ground states, depending on the switching rate, and how the energy barrier to the vortex nucleation can be measured. Magnetoresistance measurement of spintronic device will also be discussed. The work at BNL is supported by the U.S. DOE, under contract No.DE-AC02-98CH10886.

SESSION I14: Poster Session  
Thursday Evening, November 29, 2007  
8:00 PM  
Exhibition Hall D (Hynes)

**I14.1**

**Octadecanethiol SAMs as Molecular Resistors for Electrodeposition of Cobalt.** Brigid Frances OBrien, Peter Searson and Kathleen Stebe; Department of Materials Science and Engineering, Johns Hopkins University, Baltimore, Maryland.

Patterned self-assembled monolayers (SAMs) formed by soft lithography provide spatial control over surface properties and allow surface processes



to be directed to occur at specific locations. The ability of patterned SAMs to function as molecular resists for electrodeposition offers unique possibilities for the fabrication of a range of materials and structures, but has not been widely explored. A unique aspect of this process is that deposition of high fidelity features can be achieved at heights up to several hundred nanometers without lateral growth. In this paper we report on the limits of ODT SAMs as molecular resists for the electrodeposition of magnetic materials such as cobalt. We demonstrate that patterned SAMs can be used as molecular resists for the deposition of cobalt with features with no lateral growth. We report on the influence of metal ion concentration, potential, and time on the deposition process, and identify the regimes where it is possible to achieve high fidelity features without breakdown of the SAM - where breakdown is associated with the formation of Co islands in the ODT-modified regions. We extend our study of deposition kinetics to the creation of features at the nanoscale and examine their magnetic properties. These results demonstrate that SAMs can be used as molecular resists for deposition of transition metals and other elements, including alloys, with equilibrium potentials more negative than the noble metals. More importantly, this technique provides a low cost, high throughput approach for producing patterned magnetic materials and ordered arrays of catalysts.

#### I14.2

**Exchange Coupled Double Layer Films for Blue Laser CAD-MSR Magneto-optical Storage.** Xianying Wang<sup>1,2</sup>, Junhe Yang<sup>2</sup> and Yinmin Wang<sup>1</sup>; <sup>1</sup>Chemistry, Materials and Life Science Directorate, Lawrence Livermore National Laboratory, Livermore, California; <sup>2</sup>Department of materials engineering, Shanghai Institute of Technology, Shanghai, China.

Center aperture detection magnetically induced superresolution (CAD-MSR) magneto-optical (MO) storage using blue lasers is a kind of high density MO storage method, which combines the advantages of the short wavelength recording and superresolution readout techniques. But up to now, there were few reports on the mediums for this kind of storage. In this paper, we proposed exchange coupled double layer (ECDL) films for blue laser CAD-MSR MO recording. In-plane magnetized NdGdFeCo film was used as the readout layer, and the perpendicular magnetized TbFeCo film was used as the recording layer. NdGdFeCo film has large Kerr rotation under blue wavelength, so it is good for short wavelength recording. Also, because of the Gaussian distribution of the laser intensity and the temperature induced changing of the exchange coupling effect between the two films, the superresolution readout effect can be realized. Therefore, the NdGdFeCo/TbFeCo ECDL films could be a good choice for the blue laser CAD-MSR MO recording. To make the ECDL films satisfy the short wavelength recording and the CAD-MSR storage simultaneously, careful design of the compositions of the two films was needed. We first investigated the wavelength dependence of the Kerr rotation of the NdGdFeCo films under different compositions. Then the temperature dependences of the magnetization of the NdGdFeCo and TbFeCo films were measured using VSM. By choosing proper film composition and preparation conditions, we prepared the NdGdFeCo/TbFeCo double layers and measured the magneto-optical properties using a focused-laser Kerr loop measuring system with the laser irradiating from the NdGdFeCo film side. We finally found that at low laser power the Kerr loop was almost a line, while when the laser power was higher than a certain value, the Kerr loop turned to be rectangular. This proved that the magnetization orientation of the readout layer changed from in-plane to out-of-plane with the temperature rise, which meant that this medium structure could realize MSR effect. The experimental results were also proved by theoretical calculation. The magnetization orientation profiles in the NdGdFeCo/TbFeCo films under different temperatures were calculated. The results also exhibited the reorientation of the readout layer. The theoretical and the experimental results agreed well. In conclusion, we proved that the NdGdFeCo/TbFeCo ECDL films were suitable for the blue laser CAD-MSR MO recording. The results of this paper could also give some references to other ECDL systems such as Pt(Fe)Co/TbFeCo etc. used in various areas.

#### I14.3

**Effect of Ag Content on Magnetic Properties of (FePt)-Ag Sputtered Thin Films.** Paola Tiberto<sup>1</sup>, Federica Celegato<sup>1</sup>, Marco Coisson<sup>1</sup>, Vinai Franco<sup>1</sup>, Franca Albertini<sup>2</sup>, Francesca Casoli<sup>2</sup>, Simone Fabbri<sup>2</sup> and Paolo Allia<sup>3</sup>; <sup>1</sup>INRIM, Torino, Italy; <sup>2</sup>IMEM-CNR, Parma, Italy; <sup>3</sup>Physics, Politecnico di Torino, Torino, Italy.

Ordered FePt and CoPt thin films deserve particular attention owing to their very large magnetocrystalline anisotropy, which makes them attractive in high-density magnetic recording [1]. FePt systems with enhanced perpendicular magnetic anisotropy have been produced by several production techniques (such as molecular beam epitaxy, or sputtering on heated single-crystal MgO substrates). Recently it has been observed that the addition of an immiscible element such Ag promotes the formation of a granular FePt phase displaying a significant magneto-resistance effect [2]. Selected  $(\text{Fe}_{53}\text{Pt}_{47})_{100-x}\text{-Ag}_x$  multilayers ( $x = 0, 41, 54, 59, 70$  at %) have been prepared by rf sputtering on a MgO (100) substrate. The films were submitted to in situ post-annealing at 550 °C for 5100 s to possibly induce a uniaxial perpendicular anisotropy, as in Fe-Pt(001) films. AFM/MFM imaging was exploited to study the topography and the magnetic structure of the samples. X-ray diffraction patterns have been obtained for all samples. Room-temperature magnetization measurements were performed by an AGFM under a maximum field of 20 kOe. Magnetoresistance (MR) measurements at 300 K were done by the 4-contacts technique. Room-temperature hysteresis loops indicate that a variety of magnetic phases characterised by very different values of the perpendicular anisotropy constant have been obtained by varying the Ag content. All multilayers containing Ag display a negative magnetoresistance effect at room temperature. On the contrary, no significant MR signal has been measured on the material with  $x = 0$ . The effect of Ag addition on the morphological and magnetic properties of the starting  $\text{Fe}_{53}\text{Pt}_{47}$  system has been clarified by combining magnetization and magnetoresistance measurements with AFM/MFM images. In particular, the present study indicates that Ag addition is increasingly detrimental to the development of the phase with large perpendicular anisotropy. [1] S. Khizroev and D. Litvinov "Perpendicular magnetic recording" p.128, Kluwer Academic Publishers, Boston (2004) [2] Z. Zhang, K. Kang, N. Omoto, T. Suzuki, IEEE Trans. On Magn. (2003) 2827

#### I14.4

**AC Magnetic Field Heating of Magnetic Nanoparticles in Aqueous Dispersion.** Dong-Hyun Kim, Christopher S. Brazel, Duane T. Johnson and David Eugene Nikles; Center for Materials for Information Technology, The University of Alabama, Tuscaloosa, Alabama.

Our interest in designing new magnetic particles for treatment of cancer by hyperthermia therapy has lead us to prepare aqueous dispersions of cobalt ferrite nanoparticles from cobalt(II) acetylacetonate and iron(III) acetylacetonate. The particles were single crystal with an average diameter of  $5.6 \pm 0.7$  nm. The particles were dispersed in water using 11-mercaptopundecanoic acid. The dispersions were heated with ac magnetic fields with a frequencies varying from 195 to 266 kHz and field amplitudes varying from 127 to 700 Oe. An IR camera was used to monitor the temperature of the dispersions and temperature rise of up to 43 degrees Celcius were observed over a time scale of 10 minutes.



**I14.5**

**Ferromagnetic Ge<sub>1-x</sub>M<sub>x</sub> (M = Mn, Co, and Fe) Nanowires.** Yong Jae Cho, Wang Su Lee, Chang Hyun Kim, Seong Hoon Park and Jeunghee Park; Korea University, Jochiwon, South Korea.

Diluted magnetic semiconductors have attracted considerable research activities because of their great potential as key materials for spintronic devices. The demonstration of unique phenomena such as field-effect control of ferromagnetism, efficient spin injection to produce circularly polarized light, and spin-dependent resonant tunneling, opens a rich and various landscape for technological innovation in magnetoelectronics. Using the theory based on bound magnetic polaron model, Curie temperatures have been calculated for various 5% Mn-doped p-type semiconductors. There have been recent reports on the room-temperature ferromagnetism of Mn-doped Ge nanocolumns and nanowires. In order to understand the magnetic properties, it is essential to elucidate the electronic structures which are responsible for their magnetic properties. However, the electronic structures of Ge nanowires are far from being well scrutinized. In the present work, we synthesized exclusively high-purity Mn (or Co, Fe)-doped GaN nanowires, exhibiting room-temperature ferromagnetism, with controlled doping concentration using vapor transport method. The change of the electronic structures caused by the doping was thoroughly investigated by synchrotron X-ray photoelectron spectroscopy, X-ray absorption spectroscopy, and X-ray magnetic circular dichroism. We attempted to correlate the ferromagnetic properties of these nanowires with their well-defined electronic structures. Importantly, we investigated the magnetotransport properties of a single Mn-doped Ge nanowire, and found that it had a large positive magnetoresistance.

**I14.6**

**Correlation of Magnetic Nanoparticles in Fe-Co-Ni-Al-Cu Alloys.** Elvira Ibragimova and Makhmud Kalanov; Radiation solid state physics, Institute of Nuclear Physics Academy of Sciences, Tashkent, Uzbekistan.

Highly coercive dispersion solidified alloys on the base of Fe-Co-Ni-Al-Cu system consist of particles of the strong magnetic phase appearing as a result of the special thermal annealing and oriented along an external magnetic field (H) direction in non-magnetic matrix. Electron microscopic study of the sample surface shows that the particles have a rod-like shape. The neutron diffraction technique allows one to reveal the existence of the strong magnetic nanoparticles in the bulk of weakly magnetic alloy matrix and the correlation character between them that is impossible to obtain by other methods. This work presents results of neutron diffraction study with a double-crystal spectrometer (0.145 nm). Plate like samples of size 18x12x4 mm<sup>3</sup> were cut from a single crystal of alloy UNDK35 T5 along (100) plane. A sample was fixed between the electromagnet poles normally to the neutron beam and demagnetized. At H=0 there occur random variations of the background and a weak diffusion scattering at the angle of 12 minutes, which is indicative of the correlation between magnetization directions of neighboring nanoparticles of ferromagnetic type. The diameter of the ferromagnetic nanoparticles determined from the form-factor dependence of reflection intensities came to 16 nm. The coherent scattering region size was 120-160 nm. The dependence of peak intensity on the demagnetized sample orientation has shown that the scattering is around the direction [100] corresponding to the nanorod axis. At H= 6 kOe applied along the nanorod axis two intensive reflections (10) and (20) appear at the scattering angles of 12 and 24 minutes, and when it is parallel to the scattering vector the reflections disappear. It is evident of weakness of the nuclear scattering relative to the magnetic one, and the observed maxima (10) and (20) belong to the two-dimensional magnetic lattice formed by the magnetic nanoparticles, the parameter of which was 40.6 nm. Thus, the magnetic inclusions created in Fe-Co-Ni-Al-Cu systems under the thermal magnetic treatment by means of disintegration of the solid solution are strong ferro-magnetic and one-domain. The magnetic interaction of them is effective within 3-4 periods of the cell. The work was done under the national contract PFI-FA-F7-F068.

**I14.7**

**Synthesis, Structure and Identification of Self Assembled NiCa Ferrite-Polyaniline Hybrid Nanocomposites.** G.Ramachandra Reddy<sup>1</sup>, Arun S Prasad<sup>2,1</sup> and Padmanabhan Predeep<sup>1</sup>; <sup>1</sup>Molecular Electronics and Advanced Materials Laboratory, National Institute of Technology, Calicut, Kerala, India; <sup>2</sup>Centre for Advance Scientific Research and Education, Kollam, Kerala, India; <sup>3</sup>Molecular Electronics and Advanced Materials Laboratory, National Institute of Technology, Calicut, Kerala, India.

The pre characterized spinel Ni<sub>x</sub>Ca<sub>1-x</sub>Fe<sub>2</sub>O<sub>4</sub>(Nickel-Calcium Ferrite) in their nano size was used as magnetic core for the synthesis of self assembled novel materials, where the doped polyaniline (PANI) makes a fine coating around the core. For the synthesis, chemical oxidative polymerization of aniline in an aqueous medium which contains well dispersed ferrite particles was used. Ammonium peroxy disulphate (APS) was used as oxidant for initiating the polymerization reaction. The influence of ferrite content with respect to the composite structures was investigated through X-ray diffraction techniques and FTIR measurements. The DC electrical conductivity measurements were performed at room temperature for nanocomposites of all proportions in order to investigate the electrically conducting behavior and hence the electromagnetic wave absorption nature of the nanocomposite.

**I14.8**

**Magnetic Properties of Co Nanoelement Assemblies from Solid-state Dewetting onto Smooth and Patterned SiO<sub>2</sub> Substrates.** Yong-Jun Oh<sup>1,2</sup>, Caroline A Ross<sup>2</sup>, YeonSik Jung<sup>2</sup>, Yang Wang<sup>2</sup> and Carl V Thompson<sup>2</sup>; <sup>1</sup>Advanced Materials Sci. & Eng., Hanbat University, Daejeon, South Korea; <sup>2</sup>Materials Science and Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts.

Magnetic metal nanoparticle arrays have recently attracted considerable interest due to their application as in patterned magnetic recording media assembles, as well as catalyst arrays for the growth of carbon nanotubes. We have made Co nanoparticles on smooth and topographically patterned SiO<sub>2</sub> substrates through a solid-state dewetting process. The effect of annealing temperature, film thickness and topographical substrate geometries on the dewetted morphology and resultant magnetic properties will be presented. Templates consisting of square arrays of inverted pyramidal pits in Si wafer with ~200nm periods were used. These structures were fabricated using interference lithography, by undertaken two perpendicular exposures to get a square array of holes in the top negative resist layer. The pit-to-mesa width ratios of the fabricated templates were in the range of 1.5 to 8.0. Thermal oxide was grown on all Si substrates to prevent reactions between the substrate and the deposited Co film. Co films with thicknesses between 3 to 20nm were deposited onto both smooth and patterned templates using ion beam sputtering and annealed at temperatures between 650 to 900°C in forming gas. The best conditions for uniform nanoparticles were obtained above 800°C. At lower annealing temperatures, the particles exhibited characteristic bi-modal size distribution of small and coarse particles. Dewetting of polycrystalline films is known to initiate at grain boundary triple junctions in order to minimize the interface energy. If the annealing temperature is not sufficient to induce Co diffusion, the contribution of interfacial energy on the dewetting process would be greater and some limited junctions with relatively high energy would seed the particles. This will lead the formation of coarse particles besides small particles. In cases the inverted pyramid templates, the construction of



nanoparticle arrays was strongly affected by the relative Co film thickness and topographical geometries of templates. Magnetic properties of the arrays were measured using a vibrating sample magnetometer (VSM) and the results discussed based on the crystallographic orientation of Co particles analyzed using x-ray pole figures and electron back-scatter diffraction (EBSD) of each particle. In conclusion, the dewetting method onto patterned substrate has the potential to create well-ordered arrays of magnetic nanoparticles suitable for patterned media and other applications.

#### I14.9

**Magnetoresistance Studies of Zn(Cu,Al)O/ZnO Based Hetrostructures for Spintronics Applications.** Deepayan Chakraborti<sup>1</sup>, John T Prater<sup>2,1</sup> and Jagdish Narayan<sup>1</sup>; <sup>1</sup>Materials Science and Engineering, North Carolina State University, Raleigh, North Carolina; <sup>2</sup>Materials Science Division, Army Research Office, Research Triangle Park, North Carolina.

ZnO based Dilute magnetic semiconductors have been found to be a promising materials system for spintronics application by displaying room temperature ferromagnetism. For the successful fabrication of a spin-based device like Spin-LEDs, Spin-transistors, etc, we would require efficient injection of spin-polarized electrons into a semiconductor. The use of conventional ferromagnetic contacts like Fe, Ni, etc to inject spin polarized currents into semiconductors has yielded very low efficiency owing to scattering of carriers at the metal-semiconductor interface. Therefore the need was felt to incorporate room temperature ferromagnetic properties in conventional semiconductors which was achieved by doping them with small quantities of magnetic elements (transition metals). Even though room temperature ferromagnetism has been achieved in transition metal doped ZnO, the aim of fabricating spin based devices which can function at room temperature is still far from being realized. This arises from a lack of understanding of the correlation between free carrier and spin. A detailed magnetoresistance (MR) study in conjunction with magnetic properties is warranted for better understanding the injection of spin polarized carrier into semiconductors. Here we have grown a spin-valve type device structure by sandwiching a non-magnetic ZnO spacer layer (of varying thickness) between 2 layers of Cu and Al co-doped ZnO which are ferromagnetic. The layered structure has been grown epitaxially on (0001)  $\alpha$ -Al<sub>2</sub>O<sub>3</sub> by pulsed laser deposition technique. Zn(Cu,Al)O has been chosen as the ferromagnetic layer because it has not only shown good ferromagnetic and electrical properties, but also because these properties can be tuned independent of one another<sup>1,2</sup>. When the applied magnetic field (H) is perpendicular to current (I), we find negative MR for field up to 7 Tesla and temperature upto 100 K, but the MR effect diminishes considerably as the temperature is increased to room temperature. An interesting feature was observed when the magnetic field was applied parallel to current direction. The MR effect was no longer symmetric when the magnetic field was reversed. With an increase in temperature the MR curve became more and more non-symmetric. At room temperature the device structures showed such a strong asymmetry that the MR was negative when the applied magnetic field was negative and positive when the field was positive. With increase in thickness of the intermediate non-magnetic layer the MR decreased with H  $\perp$  I and became more asymmetric when H  $\parallel$  I. The asymmetry in MR, when H  $\parallel$  I, indicates that the spins do not reverse on reversing the field. Such an effect can be very useful in a number of spin based devices like Spin-valves, diodes, transistors, etc. <sup>1</sup> D. Chakraborti, J.T. Prater, and J. Narayan, 2007 TMS Annual Meeting, Orlando, FL <sup>2</sup> D. Chakraborti, J.T. Prater, and J. Narayan, 2007 MRS Spring Meeting, San Francisco, CA (Presentation no. K3.2)

#### I14.10

**Epitaxial Growth of Ordering Fe<sub>3</sub>Si Thin Films on Si with MgO Buffer Layer.** Kensuke Akiyama, Satoru Kaneko, Teiko Kadowaki and Yasuo Hirabayashi; Kanawaga Industrial Technology Center, Ebina, Kanagawa, Japan.

The performance of LSIs is required to be further improved to realize advanced information systems. Downsizing field-effect transistors is common approach to achieve high-speed operation with low power consumption. However, such conventional approach reaches to physical limits. Therefore, a new approach for advanced devices is strongly required. A spin transistor is a promising candidate. The integration of magnetism into semiconductor has been attracting much attention. Spin-polarized carrier injection from a ferromagnetic source into a semiconductor, or from ferromagnetic-insulator-semiconductor (MIS) structure is one of the hot topics in this field. The ferromagnetic silicide (Fe<sub>3</sub>Si) is attractive for Si-based spin transistor applications, because the Fe<sub>3</sub>Si ordering phase (DO<sub>3</sub>-type Fe<sub>3</sub>Si) is spinpolarized at the Fermi level, i.e., half-metallic alloy.

In this study, we succeeded in the epitaxial growth of Fe<sub>3</sub>Si thin film on the (100) Si with MgO or MgAl<sub>2</sub>O<sub>4</sub> buffer layer by rf magnetron sputtering method. We also measured the degree of ordering structure of this epitaxial Fe<sub>3</sub>Si film by electrical and magnetic properties that depend on geometry of atom arrangement.

20-nm-thick epitaxial MgO and MgAl<sub>2</sub>O<sub>4</sub> buffer layers were prepared on (100) Si by rf magnetron sputtering method using metal target. (100)-oriented epitaxial Fe<sub>3</sub>Si thin films were epitaxially grown on (100) Si substrates with the buffer layers in argon atmosphere at 1023K, while  $\beta$ -FeSi<sub>2</sub> phase forms on Si substrates without these buffer layers. It is apparent that these buffer layers prevent the reaction between the films and Si substrate, and Si-diffusion from substrate.

The electrical resistivity of these epitaxial Fe<sub>3</sub>Si thin films was about 3-8  $\mu\Omega$ cm at 20K. The residual electrical resistivity of Fe<sub>3</sub>Si depends on the degree of long-range ordering in the crystal. The resistivity decreases with degree of ordering increasing, and inhibits several  $\mu\Omega$ cm in the case of DO<sub>3</sub>-type Fe<sub>3</sub>Si. Thus, it is considered that these epitaxial Fe<sub>3</sub>Si thin films are constituted with DO<sub>3</sub>-type Fe<sub>3</sub>Si.

#### I14.11

**Mn Diffusion in GaAs: The Effect of Different Growth Techniques.** Otso Koskela<sup>1</sup>, Petteri Pusa<sup>2</sup>, Filip Tuomisto<sup>3</sup>, Janusz Sadowski<sup>4</sup> and Jyrki Raisanen<sup>1</sup>; <sup>1</sup>University of Helsinki, Helsinki, Finland; <sup>2</sup>University of Liverpool, Liverpool, United Kingdom; <sup>3</sup>Helsinki University of Technology, Espoo, Finland; <sup>4</sup>University of Regensburg, Regensburg, Germany.

Manganese is of significant interest when considering the possibility of deploying magnetic impurities in gallium-arsenide. Magnetic impurities provide the possibility of employing both electronic and magnetic properties of doped semiconductors aiming towards spintronics applications. We have studied the diffusion of Mn in GaAs grown by low temperature molecular beam epitaxy (LT-MBE) with varied growth conditions and liquid encapsulated Czochralski (LEC). The Mn diffusion study was carried out by employing the modified radiotracer technique; <sup>52,54</sup>Mn tracers were implanted in the GaAs samples at CERN/ISOLDE and the Mn concentration profiles were determined by low energy ion sputtering. Diffusion properties were determined in the different sets of GaAs samples with varying concentrations of As antisites and Ga vacancies in the temperature range from 700 to 850 °C. For all materials, two distinct diffusion mechanisms, fast and slow, were observed. The slow component is evidently concentration dependent and fast component is assumed to diffuse via interstitials. For the fast diffusion component Arrhenius plots are provided and discussed. The noted diffusion was fastest for semi-insulating GaAs grown by liquid encapsulated Czochralski (LEC).



**I14.12**

**Large Tunnel Magnetoresistance in Co-evaporated C60-Co Thin Films.** Seiji Sakai<sup>1</sup>, Isamu Sugai<sup>1,2</sup>, Seiji Mitani<sup>2</sup>, Yoshihiro Matsumoto<sup>1</sup>, Koki Takanashi<sup>2,1</sup>, Hiroshi Naramoto<sup>1</sup>, Pavel V. Avramov<sup>1</sup>, Satoru Okayasu<sup>1</sup> and Yoshihito Maeda<sup>3,1</sup>; <sup>1</sup>Advanced Science Research Center, Japan Atomic Energy Agency, Tokai-mura, Naka-gun, Ibaraki, Japan; <sup>2</sup>Institute for Materials Research, Tohoku University, Sendai, Miyagi, Japan; <sup>3</sup>Department of Energy Science and Technology, Kyoto University, Kyoto, Japan.

Recently, organic molecule-based systems have attracted much attention as a potential candidate for spintronics applications. The reported magnetoresistance (MR) for the organic molecule-based systems, however, was as small as a few - few 10's %, on the contrary to the anomalously high or complete spin-polarization predicted by the quantum chemical calculations. In 2006, we have found that the alternatively deposited fullerene (C60)-cobalt(Co) thin film exhibits a significant MR effect whose magnitude changes with the applied bias voltage and attains 80% (S. Sakai et al., Appl. Phys. Lett. 89, 113118 (2006) S. Sakai et al., Mater. Trans. 48, 754 (2007)). In the present study, the bias-voltage dependences of the magnetotransport properties were investigated for the co-deposited C60-Co films with a nano-granular structure. The C60-Co films were deposited on MgO(001) substrates by evaporating Co (99.99% purity) and C60 (99.99% purity, sublimed) simultaneously. The Co content, x (x: the number of Co atoms per a C60 molecule; C60Cox) and the film thickness were adjusted to x = 8-17 and 50 nm, respectively. The measurements of electrical and magnetotransport properties were performed in a two-terminal geometry with silver electrodes (gap length of 0.03-0.25 mm). The C60-Co films are revealed to have a nano-granular structure composed of a matrix of the C60-Co compound (C60Co5) and the embedding Co nanoparticles (average particle size ~1-2 nm, interparticle distance ~2-3 nm) from the Raman spectroscopic features and the superparamagnetic behaviors represented by the blocking temperatures of 10-20 K. The electrical resistivity near zero bias exhibited a characteristic temperature dependence to the tunnel conduction in granular systems. It is found that the MR behaves a bimodal dependence on the voltage-drop (V(drop)) between Co nanoparticles. MR shows significant decrease and increase with V(drop)-increase in the low and high-bias regions which are separated by a certain V(drop) in the range of a few-10mV. The MR change through these regions is as large as twice. The maximum MR observed in the respective regions are 80% (at near zero bias in the low-bias region) and 90% (at the highest bias in the high-bias region) in the temperature range lower than 10 K. The MR effect observed for the C60-Co films is, as far as we know, the largest one in granular systems, and is significant larger than MR of 50% expected for the sequential tunneling in granular systems assuming complete spin-polarization (P = 1). The bias-dependent MR change is suggested to be associated with the charging effect of Co nanoparticles. The anomalously large MR near zero bias is possibly due to some enhancement effect of the C60-Co compound, in addition to the high spin-polarization at the Co nanoparticle/C60-Co compound interface.

**I14.13**

**Magnetism and Recoilless Fraction of Cerium-Doped Hematite Nanoparticles System.** Monica Sorescu<sup>1</sup> and Lucian Diamandescu<sup>2</sup>; <sup>1</sup>Physics, Duquesne University, Pittsburgh, Pennsylvania; <sup>2</sup>Materials Science, National Institute of Materials Physics, Bucharest, Romania.

Cerium-doped hematite particles of the type  $x\text{CeO}_2-(1-x)\alpha\text{-Fe}_2\text{O}_3$  ( $x=0-1$ ) were obtained using mechanochemical activation and characterized by X-ray diffraction (XRD) and Mossbauer spectroscopy. XRD patterns yielded the dependence of lattice parameters and particle size as a function of ball milling time for each value of the molar concentration x. The particle dimension reached the value of 9 nm after 16 hours of ball milling. For  $x=0.1$ , the Mossbauer spectra were fitted with one or alternatively, two sextets, corresponding to Zr ions substituting Fe ions in the hematite structure. For  $x=0.5$ , Mossbauer spectra fitting required the addition of a quadrupole-split doublet, representing Fe substituting Zr in the ZrO<sub>2</sub> lattice. This transition can be in principle evidenced by recording the recoilless fraction (f) as a function of the ball milling time, provided there is a precise enough method to do so. We applied the dual absorber method developed by us for the precise determination of the recoilless fraction using a second absorber (for instance, a stainless steel foil) and a single room temperature Mossbauer spectroscopy measurement. Indeed, we observed the occurrence of a minimum in the values of the recoilless fraction for t=4 hours of milling, followed by a further decrease of the f factor due to appearance of nanoparticles in the system. Finally, a set of experiments was carried out in order to identify the main features of the process if the system were synthesized by magnetomechanical activation (magnetic ball milling). Because the magnetic field applied tends to separate the hematite (which is magnetic) from ceria (nonmagnetic), we obtained only the first step of the reaction for 16 hours of magnetic ball milling. It took about 200 hours to generate a phase structure similar to the one obtained by conventional ball milling. These results indicate that magnetic ball milling is an excellent tool to synthesize dilute magnetic systems. The system synthesized herewith is expected to be of great importance in catalytic and sensing applications.

**I14.14**

**Magnetic Properties of Cobalt Nanoclusters.** Margarita Rivera<sup>1</sup>, Clara Hilda Rios-Reyes<sup>1,2</sup> and Luis Humberto Mendoza-Huizar<sup>3</sup>; <sup>1</sup>Materia Condensada, Instituto de Física, UNAM, Mexico DF, Mexico; <sup>2</sup>Departamento de Materiales, Universidad Autónoma Metropolitana-Azcapotzalco, Mexico DF, Mexico; <sup>3</sup>Centro de Investigaciones Químicas, Universidad Autónoma del Estado de Hidalgo, Pachuca, Hgo., Mexico.

In this work, the morphological and magnetic properties of cobalt nanoclusters electrodeposited from ammonium and sulphate solutions onto highly oriented pyrolytic graphite electrodes were investigated. At -900 mV reduction potential, the magnetic properties of the clusters were found to strongly depend on the electrolyte solution as well as in the final size and shape of the aggregates as seen by AFM. By using MFM, mono and multidomain magnetic states were clearly observed. From the MFM images, the critical size of monomagnetic domains was measured and it agreed with a theoretical single domain model. The experimental width of a magnetic domain wall also agreed with theoretical calculations.

**I14.15**

**Development of Mesoporous Silica Thin Films as Templates for Magnetic Nanowire Networks.** Martin Gerard Bakker<sup>1,2</sup>, Christopher Thomason<sup>1</sup>, Jason Manning<sup>1,2</sup> and Roger Campbell<sup>2</sup>; <sup>1</sup>Center for Materials for Information Technology, The University of Alabama, Tuscaloosa, Alabama; <sup>2</sup>Department of Chemistry, The University of Alabama, Tuscaloosa, Alabama.

Mesoporous silica thin films are a promising matrix for formation of magnetic nanowires and nano-networks. We have developed methods for forming thin (300 nm) thick films of mesoporous silica on metal substrates. We have formed thin films containing regular arrays of spheres or cylinders using block copolymer templates. Under appropriate conditions the cylinders have a strong orientational preference parallel to the substrate surface. Treatment with solvent removes the block copolymer, generating a porous substrate. Due to the presence of micropores in the



silica walls, both sphere and cylinder containing phases are sufficiently bicontinuous to allow metal to be grown into the mesoporous silica films by electrodeposition. Prolonged electrodeposition leads to growth of metal on the top surface of the mesoporous silica film. The growth of metal through the micropores in the silica walls will produce constrictions in the metal networks with diameters of 1 nm or less. Such systems are therefore of potential interest for resistance and magnetoresistance studies. However, the complex nature and small thickness of the thin films, poses significant experimental challenges. We will report on progress being made in developing an appropriate device structure for making these measurements.

#### I14.16

**Atomic-Scale Segregation and Fluctuations in Chemical Ordering FePt Thin Films.** Karen L Torres and Gregory B Thompson; Metallurgical & Materials Engineering, University of Alabama, Tuscaloosa, Alabama.

The thermal stability of very small magnetic crystals or grains can be improved if the material has a large  $K_u$  value. The L10 phase of FePt has been identified as a candidate for next-generation media because of its high  $K_u$ . However, when this intermetallic is sputter-deposited as a polycrystalline thin film, a metastable solid solution face-centered-cubic phase (A1) is formed. By annealing at temperatures in excess of 500°C, the crystalline lattice atomistically orders into the desired hard magnetic L10 phase. Unfortunately, this annealing step results in grain growth destroying the narrow nano-granular size distribution needed for small, uniform bits. Moreover, grain coarsening has been observed to correlate with a higher degree of atomistic ordering. We have performed a series of atom probe and transmission electron microscopy studies to investigate how minute compositional fluctuations in FePt contribute and evolve in the A1 to L10 phase transformation and grain coarsening. A series of  $\text{Fe}_x\text{Pt}_{1-x}$  (where  $x$  varies from 40 to 60 at. %) were sputter-deposited onto a Si substrate. The atom probe specimens were analyzed in an Imago Local Electrode Atom Probe (LEAP). The atom probe reconstruction showed small levels of Pt segregation and clustering at grain boundaries in the as-deposited films. These results provide experimental verification of modeling predictions that atomic Pt will segregate to free surfaces in FePt to lower the total free energy of the system. Upon annealing, and depending upon the Pt concentration levels, the Pt segregation and local clustering was enhanced, even for chemically ordered films. The effect of different times, temperatures and compositions on the segregation, ordering and grain morphology will be addressed.

#### I14.17

**Magnetization and Magnetotransport Properties of Thermally Evaporated Co-Sn-Co Trilayer: Role of Interlayer Roughness.** Paolo Allia<sup>1</sup>, Alessandro Chiolero<sup>1</sup>, Angelica Chiodoni<sup>1</sup>, Marco Coisson<sup>2</sup> and Paola Tiberto<sup>2</sup>; <sup>1</sup>Physics, Politecnico di Torino, Torino, Italy; <sup>2</sup>Materiali, INRiM, Torino, Italy.

A Co(15 nm)/Sn(40 nm)/Co(15 nm) trilayer was produced by high-vacuum thermal evaporation on a polished Si(100) substrate. The distribution and homogeneity of Co and Sn was checked by means of field effect scanning electron microscopy (FESEM) and energy dispersive X-ray spectroscopy (EDX). Magnetic hysteresis loops were measured from 8 to 300 K in an alternating-field gradient magnetometer (H: up to  $\pm 18$  kOe, in the plane of the layers). Magnetoresistance measurements were performed in the current-in-plane configuration by means of a 4-contact technique with soldered contacts in a superconducting magnet (temperature: 2 to 121 K; magnetic field: up to  $\pm 70$  kOe). EDX compositional micromaps of the sample surface show a correlation of the elemental distribution with respect to morphological features: Sn is preferentially distributed in grain-like structures while Co provides a uniform signal from the sample. In order to evidence this relationship a numerical algorithm has been developed; its self-consistency has been checked by implementing a numerical simulation of the scattering process that X photons undergo when emitted by the excited sample. The results of simulation are in very good agreement with the experimental observations. Combined morphological and compositional data indicate that the Co cap layer is markedly non-planar and possibly non-continuous owing to the high intrinsic roughness of the underlying Sn interlayer, while the Co underlayer is continuous and planar. This information has been exploited to interpret the magnetic and magnetotransport properties of this trilayer. Hysteresis loops indicate a multi-phase magnetic behavior and can be decomposed into three contributions with different coercive fields, arising from the Co underlayer, the Co cap layer, and to a small, slowly-saturating magnetic fraction which is ascribed to Co nanoparticles embedded in Sn. Three distinct magnetoresistance effects are singled out in this material: below about 1 kOe, a positive magnetoresistance is observed at all temperatures. At higher fields, a negative unsaturating magnetoresistance is measured; above about 30 kOe, another positive magnetoresistance effect appears, which becomes predominant below 10 K. This behavior is interpreted in the light of the three-phases model. The nonsaturating magnetic phase is associated to the negative magnetoresistance observed above 1 kOe. However, this effect is masked (particularly at low temperatures) by a positive magnetoresistance contribution which is ascribed to ordinary magnetoresistance (OMR) of all metals constituting the trilayer. Finally, the low-field positive magnetoresistance is strongly peaked at the coercive field of the Co underlayer and is therefore ascribed to anisotropic magnetoresistance (AMR) related to the magnetic domain walls in the underlayer.

#### I14.18

**Ferrite Films by a 'Low Temperature', 'Low Cost', 'No Post-Annealing' Spin-Spray Process for High Frequency Applications.** Ailoor K Subramani<sup>1</sup>, Nobuhiro Matsushita<sup>1</sup>, Tomoaki Watanabe<sup>1</sup>, Masaru Tada<sup>2</sup>, Masanori Abe<sup>2</sup>, Koichi Kondo<sup>3</sup> and Masahiro Yoshimura<sup>1</sup>; <sup>1</sup>Materials and Structures Laboratory, Tokyo Institute of Technology, Yokohama, Japan; <sup>2</sup>Department of Physical Electronics, Tokyo Institute of Technology, Tokyo, Japan; <sup>3</sup>NEC Tokin Corporation, Sendai, Japan.

The miniaturization and complex digital applications of wireless communication, computers, LAN and other networks have propagated conducted and radiated electromagnetic noise (EMI) that severely disturbs the operation of such sensitive equipments. High working clock frequency of these equipments limits the use of noise suppressors that are already available in the market. Ferrite films exhibiting large magnetic loss in GHz range are the prime candidates for noise suppression materials. For actual use as GHz noise suppressors, the films must undergo reflow-soldering process (heat treatment at 260 °C for 3 minutes) without deteriorating its electrical and magnetic properties. To obtain better noise suppression properties even after heat treatment is still challenging. Hence, the aim of this study was to prepare heat resistant ferrite films by controlling the surface resistance (R) and noise suppression properties. Highly crystallized spinel ferrite films can be prepared by spin-spray technique at a very low temperature of 90 °C without any post-annealing [1, 2].  $\text{Mn}_x\text{Zn}_y\text{Fe}_{3-x-y}\text{O}_4$  films with different compositions and morphology were prepared by varying the experimental conditions. Their structural, morphological, electrical and magnetic properties were studied before and after heat treatment. The structural analysis of the films by XRD revealed that the films had single-phase spinel structure with no preferential orientation. The SEM images depicted a columnar structure grown perpendicular from the substrate surface with diameter ranging to few hundred nanometers. The hysteresis loops of the films showed a slight decrease in the saturation magnetization ( $M_s$ ) after heat treatment and increase in uniaxial anisotropy field ( $H_k$ ) and coercivity ( $H_c$ ). The films also exhibited a decrease in imaginary permeability in the lower frequencies and the resonance frequency ( $f_r$ ) shifted to



a higher frequency range. The film characteristics were as follows:  $M_s$  (450 to 570 emu/cc),  $H_c$  (18 to 45 Oe),  $H_k$  (43-86 Oe),  $R$  ( $10^3$  to  $10^7$  ohm/sq), initial permeability  $\mu'$  (25 to 60), imaginary permeability  $\mu''$  (20 to 38),  $f_r$  (300 to 1000 MHz). The S parameters ( $S_{11}$  and  $S_{21}$ ) of the films were measured from 50 MHz to 10 GHz to evaluate the conducted noise suppressing properties. The films prepared at optimum condition exhibited reflection loss ( $S_{11}$ ) less than -10 dB and transmission loss ( $\Delta P_{loss}$ ) of upto 60% at 10 GHz. The relation between the surface resistance and noise suppression properties showed that a surface resistance  $R > 10^5$  ohm/sq was required to retain better noise suppression after heat treatment. Thus prepared ferrite films can be practically used as noise suppressors (low pass filters). (1) N. Matsushita, T. Abe, K. Kondo, S. Yoshida, M. Abe, J. Appl. Phys. 97 (2005) 10G106-1-3 (2) A. K. Subramani, N. Matsushita, T. Watanabe, M. Tada, M. Abe, and M. Yoshimura, J. Appl. Phys. 101 (2007) 09M504-1.

**I14.19****Abstract Withdrawn****I14.20**

**Magnetic Anisotropy and Microstructure of Permalloy ( $Ni_{80}Fe_{20}$ ) Thin Films Deposited under Magnetic Field.** Sung-Uk Jang, Soon-Ju Kwon, Sangho Jin and Nokeun Park; Material Science and Engineering, POSTECH, Pohang, South Korea.

Magnetic property control of a permalloy ( $Ni_{80}Fe_{20}$ ) film is a major challenge in various technological applications. They have studied effects of doping, normal annealing, annealing in a magnetic/electric field, buffer layer, and composition. This paper studies the effects of magnetic field. Permalloy films of 100 nm thick are deposited at various magnetic fields of 0, 600, 850, and 1100 gauss (applied parallel to the substrate) in an e-beam evaporator with the base pressure of  $3.0 \times 10^{-7}$  torr. The structure of film is characterized using GAXRD (Grazing Angle X-Ray Diffraction), AFM, and MFM. It is proven that the microstructure, e.g. texture and lattice parameter, changes with the direction and the strength of the magnetic field. Furthermore, a strong relationship is found between the structure and the magnetic properties of the film, especially the magnetic anisotropy. This implies that use of magnetic field may control the magnetic properties of a film.

**I14.21****Abstract Withdrawn****I14.22**

**Magnetic Antidot Arrays Made Using Block Copolymer Templates.** Vivian Peng-Wei Chuang<sup>1</sup>, WonJoon Jung<sup>1</sup>, Joy Cheng<sup>2</sup>, Oun-ho Park<sup>2</sup>, Ho-Cheol Kim<sup>2</sup> and Caroline A Ross<sup>1</sup>; <sup>1</sup>Materials Sci. and Engg., Massachusetts Institute of Technology, Cambridge, Massachusetts; <sup>2</sup>IBM Almaden Research Center, San Jose, California.

Magnetic films with periodic arrays of holes (antidot arrays) have very different magnetic properties compared to a continuous film [1]. In this study, we examine both single layer 3.5 nm Co antidot arrays and pseudo-spin-valve Co 3.5nm /Cu 5nm /NiFe 3nm close-packed antidot arrays with periodicity of 26 nm and 40 nm. These periods are smaller than previously reported for multilayer antidot arrays, and allow trends in behavior to be followed as the hole size decreases below 20 nm. The antidot arrays were fabricated over large area (> 1 sq. cm) substrates by ion-beam sputtering of metal films over hole arrays formed from a polystyrene (PS)-b-poly(ethylene oxide) (PEO) block copolymer containing organosilicates (OS) within the PEO block. The PS-PEO was spin-coated on top of a polydimethylglutarimide (PMGI) film. The PS minority block forms circular microdomains within the PEO+OS matrix. An oxygen reactive ion etch removes PS and unprotected PMGI and creates channels of period 26 nm or 40 nm, and diameters 12 nm or 17 nm, depending on the molecular weights of the PS-PEO. Magnetic properties were measured using both alternating gradient magnetometer and magnetoresistance measurements, and modeled using a micromagnetic code. Compared with a continuous thin film, the coercivities of the Co and Co/Cu/NiFe antidot arrays were higher, and the saturation field was considerably increased. The giant magnetoresistance of the multilayer was 0.24% for the continuous film and 0.26% or 0.21 % for the two antidot arrays. In the multilayer, unlike the continuous film, the NiFe reverses at positive fields due to the strong magnetostatic interactions between the Co and NiFe layers present near the holes. As the inter-hole spacing is decreased, both experiment and simulation results show that the coercivity and switching field distribution is reduced, unlike the behavior seen in films with micron-sized holes [2, 3]. The simulation shows in particular the trapping of 360 degree domain walls between rows of holes, which are eliminated only at fields above 5000 Oe. We will describe the role of the holes in the reversal process, and the control of magnetic properties that can be achieved by manipulating the hole geometry. [1] Castano F J, Nielsch K, Ross C A, Robinson J W A, Krishnan R 2004 Appl. Phys. Lett. 85 2872. [2] Wang C C, Adeyeye A O, Wu Y H 2003 J. Appl. Phys. 94 6644. [3] Heyderman L J, Nolting F, Backes D, Czekaj S, Lopez-Diaz L, Klaui M, Rudiger U, Vaz C A F, Bland J A C, Matelon R J, Volkmann U G, Fischer P 2006 Phys. Rev. B 73, 214429.

**I14.23**

**Magnetic and Transport Properties of Highly Ordered, Controllable Nanowire and Heterostructure Arrays Prepared using Pre-patterned AAO Templates.** Adam Robinson and J. L. MacManus-Driscoll; Department of Materials Science and Metallurgy, University of Cambridge, Cambridge, United Kingdom.

Anodic aluminium oxide (AAO) templates form an ideal route to the production of arrays of magnetic nanostructures; they are robust, insulating, withstand high temperatures and can be produced with a range of geometries. However, relatively little work has been carried out on the production of thin film templates on supporting substrates for device fabrication. Here we present work on the production of thin (<1µm), perfectly ordered AAO templates on supporting silicon substrates by focussed ion beam (FIB) pre-patterning and their use in the production of highly ordered magnetic nanowire and heterostructure arrays. Areas up to 15 x 15 µm were pre-patterned using a FIB and anodized to produce perfectly ordered templates with controlled pitch (100 to 200 nm), pore diameter (50 to 70 nm) and geometry (hexagonal or square arrays). Filling of the templates was carried out by computer controlled electrodeposition, which allows for the production of heterostructures with nanoscale precision. We present magnetic and transport data on arrays of heterostructures and multilayered nanowires produced using this technique

**I14.24**



**Fe  $L_{2,3}$  X-ray Magnetic Circular Dichroism and X-ray Absorption Spectroscopic Studies of Electrodeposited  $Fe_3O_4$  Thin Films.** Chien-Lung Teng and Mary Ryan; Department of Materials and London Centre for Nanotechnology, Imperial College London, London, United Kingdom.

Magnetite ( $Fe_3O_4$ ) has been recently attracted much attention due to its potential applications in spin-based devices. In this work the Fe  $L_{2,3}$  X-ray magnetic circular dichroism (XMCD) combined with soft x-ray absorption spectroscopy (XAS) was used to examine  $Fe_3O_4$  thin films electrochemically grown at various potentials onto copper foils. A large variation in film characteristics is observed over a relatively small window of deposition potential within the region for spinel formation. The XAS spectra of the film deposited at 100 mV vs. Au [0 V (Au) = -0.260 V vs. NHE] shows a characteristic of maghemite ( $\gamma-Fe_2O_3$ ) with a deep shoulder around 709 eV. Consequently, there is no MCD signal observed. This phase is favoured at higher potentials due to the driving force for oxidation of  $Fe^{2+}$  to  $Fe^{3+}$  ions in the electrolyte. The dominant phase changes to  $Fe_3O_4$  at slightly lower potentials (50 and 25mV). The Fe  $L_3$ -edge spectra are much broader for both cases, and MCD signals are observed. The calculation of the integrated values of the Fe  $L_2$ -edge spectra between 719 and 730 eV for the  $I_+$  and  $I_-$  spectrum separately reveals that the asymmetry ratio increases with decreasing applied potential indicating a change in the local magnetic properties of the material. In addition there is a notable increase in the asymmetry on annealing which corresponds directly to a change in the  $Fe^{3+}$  octahedrally co-ordinated sites.

#### I14.25

**Magnetic Properties of Alumina Template Synthesized Ferromagnetic and Polyaniline Composite Nanowires.** Derrick Brittain, Adam L Friedman and Latika Menon; Physics, Northeastern University, Boston, MA, Massachusetts.

Ferromagnetic nanowires have remarkable magnetic properties including high coercivities and strong magnetic shape anisotropy. Polyaniline has also been shown to be a remarkable material, having many interesting physical properties including high capacitances. In this study, we use porous alumina templates and electrodeposition to fabricate Fe, Ni, and Co nanowires. We also use the same techniques to grow polyaniline nanowires and make polyaniline-ferromagnetic nanowire composite structures. We measure the magnetic properties of these structures as a function of their diameter and compare the results. We study how the polyaniline effects the magnetism. Preliminary results will be presented.

#### I14.26

**Shubnikov-de Haas Oscillations in an Individual Single-crystalline Bi Nanowire.** Jeongmin Kim, Wooyoung Shim, Seunghyun Lee, Kyejin Jeon and Wooyoung Lee; Department of Materials Science and Engineering, Yonsei University, Seoul, South Korea.

Semimetallic bismuth (Bi) is a particularly favorable material with which to study its unusual electronic properties of quantum wires due to its highly anisotropic Fermi surface, low carrier concentrations, long carrier mean free path  $l$  and small effective carrier mass  $m^*$ . In single crystals, these characteristics lead to very large ordinary magnetoresistance (OMR) effects and pronounced quantum oscillations such as Shubnikov-de Haas (SdH) oscillations and related effects. For these studies, materials with lower dimensions such as nanowires are often required, and 4-probe measurements of an individual nanowire is necessary to obtain quantitative information such as the charge density and the anisotropic of Fermi surface. In the present work, we report the observation of Shubnikov-de Haas oscillations in an individual single-crystalline Bi nanowire. We have successfully grown single-crystalline Bi nanowires via heat treatment at 270 °C for 10 hours by utilizing the relaxation of stress from sputtered Bi films. For a 400-nm-diameter Bi nanowire, the largest transverse and longitudinal OMR of 2496% at  $T = 110$  K and -38% at  $T = 2$  K were observed, indicating that the Bi nanowires grown by the stress-released method have the longest mean free paths  $l$ , and are high-quality single crystalline. Mean free path is directly related to the observation of SdH oscillations that is characterized by an exponential decay,  $\exp(-l/wc\tau)$ , where relaxation time  $\tau$  is defined  $\tau = el / m^*$ . The observation of robust SdH oscillations proves that the Bi nanowire is the high quality, single-crystalline. The oscillations with the field perpendicular to the nanowire exhibit higher amplitude by one order than those of parallel to the nanowire. These results are good qualitative agreement with the large transverse MR data, defined by  $wc\tau$ . The observed period of SdH oscillations with the field perpendicular to the nanowire ( $n = 3$ ) is small, relative to those with the field perpendicular to the nanowire ( $n = 6$ ), therefore ensuring that Bi nanowire is oriented along the trigonal direction, i.e., (001). These results are also consistent with TEM analysis and the preferred orientation of (001) in the films where nanowires start to grow. It is noteworthy that non-periodic oscillations observed in our sample are attributed to the increase of effective carrier mass in the nanowire due to the increase of energy at the wire boundary. Further description of the cyclotron behavior in terms of SdH oscillations in the single-crystalline Bi nanowire in the ballistic regime will be discussed in detail.

#### I14.27

**Nano-Effects on Magnetic Refrigerants.** Robert D Shull, National Institute of Standards & Technology, Gaithersburg, Maryland.

Upon the removal of a magnetic field from a material, the resulting reduction in magnetic spin alignment represents an increase in the material's spin entropy ( $\Delta S$ ). If the field reduction is performed adiabatically so that the total entropy change is zero, then the increased spin entropy is offset by an equal decrease in lattice entropy, as reflected by a decrease in the temperature of the material. This  $\Delta T$  is called the magnetocaloric effect, and it is a property of the material and its magnetic state. This is based on a reversible process and so Carnot efficiencies (which is the best one can achieve) are possible. The competing technology of the expansion and compression of a gas is not a reversible process. Here a description of the effect and its magnitude for different types of materials will be presented, including a description of the "Enhanced Magnetocaloric Effect" discovered by the author a few years ago in magnetic nanocomposites. Experimental verification of the enhanced magnetocaloric effect in nanocomposites will be provided by experimental data for a  $Gd_3G_{5-x}Fe_xO_{12}$  (GGIG) magnetic nanocomposite, that is superparamagnetic and possesses magnetocaloric effects 3-4 times larger than those of the presently preferred low-temperature paramagnetic refrigerant, gadolinium gallium garnet (GGG). This new material possesses the potential for both increasing the operating temperature of magnetic refrigerators and lowering the magnetic fields required for their operation. Magnetic refrigerators could then be substantially reduced in size, made much more efficient, and enable cooling to much higher temperatures. Lastly, a few comments will be made regarding hysteresis effects on magnetic refrigerants using  $Gd_5Ge_2Si_2Fe_{0.1}$ , as an example.

#### I14.28

**Polymeric Magnetomicelles: Synthesis and Characterization for use as MR Imaging Probe.** Dattatri Nagesha<sup>1</sup>, Rishikesh Sawant<sup>2</sup>, Evin Gultepe<sup>1</sup>, Vladimir Torchilin<sup>2</sup> and Srinivas Sridhar<sup>1</sup>; <sup>1</sup>Physics, Northeastern University, Boston, Massachusetts; <sup>2</sup>Pharmaceutical Sciences, Northeastern University, Boston, Massachusetts.



Superparamagnetic iron oxide nanoparticles (SPIONs) are increasingly being used in diagnostic as a contrast enhancing agent in magnetic resonance imaging (MRI) and in therapy as an energy delivery agent in magnetic hyperthermia. We have developed SPIONs encapsulated polymeric magnetomicelles using polyethylene glycol/phosphatidylethanolamine (PEG-PE). These polymeric magnetomicelles were characterized for their size, surface charge and magnetic susceptibility. For use as contrast agent, the T2 relaxation of these magnetomicelles was measured using Varian INOVA 500 MHz Nuclear Magnetic Resonance (NMR) spectrometer. To enhance targeting capability, 'immunomicelles' containing cancer cell-specific anti-nucleosome monoclonal antibody 2C5 (mAb 2C5) were formulated. This was tested by in vitro studies using human breast carcinoma MCF-7 cells. Specificity of these micelles was compared against 'plain' magnetomicelles and 'non-specific' bovine IgG magnetomicelles. Results from this work using polymeric magnetomicelles as MRI probe will be presented. This work was supported by the IGERT Nanomedicine Science and Technology (NSF-0504331).

#### I14.29

**Synthesis of Palladium and Platinum Nanowires and Their Magnetic Properties.** Xiaowei Teng<sup>1</sup>, Weiqiang Han<sup>1</sup>, Wei Ku<sup>2</sup> and Markus Huecker<sup>2</sup>; <sup>1</sup>Center for Functional Nanomaterials, Brookhaven National Laboratory, Upton, New York; <sup>2</sup>Condensed Matter Physics and Materials Science Department, Brookhaven National Laboratory, Upton, New York.

Several 4d and 5d metals such as palladium and gold have been showed ferromagnetism in two dimensional (2D) atomic layers and zero dimensional (0D) nanoclusters in contrast to diamagnetism or paramagnetism in their bulk counterparts. However, there have been no experimental reports on one dimensional (1D) nanowires of 4d or 5d metals, mainly because of limitation to synthesize monodispersed nanowires. Here, we use a solution phase approach to synthesize Pd and Pt nanowires with aspect ratio over 15. Both surfactant and oxygen content play important role in the formation of nanowires. High resolution TEM and X-Ray diffraction were used to characterize the structure of as-made nanomaterials. Moreover, SQUID data showed, instead of paramagnetism in their bulk form, both nanowires show ferromagnetism up to room temperature. Our results demonstrate the unique features of one dimensionality in conventional nonmagnetic metals, and are expected to initiate more advanced studies of the magnetic properties of 1D nanomaterials.

#### I14.30

**In-plane Magnetization Reversal of Ferromagnetic Nanowire Arrays.** Fanny Béron, David Ménard and Arthur Yelon; Génie physique, École Polytechnique de Montréal, Montréal, Quebec, Canada.

The magnetization reversal of nanowire arrays has been investigated by measuring the set of first-order reversal curves (FORCs) when a magnetic field is applied perpendicular to the nanowire axis (in-plane, IP). The nanowires are electrodeposited into alumina templates, with axes perpendicular to the template plane. According to Stoner-Wohlfarth theory for coherent rotation, the magnetization reversal of a long single domain ferromagnetic nanowire should be fully reversible when the magnetic field is applied perpendicular to the nanowire axis. However, for high-density arrays of CoFe, CoFeB and Ni (diameter = 15 to 175 nm, length = 1 to 60  $\mu$ m, interwire distance = 50 to 300 nm, easy axis parallel to the nanowire axis), the experimental hysteresis curves can exhibit a coercivity up to a few hundreds of Oe. The experimental IP FORC diagrams [1] lead to a distribution with two distinctive features [2,3]: a high reversible ridge and a small irreversible peak apparently coming from symmetric hysterons with a switching field of several hundreds of Oe. According to Hertel [4], the interaction field created by the array leads to a multi-domain state, with domains parallel and anti-parallel to the nanowire axis (easy axis), separated by a small domain perpendicular to the nanowire axis (hard axis). It may be the reversal of these small perpendicular domains which creates the hysteresis and the irreversible peak. In order to investigate this assumption, the magnetization  $M$ , has been measured as a function of angle  $\theta$ , as the sample, saturated and lying in the IP plane, is turned and a static negative magnetic field is applied. The  $M$  vs  $\theta$  curves are close to  $\cos \theta$  in form. Their amplitude decreases as saturation approaches. This amplitude is compatible with its association with the small perpendicular domains. **References** [1] C.R. Pike, A.P. Roberts, K.L. Verosub, J. Appl. Phys. **85**, 6660 (1999). [2] F. Béron, L. Clime, M. Ciureanu, D. Ménard, R.W. Cochrane, A. Yelon, J. Nanosci. Nanotechnol. (accepted for publication) [3] F. Béron, L. Clime, M. Ciureanu, D. Ménard, R.W. Cochrane, A. Yelon, J. Appl. Phys. **101**, 09J107 (2007). [4] R. Hertel, J. Appl. Phys. **90**, 5752 (2001).

#### I14.31

**The Fabrication of Magnetic Quantum Dot Arrays Using Porous Alumina Templates.** Steven Bennett, Don Heiman and Latika Menon; Physics, Northeastern University, Boston, Massachusetts.

The recent surge of interest in the field of spintronics has heightened the demand to find ways of injecting spin polarized electrons into semiconductors. The greatest barriers that must be overcome in order to create spintronic devices is to find methods/materials for injecting, transporting, manipulating and detecting electrons while preserving their spin oriented state. Quantum dots may hold the answer [1]. Due to their small size and charge confinement in semiconductors they can exhibit properties not found in bulk form. Currently, fabrication of these quantum dot structures ranging from 30-60nm are synthesized using MBE, and rely on a lattice mismatch between the dot material and the substrate. An increased interest in semiconductors for spintronics applications which do not exhibit crystal lattice mismatch with semiconductor substrates forces the founding of different methods for their fabrication. In this study we demonstrate the use of nanochannel porous alumina templates as masks [2,3] for the fabrication of organized hexagonal arrays of both manganese doped semiconductor and ferromagnetic metal quantum dots. The techniques of MBE and thermal evaporation are used in conjunction with reactive ion etching. Our 5-step process starts with the MBE growth of the desired material with a thickness corresponding to the ending dot height. A nanochannel porous alumina template is then used as a template for thermal evaporation. The evaporated metal (Cr) migrates down the pores and forms a nanodot array on the surface. This metal nanodot array then serves as a template for reactive ion etching in order to remove the surrounding semiconducting film. **REFERENCES:** [1] M. Wilczynski, R. Swirkowicz, W. Rudzinski, J. Barnas, and V.Dugaev, Journal of Magnetism and Mag. Mat. 290-291 (2005) [2] H. Masuda, K. Yasui, and K. Nishio, Adv. Mater., **12**, No.14 (2000) [3] J. Liang, H. Chik, A. Yin, and J. Xu, Journal of App. Phys., Vol. 91 #4 (2002)

#### I14.32

**Abstract Withdrawn**

#### I14.33

**First Order Reversal Curve Measurements of Hierarchically Self-assembled Iron Oxides Nanostructures.** Julia Martina Linke<sup>1</sup>, Judith L



Driscoll<sup>1</sup>, Richard J Harrison<sup>2</sup> and Ahmed Kursumovic<sup>1</sup>; <sup>1</sup>Materials Science and Metallurgy, Cambridge University, Cambridge, United Kingdom; <sup>2</sup>Earth Sciences, University of Cambridge, Cambridge, United Kingdom.

The first order reversal curve (FORC) method is an experimental tool to characterise hysteretic processes in samples containing mixtures of magnetic phases or grain sizes. It has only become available with recent advancements in the automation of vibrating-sample and alternating-gradient magnetometers. Until the 1990's major hysteresis loops, which present bulk averages, were most widely used for magnetic characterisation. By contrast, the FORC method is based on a set of minor partial hysteresis loops below and up to saturation [1]. From this data the distribution of switching fields and local interaction fields between particles or grains can be determined, which allows modelling of more complex magnetic interactions in nanomaterials. We used the FORC method to investigate the magnetic properties of alpha-Fe<sub>2</sub>O<sub>3</sub> and Fe<sub>3</sub>O<sub>4</sub> nanostructures on silicon. The self-assembled iron oxide fractals were deposited from aqueous and ethanolic FeCl<sub>3</sub> solutions by ultrasonic aerosol assisted chemical vapour deposition (UAA CVD). In comparison to conventional CVD, ultrasonic assisted CVD allows an operation at low temperatures and atmospheric pressure. It offers great flexibility over porosity, crystallinity, composition and thickness, and provides a simple and cost-efficient synthesis route for iron oxide nanostructures which could be important building blocks for magnetic sensors and biomedical devices. [1] Roberts A.P., Pike C.R., Verosub K.L.: J. Geophys. Res., 105 (B12), p28, 461, 2000

#### I14.34

**Preparation and Characterization of Nanocrystalline Misch-metal Substituted Yttrium Iron Garnet Powder by Sol-Gel Combustion Process.** Shahrzad Hosseini Vajargah, Ziarat Ali Nemat and Hamid Reza Madaah Hosseini; Material Science & Engineering, Sharif University of Technology, Tehran, Tehran, Iran.

The nanocrystalline Y<sub>3-x</sub>MMxFe<sub>5</sub>O<sub>12</sub> powders (MM denotes as Misch-metal, x= 0.0, 0.25, 0.5, 0.75 and 1.0) were synthesized by a sol-gel combustion method and their magnetic properties, crystallite structures and morphology of particles were investigated using X-ray diffraction (XRD), vibrating sample magnetometer (VSM) and scanning electron microscopy (SEM). The XRD patterns show that the single phase garnet of Y<sub>3-x</sub>MMxFe<sub>5</sub>O<sub>12</sub> has been formed at x values less than 1.0. The saturation magnetization of powders decreases with increasing MM content and reaches the maximum at Y<sub>3</sub>Fe<sub>5</sub>O<sub>12</sub>. The crystallite sizes of powders calcined at 800 degree Centigrade for 3 hours were in the range of 38-53 nm. The calcined powders showed porous feature due to the liberation of large amount of gases during combustion.

#### I14.35

**Spin Crossover Framework Materials: Guest-Dependence and Pressure Effects.** Gregory J Halder<sup>1</sup>, John A Schlueter<sup>1</sup> and Karena W Chapman<sup>2</sup>; <sup>1</sup>Materials Science Division, Argonne National Laboratory, Argonne, Illinois; <sup>2</sup>Advanced Photon Source, Argonne National Laboratory, Argonne, Illinois.

Spin crossover is a well-known form of molecular switch in which changes in the electronic configuration at a metal center lead to distinctive changes in molecular geometry, color and magnetism. The incorporation of these switching centers into porous molecular materials ('metal-organic frameworks') has shown potential for their application as molecular sensors, where the switching properties are influenced by the nature of the guest species. [1] Here, the guest- and pressure-dependent magneto-structural properties of a series of iron(II)-based materials will be presented. The study of pressure effects on spin crossover framework materials is unique in investigating the interplay between framework flexibility and magnetic properties. [1] G. J. Halder, C. J. Kepert, B. Moubaraki, K. S. Murray, J. D. Cashion, Science 2002, 298, 1762.

#### I14.36

**Large Magnetoresistance Variation of Pseudo Spin Valves with Different Nano Oxide Layer Position.** Jeong Dae Suh<sup>1</sup> and Caroline Anne Ross<sup>2</sup>; <sup>1</sup>Medical Information Convergence Research Team, Electronics and Telecommunications Research Institute, Daejeon, South Korea; <sup>2</sup>Department of Materials Science and Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts.

We have investigated the influence of the nano-oxide layer positions on the magnetoresistance of the NiFe(9nm)/Cu(4nm)/Co(5nm) pseudo spin valves. Nano-oxide layer positions had a several effects on the multilayer structure that change its magnetotransport behavior. Magnetoresistance ratio varied between 2.8% and 0.15% depending on the nano-oxide layer positions. The increase of the magnetoresistance ratio was accompanied by increase in resistance change, decrease in sheet resistance, and decrease in surface roughness. Theoretical model was compared with the variation of magnetoresistance ratio with nano-oxide layer positions. Nano-oxide position influence was explained well by the specular scattering or the current shunting effect. Our results showed that appropriate placement of a nano-oxide layer was essential for optimize magnetoresistance and properties of spin valves.

#### I14.37

**Magnetic Sensors with Different Geometry to Magnetic Nanoparticle Detection for Biosensor Application.** Jeong Dae Suh and Myung Ae Chung; Medical Information Convergence Research Team, Electronics and Telecommunications Research Institute, Daejeon, South Korea.

Biomolecule detection using a superparamagnetic nanoparticle as a label shows a new opportunity for biological and medical diagnostic applications. Recently, superparamagnetic nanoparticle detection by magnetic resistive sensor has received growing attention for this purpose. In this work, we report the results for magnetic biosensors based on a Si/SiO<sub>2</sub>/Ta(5nm)/NiFe(3nm)/IrMn(15nm)/Cu(3nm)/NiFe(6nm)/Ta(5nm) spin valves with different shapes from bar, cross, and ring type structures and different dimensions from 3x3 to 100x100 μm<sup>2</sup> for the detection of micrometer and nanometer sized labels. Here we describe the design and performance of our magnetic sensors and compare its performance. It was observed that sensor response increased with label concentration and sensor dimensions. The simple ring type magnetic sensors can be expected for the development of magnetic biochip analysis system with high sensitivity and selectivity.

#### I14.38

**Development of Strategies to Improvement Ordering and Perpendicular Alignment of Cylinder Phase Block Copolymers Used as Templates for Bit Patterned Media.** Vishal Warke<sup>1,2</sup>, Garrett Seth<sup>2</sup>, Tim Snowden<sup>2</sup>, Martin Gerard Bakker<sup>1,2</sup>, Michael Curry<sup>1,4</sup>, Kunlun Hong<sup>3</sup>,



Phillip Britt<sup>3</sup> and Jimmy Mays<sup>3</sup>; <sup>1</sup>Center for Materials for Information Technology, The University of Alabama, Tuscaloosa, Alabama; <sup>2</sup>Department of Chemistry, The University of Alabama, Tuscaloosa, Alabama; <sup>3</sup>Center for Nanophase Materials Science, Oak Ridge National Laboratory, Oak Ridge, Tennessee; <sup>4</sup>Physical Sciences, The University of West Alabama, Livingston, Alabama.

Bit patterned media, including media fabricated with a gradient in composition, is being developed as a potential path to higher information storage density. The noise level in such media is significantly impacted by the precision of the ordering of the individual bits and by the narrowness of their size distribution. Block copolymers that phase separate on the appropriate length scale are one method of pattern generation that is receiving considerable attention. For cylinder forming block copolymer phases the ordering and degree of perpendicular alignment is largely determined by the matching of the substrate surface to the block copolymer. If the chemical properties of the substrate surface match the average for the block copolymer, then thin films of the block copolymer align perpendicularly on annealing. Although there are a number of examples where the substrate surface fortuitously matches the block copolymer, in general an orienting layer is necessary to provide the appropriate match. The most popular orienting layer has been a random copolymer with the same average composition as the block copolymer. In order to produce suitably thin orienting layers it has been necessary to chemically tether the random copolymer to the substrate. Previously used chemistry has not been suitable for noble metal substrates such as platinum. We have been developing an alternate approach using thiol functional groups which we anticipate will be more suitable for Pt capped substrates. We will also report on progress on an alternative strategy which completely bypasses the need to synthesize random copolymers. This is the use of thin carbon coatings which have been found to be a good match for the polystyrene-poly(methylmethacrylate) block copolymers commonly used.

#### I14.39

**Fabrication of Tilted Magnetic Easy Axis L10-FeCoPd Nanoparticles.** Andras Kovacs and Yoshihiko Hirotsu; The Institute of Scientific and Industrial Research, Osaka, Japan.

The tetragonal L10 structure has large magnetocrystalline anisotropy which makes this material suitable for high-density perpendicular magnetic recording media application. In general, a nm-sized, magnetically isolated, uniaxially aligned nanoparticles must be prepared for recording densities of Tbit/in<sup>2</sup>. The high storage density is accessible with perpendicular recording, where the magnetization of the recording nanocrystals is perpendicular to the film plane, therefore the orientation of magnetic easy axis is essential to good performance. In contrast, the densely packed, aligned nanocrystals needs much higher writing field than are currently available from magnetic recording heads. An alternative recording geometry are being proposed to overcome this problem, namely that, the tilted magnetic recording media, in which the easy axis is tilted from the perpendicular direction by 45 degree. According to Stoner-Wohlfarth model, the switching field is sensitive to the applied external field direction, i.e. the switching field has a minimum at 45 deg. and has a good tolerance in angle dispersions. In this work the magnetic nanoparticles with tilted magnetic easy axis are prepared by sequential evaporation of Pd, Co and Fe onto heated MgO (110) substrate and followed by post-deposition annealing. The ternary Pd-Co-Fe systems is chosen for the reason of beneficial impact of Co addition to L10-FePd nanoparticles such as slight decrease of L10 ordering temperature, increase of saturation magnetization and enhancement of preferential magnetic easy axis formation. We investigated the L10 ordering and the magnetic easy axis evolution of individual nanoparticles in cross-sectional view using the transmission electron microscopy (TEM) including the high resolution observation. The TEM analysis of the as-deposited samples shows the nanoparticle-complex formation of Pd and CoFe phases. Shape of the first evaporated epitaxial Pd crystals is found to be a truncated, diagonally cut octahedral shape with large {100} and {111} surfaces. The bcc-CoFe phase is covered the Pd crystals. The heat treatment of the samples induced the L10 ordering in the nanoparticles. It is found that the L10 nanoparticles with two magnetic easy axis tilted by 45 deg. to the surface normal were formed. Magnetic properties are measured by SQUID magnetometer. The obtained magnetic hysteresis loops measured from three directions showed a strong magnetic anisotropy of the particles. Since the magnetic easy axes are tilted the hysteresis measured along the surface normal ([110] direction) is similar to a hard magnetic particles measured at an angle to the easy axis. The coercivity is measured as 1.5 kOe along this direction. The hard axis lay in the [100] direction, while the hysteresis loop with high remanence magnetization is measured along the [1-10] direction. The role of interdiffusion and the initial shape of Pd particles in magnetic easy axis formation are discussed.

#### I14.40

**Vertically Aligned Mn-doped Fe<sub>3</sub>O<sub>4</sub> Nanowire Arrays: Magnetic Properties and Gas Sensing at Room Temperature.** Seon Oh Hwang<sup>1</sup>, Chang Hyun Kim<sup>1</sup>, Yoon Myung<sup>1</sup>, Jeunghee Park<sup>1</sup>, Chang Soo Hahn<sup>2</sup> and Jae Young Kim<sup>3</sup>; <sup>1</sup>Materials Chemistry, Korea University, Jochiwon, South Korea; <sup>2</sup>Nano-mechanical Systems Research Center, Korea Institute of Machinery and Materials, Daejeon, South Korea; <sup>3</sup>Pohang Accelerator Laboratory, POSTECH, Pohang, South Korea.

Recently, interest in room-temperature magnetic 1-dimensional nanostructures has been steadily increasing, because of their potential application in perpendicular data recording and spintronic devices. Iron oxides are the most popular materials and possess many advantages in technological applications, due to their exclusive combination of electric and magnetic properties. Herein, vertically-aligned Mn (10%)-doped Fe<sub>3</sub>O<sub>4</sub> nanowire (NW) arrays were produced by the reduction/substitution of the pre-grown Fe<sub>2</sub>O<sub>3</sub> nanowires. They are ferromagnetic with a Verwey temperature (T<sub>v</sub>) at 130 K, which is lower than that of the undoped Fe<sub>3</sub>O<sub>4</sub> NWs (T<sub>v</sub> = 138 K). X-ray magnetic circular dichroism measurement reveals that the Mn<sup>2+</sup> ions preferentially occupy at Oh sites by the substitution of Fe<sup>2+</sup> ions. The occupation of Mn<sup>2+</sup> at Oh sites (B-sites) disturb slightly the charge ordering between Fe<sup>3+</sup> and Fe<sup>2+</sup> (or Mn<sup>2+</sup>) ions, which may reduce Verwey temperature. The n-type Mn doping in the conduction path of Fe ion network at the B sites increases the conductivity by a factor of 500 at room temperature. The highly sensitive gas sensors, fabricated using these nanowire arrays, show the decrease of the resistance upon exposed to various gases working at room temperature. The sensitivity is correlated well with the bond strength of molecules. Since these NW sensors exhibit the highest sensitivity toward H<sub>2</sub>O vapor, their response to relative humidity has been measured, suggesting a very promising application as humidity sensors. Furthermore, this ferromagnetic Mn-doped Fe<sub>3</sub>O<sub>4</sub> NW array can be also useful for high-density magnetic recording applications.

#### I14.41

**Coherent Growth of Semiconductor Nanocrystals on FePt Nanoparticles.** Shuli He<sup>1,2</sup>, Savas Delikanli<sup>1</sup>, Hongwang Zhang<sup>1</sup> and Hao Zeng<sup>1</sup>; <sup>1</sup>Physics, University at Buffalo, SUNY, Buffalo, New York; <sup>2</sup>The Capital Normal University, Beijing, China.

Synthesis of hybrid nanoparticles opens up new possibilities for investigating interactions between different nanoscale components and new technological applications based on combinations of materials properties which is not available in homogeneous nanoparticles. The peanut-like



FePt-CdS and core/shell structured FePt-PbS nanoparticles based on spontaneous epitaxial nucleation and growth of the semiconducting component onto FePt-seed nanoparticles were synthesized in high-temperature organic solution phase. X-ray diffraction (XRD) results indicate that FePt nanoparticles have a fcc structure, CdS and PbS components are both of zinc blend structure. Transmission electron microscopy (TEM) images show core/shell FePt/PbS nanoparticles with about 4nm core and 3nm shell, and peanut-like FePt/CdS nanoparticles with about 5nm FePt and 7nm CdS. The interface between FePt and semiconductor nanoparticles is coherent. Both the magnetic properties of FePt and luminescence properties of CdS/PbS are retained. The photoluminescence intensity of the semiconducting component is significantly reduced compared to their single component counterparts, suggesting charge transfer between the semiconducting and magnetic components.

#### I14.42

**Synthesis and Characterization of PMMA Coated Magnetite Nanocomposites by Emulsion Polymerization.** Ming Zhang<sup>1,2</sup> and Charles J O'Connor<sup>1,2</sup>; <sup>1</sup>Department of Chemistry, University of New Orleans, New Orleans, Louisiana; <sup>2</sup>Advanced Materials Research Institute, University of New Orleans, New Orleans, Louisiana.

Poly (methyl methacrylate) (PMMA) coated magnetite nanocomposites have been successfully synthesized by emulsion polymerization method. The composites show the well-defined core-shell structure and superparamagnetic property. The hydrophobic magnetite nanoparticles were prepared in high temperature organic solution separately and introduced to the emulsion system with the initiator and hydrophobic monomer such as MMA to form the core-shell structure nanocomposites. The morphology, structure, composition and magnetic property of the products were investigated by transmission electron microscopy (TEM), X-ray powder diffraction (XRD), SQUID magnetometry and FTIR spectroscopy.

#### I14.43

**Design and Magnetic Performance of High-Spin Organic Polymer: Nanometer-Sized and Branched Poly(aminium triphenylene).** Takeshi Ibe, Shu Kaiho and Hiroyuki Nishide; Department of Applied Chemistry, Waseda University, Tokyo, Japan.

A large number of high-spin molecules and polymers have been synthesized as possibly candidates for a purely organic-derived magnetic materials in the past two decades. The arylaminium radicals are attractive radical spin sources satisfying a substantial chemical stability even at room temperature. [1] In this report, a method has been developed for defect-rarely p-doping of arylamine polymers based on an expanded triphenylenetriamine motif. The quantitatively p-doped arylamine polymers afford stable high-spin state with a large magnetic moment. The oxidative doped polyarylamines, poly(aminium cationic radical)s, were generated by chemical oxidation of the corresponding neutral polyarylamines synthesized by the palladium-catalyzed polycondensation of triphenylene or naphthalene monomers. The polyradicals were stable even at room temperature under air atmosphere: lifetime > 1 month at ambient conditions. The SQUID measurement indicated a very high-spin alignment with spin quantum number  $S > 10$  on the polyaminium radical. The  $S$  was tunable with a doping amount. The polymers were soluble in common organic solvents, to yield as a flexible film or a solid powder. The nanometer-sized polyradicals were detected by atomic and magnetic force microscopies. [1] E. Fukuzaki, and H. Nishide, J. Am. Chem. Soc. 128, 996 (2006)

#### I14.44

**Novel Multifunctional PHDCA/PEI Nano-drug Carriers (MPDCs) for Simultaneous Magnetically-targeted Cancer Therapy and Diagnosis via Magnetic Resonance Imaging (MRI).** Sung-Baek Seo<sup>1,2</sup>, Jaemoon Yang<sup>2</sup>, Woochan Hyung<sup>2</sup>, Eun-Jin Cho<sup>1,5</sup>, Yongjin Song<sup>3</sup>, Ho-Geun Yoon<sup>4</sup>, Jin-Suck Suh<sup>1,5</sup>, Yong-Min Huh<sup>1,5</sup> and Seungjoo Haam<sup>1,2</sup>; <sup>1</sup>Chemical engineering, Yonsei university, Seoul, South Korea; <sup>2</sup>Graduate Program for Nanomedical Science, Yonsei University, Seoul, South Korea; <sup>3</sup>Department of Physics, College of Natural Science, Ajou University, Suwon, South Korea; <sup>4</sup>Department of Biochemistry and Molecular Biology, Yonsei University, Seoul, South Korea; <sup>5</sup>Department of Radiology, Yonsei University, Seoul, South Korea.

Novel multifunctional magnetic polycation drug carriers (MPDCs) were synthesized to provide simultaneous magnetically targeted cancer therapy and diagnosis via magnetic resonance imaging (MRI). The MPDCs consist of ultra-sensitive magnetic nanocrystals as MR probes and for magnetic targeting, and a chemotherapeutic agent encapsulated in poly(hexadecylcyanoacrylate) (PHDCA) nanoparticles. The PHDCA nanoparticles were further coated with polycationic polyethylenimine (PEI) to enhance cellular uptake efficiency. The MPDCs demonstrated ultra-sensitivity via MRI and sufficient magnetic mobility under an external magnetic field. Drug loading efficiency and release kinetics were also investigated. From the cell viability data, the MPDCs were non toxic and the DOX-loaded MPDCs exhibited excellent tumoricidal efficacy.

#### I14.45

Abstract Withdrawn

#### I14.46

Abstract Withdrawn

SESSION I15: Magnetic Materials for Biomedical Applications  
Chairs: Jinming Gao and J. Ping Liu  
Friday Morning, November 30, 2007  
Commowearth (Sheraton)

#### 8:30 AM I15.1

**Fabrication of Multifunctional Heterostructured Magnetic Nanoparticles.** Yun-Hao Xu, Xiaoqi Liu and Jian-Ping Wang; Department of Electrical and Computer Engineering, University of Minnesota, Minneapolis, Minnesota.

Magnetic nanoparticles (NPs) have been demonstrated to have great potential in medical applications such as cancer diagnosis and therapy as well as information technology such as spintronics and data storage. For most of these applications, multifunctionality is required. For example, to facilitate the usage of magnetic NPs in various biomedical applications, a biocompatible surface is needed in addition to the magnetic properties of



the NPs. In this presentation, we report the fabrication of high quality multifunctional heterostructured magnetic nanoparticles.[1] The NPs were synthesized directly in gas phase with no post-treatment required.[2] A case with particular interest of biomedical applications will be presented in detail. The NPs consist of three elements, Fe, Co and Au, in the form of FeCo alloy core and Au shell, indicated by composition analysis on single particle. FeCo alloy has the highest saturation magnetization among currently available materials while Au is very easy to work with through thiol-chemistry. The NPs have cubic shape and high crystallinity. Electron diffractions as well as high resolution transmission electron microscopy (HRTEM) images have been used to reveal the epitaxial relationship between bcc FeCo and fcc Au. Another application of the technique with great interest is exchange-spring magnet, which has been proposed to increase the energy product (BH)<sub>max</sub> for permanent magnets by coupling hard and soft magnetic materials.[3] Magnetically hard (L10) FePt NPs were synthesized in gas phase [4] and embedded in a magnetically soft FeCo matrix in situ, which combines the high anisotropy of FePt and high magnetization of FeCo into the composite. Alternatively, heterostructured NPs coupling hard and soft magnetic components at single particle level are also achievable by the technique. Results on CoCr and some ternary alloys will be presented as well. [1] Y. H. Xu et al, J. Magn. Magn. Mater. 311 (1), 131 (2007). [2] H. Haberland et al, J. Vac. Sci. Technol., A 10 (5), 3266 (1992). [3] E. F. Kneller and R. Hawig, IEEE Trans. Magn. 27 (4), 3588 (1991). [4] J. M. Qiu and J. P. Wang, Adv. Mater. (2007); Appl. Phys. Lett. 88 (19) (2006).

8:45 AM I15.2

Abstract Withdrawn

9:00 AM \*I15.3

**Surface Functionalization of Iron Oxide Nanoparticles.** Jinhao Gao<sup>1</sup>, Bei Zhang<sup>2</sup>, Xixiang Zhang<sup>2</sup> and Bing Xu<sup>1</sup>; <sup>1</sup>Chemistry, The Hong Kong University of Sci. and Technol., Hong Kong, China; <sup>2</sup>Physics, The Hong Kong University of Sci. and Technol., Hong Kong, China.

Iron oxide nanoparticles are an important class of nanomaterials for a broad range of biomedical applications because of their superparamagnetism and biocompatibility. The success of the biomedical application of iron oxide nanoparticles also relies on their surface functionalization, which requires a robust and versatile surface anchor. Here we report the detailed examination on the dopamine-based surface modification of iron oxide nanoparticles. We use dopamine (2-(3,4-dihydroxyphenyl)ethylamine) and L-dopa (3,4-dihydroxy-L-phenylalanine) as two surface modifiers and choose Fe<sub>2</sub>O<sub>3</sub> hollow nanoparticles and Fe<sub>3</sub>O<sub>4</sub> nanoparticles as two representative substrates. Optical and TEM images prove that iron oxide nanoparticles are dispersed very well in hexane or water before and after surface modification, respectively. The analysis of UV-Vis spectra indicates that dopamine and L-dopa are stable before and after being immobilized on the surface of iron oxide nanoparticles when the pH value of the environment is about 7. The magnetic properties (SQUID) analysis further shows that the magnetic moments of the decorated iron oxide nanoparticles change very little, indicating no degradation of the nanoparticles. Thus, dopamine indeed serves as a robust anchor for the surface functionalization of iron oxide nanoparticles that are useful for biomedical applications. In this talk, we will also discuss several applications of biofunctional iron oxide nanoparticles that used dopamine as an anchor.

9:30 AM I15.4

**Colloid Stability of Multifunctional Biopolymer Modified Magnetic Nanoparticles for Cellular Interactions.** Nefertiti Patrick<sup>1,2,3</sup>, Ebony Ayres<sup>3</sup>, Otto Wilson<sup>1</sup>, Patrick Mehl<sup>4</sup>, Gary Harris<sup>3</sup> and Winston Anderson<sup>5</sup>; <sup>1</sup>Biomedical Engineering, The Catholic University of America, Washington, District of Columbia; <sup>2</sup>Applied Physics, University of Michigan, Ann Arbor, Michigan; <sup>3</sup>Materials Science and Engineering, Howard University, Washington, District of Columbia; <sup>4</sup>Biomagnetics, The Catholic University of America, Washington, District of Columbia; <sup>5</sup>Biology, Howard University, Washington, District of Columbia.

The surface chemistry of magnetic nanoparticles (mnps) is a very important parameter in controlling the colloid stability and interactions with biologically based cells. The influence of natural polymers (chitosan, gum Arabic) and synthetic polymers (polyethyleneimine (PEI)) on the chemical and physical characteristics of mnps was studied via dynamic light scattering, electrophoretic light scattering, and transmission electron microscopy. The time of addition for the natural polymers played a role in the overall particle size and colloid stability for the mnps. The incorporation of chitosan during the synthesis procedure resulted in a noticeable increase in the particle size of the mnps from approximately 20 nm for mnps synthesized in the absence of biopolymer to greater than 75 nm for mnps synthesized in the presence of chitosan. The presence of gum Arabic during the synthesis reaction resulted in an even greater size increase (> 200 nm). The size increase was most likely due to polymer bridging and agglomeration effects. The electrophoretic mobility for the mnps was negative at physiological pH and only in the presence of PEI were positive electrophoretic mobilities achieved. The implications of mnp electrophoretic mobility on cell uptake and cell viability for fibroblast and prostate carcinoma cells will be highlighted in this talk.

9:45 AM I15.5

**Cell Specific Targeting of Multifunctional  $\gamma$ -Fe<sub>2</sub>O<sub>3</sub> Nanoparticles Through Surface Binding of dsRNA.** Wolfgang Tremel<sup>1</sup>, Ibrahim Shukoor<sup>1</sup>, Filipe Natalio<sup>2</sup>, Muhammad Nawaz Tahir<sup>1</sup>, Werner E. G. Mueller<sup>2</sup> and Heinz-Christian Schroeder<sup>2</sup>; <sup>1</sup>Chemistry, Universität Mainz, Mainz, Germany; <sup>2</sup>Chemistry, Universität Mainz, Mainz, Germany; <sup>3</sup>Medicine, Universität Mainz, Mainz, Germany; <sup>4</sup>Chemistry, Universität Mainz, Mainz, Germany; <sup>5</sup>Medicine, Universität Mainz, Mainz, Germany.

One of the emerging goals of nanotechnology is to functionalize inert and biocompatible materials to impart precise biological functions. Significant research efforts have been made to tailor the nanoparticle surfaces and in order to modulate pharmacokinetic properties. Nanomaterials can be synthesized and loaded with traditional low molecular drugs as well as with high molecular peptides, proteins and ribonucleic acids (RNA) which are inherently difficult to deliver due to their size and polarity. RNA is an emerging biopharmaceutical drug class, which can be applied as regulators of cellular gene expression (siRNA, microRNA), as well as immune stimulators and recombinant vaccines. The high potential of antigen coding RNA as recombinant vaccines for prevention and therapy of infectious diseases and cancer is limited by its fast degradation in extracellular space. Immobilization onto magnetic nanocarriers may turn out to be a promising option to circumvent the degradation of vaccine RNA thereby improving its immunopharmacological properties. From a therapeutic viewpoint, the simultaneous activation of several receptors or the potential for binding to different targets would offer new and intriguing perspectives. From an analytical point of view, the availability of multifunctional carrier particles would greatly enhance the application potential, as it permits the manipulation and the simultaneous monitoring of drug loaded particles. In this contribution we demonstrate that double stranded RNA [poly(IC)] can be immobilized onto  $\gamma$ -Fe<sub>2</sub>O<sub>3</sub> nanoparticles carrying a protective thin silica coating



containing an embedded fluorescent dye. The silica layer can be functionalized using conventional silanization techniques. Subsequently, the free amino head group of the silane monolayer can be used for the specific binding of phosphate groups present in the nucleic acid polymer poly(IC). Poly(IC) contains a 5' end phosphate group which makes it amenable to functionalization by making use of phosphoramidate chemistry. The biological activity of these poly(IC) coated magnetic nanoparticles is demonstrated by cell receptor specific binding to Human Embryonic Kidney and breast cancer cells. In an alternative approach  $\gamma$ -Fe<sub>2</sub>O<sub>3</sub> and MnO nanoparticles were functionalized and protected using a multidentate functional copolymer carrying anchor groups for the surface binding to the iron oxide nanoparticles and free amino groups for the attachment of the poly(IC) ligands using phosphoramidite chemistry. A third active group of the block polymer can be used for binding fluorescent tags. Finally, polymer coated superparamagnetic  $\gamma$ -Fe<sub>2</sub>O<sub>3</sub> nanoparticles were derivatized with a synthetic double-stranded RNA [poly(IC)], a known allosteric activator of an enzyme, a latent synthetase, to separate a single 35 kDa protein from a crude protein abstract. The functionalized  $\gamma$ -Fe<sub>2</sub>O<sub>3</sub> can be recovered for further use.

#### 10:30 AM \*I15.6

**Magnetic Nanoparticles for Cancer Imaging and Drug Delivery Applications.** Jinming Gao, Simmons Comprehensive Cancer Center, University of Texas Southwestern, Dallas, Texas.

Nanoparticles with advanced magnetic properties have been actively pursued for potential biomedical applications, including molecular imaging, diagnosis, and therapy of cancer. Our lab is interested in the development of novel superparamagnetic nanoparticles as ultra-sensitive magnetic resonance imaging (MRI) contrast agents for cancer molecular imaging and targeted drug delivery applications. MRI is an important diagnostic imaging technique that provides superb *in vivo* imaging capability with excellent soft tissue contrast. However, the primary limitation of MRI in molecular imaging applications has been its lower sensitivity for the detection of targeted agents over other imaging modalities (e.g. nuclear imaging). Recently, we have synthesized a series of superparamagnetic iron oxide (SPIO) nanocrystalline structures with the general chemical formula Fe<sub>23</sub>+O<sub>3</sub>M<sub>2</sub>+O, where M<sup>2+</sup> is a divalent metal ion (e.g. Mn, Co, Zn). Compared to magnetite (Fe<sub>3</sub>O<sub>4</sub>) or commercial Feridex®, these new magnetic nanoparticles have shown increased saturated magnetization moment by SQUID analysis and enhanced transverse proton relaxation rates (1/T<sub>2</sub>) by MRI. In parallel, a new nanocomposite design of superparamagnetic polymeric micelles has also been developed by incorporating a cluster of the above nanoparticles into the hydrophobic cores of the polymeric micelles. Polymeric micelles are supramolecular core-shell nanoparticles that are self-assembled from amphiphilic block copolymers (e.g., poly(ethylene glycol)-poly(D,L-lactic acid), PEG-PDLA). The resulting nanoplateform has the following advantages in cancer imaging and drug delivery applications: (1) Clustering of SPIO nanoparticles inside the micelle core considerably increases the T<sub>2</sub> relaxivity (471 Fe mM<sup>-1</sup>s<sup>-1</sup> at 1.5 T) and the MR detection limit to nanomolar micelle concentrations; (2) Encapsulation of anticancer agents inside the micelle core introduces the therapeutic functions without affecting the other physico-chemical properties of the micelles; (3) Versatile surface chemistry allows for the attachment of biochemical ligands on the micelle surface to achieve cancer specificity. Specifically, cyclic Arg-Gly-Asp (cRGD)-encoded micelles were able to selectively target  $\alpha$ v $\beta$ 3 integrins, a molecular marker for tumor angiogenesis *in vitro* and *in vivo*. (4) Finally, *in vitro* cell culture experiments showed the feasibility of magnetic targeting where micelles with SPIO loading resulted in significantly increased micelle uptake in tumor cells under external magnetic field. These results demonstrate the exciting potential of magnetic nanoparticles for cancer molecular imaging and targeted drug delivery applications.

#### 11:00 AM I15.7

**Biomedical Engineered Ferrofluids.** Birgit Fischer<sup>1</sup>, Leidong Mao<sup>1</sup>, Mustafa Gungormus<sup>2</sup>, Candan Tamerler-Behar<sup>2,3</sup>, Mehmet Sarikaya<sup>2</sup> and Hur Koser<sup>1</sup>; <sup>1</sup>Electrical Engineering, Yale University, New Haven, Connecticut; <sup>2</sup>Materials Science and Engineering, University of Washington, Seattle, Washington; <sup>3</sup>Department of Molecular Biology and Genetics, Istanbul Technical University, Istanbul, Turkey.

Ferrofluids are colloidal suspensions comprised of nanosized magnetic particles that are stabilized with a surfactant [1]. Their unique characteristic of combining liquid and magnetic material properties has led to a myriad of technical and medical applications, including their use as liquid seals and bearings, in hard disk drives and speakers, as magnetic brakes, as contrast agents in magnetic resonance imaging and as targeted drug delivery conduits [2]. In most ferrofluid applications, stability of the colloidal suspension is critical. Agglomeration of particles eventually leads to product performance deterioration. In biomedical applications, particle agglomeration *in vivo* may even lead to dangerous scenarios, such as artery blockages and organ damage. Here we present a new approach to stabilizing water-based ferrofluids at neutral pH using genetically engineered peptides for inorganics (GEPI's). Such GEPI's selected for specific and strong binding to the surface of nanoparticles not only increase colloidal stability by acting as a thin surfactant, but they also enable an efficient route for rendering the ferrofluid bio-functional and bio-compatible. As part of this work, cobalt-ferrite magnetic nanoparticles were synthesized via the co-precipitation method [3] and covered with a thin silica shell (see Figure 1) [4]. The resulting ferrofluid was then mixed with silica-binding GEPI's and its stability was characterized using in a ferro-microfluidic device. This chip actuates the ferrofluid directly via magnetic fields alone, and the pumping spectrum as a function of frequency reveals information about the size of the magnetic nanoparticles [5]. An ideal ferrofluid with monodisperse particles displays a single and clear pumping peak; agglomeration can directly be observed as a broadening of the pumping spectrum. As depicted in Figure 2, adding GEPI's to the ferrofluid causes an increase in the amplitude of the peak and narrows it, indicating less particle agglomeration and a more ideal ferrofluid. Results of light-scattering experiments confirm that the GEPI's are binding to the magnetic nanoparticles and remaining bound even when the ferrofluids are significantly diluted; average nanoparticle hydrodynamic diameter increases slightly from 45.9 nm to 46.4 nm when the GEPI's are introduced. These values are consistent with peak locations in the pumping spectrum.

#### 11:15 AM I15.8

**Iron/Iron Oxide Nanocomposite Particles for Magnetic Hyperthermia.** Ian Baker<sup>1</sup>, Q. Zeng<sup>1</sup>, G. Zhang<sup>1</sup>, U. J. Gibson<sup>1</sup>, J. A. Loudis<sup>1</sup>, P. J. Hoopes<sup>1</sup>, J. B. Weaver<sup>1</sup>, R. R. Strawbridge<sup>2</sup>, Z. E. Pierce<sup>2</sup>, J. Tate<sup>2</sup>, J. Ogden<sup>2</sup> and K. Sung<sup>3</sup>; <sup>1</sup>Thayer School of Engineering, Dartmouth College, Hanover, New Hampshire; <sup>2</sup>Dartmouth Medical School, Dartmouth College, Hanover, New Hampshire; <sup>3</sup>Mount Holyoke College, South Hadley, Massachusetts.

Magnetic nanoparticles for hyperthermia applications for cancer treatment must develop sufficient heat at the lowest possible frequency and the smallest external magnetic field strength. In this paper, we describe the production and subsequent microstructural characterization of single-domain, Fe/Fe oxide core/shell composite nanoparticles for this application. The nanoparticles were synthesized, using a reverse micelle technique, to utilize the high M<sub>s</sub> of an iron core (120-190 emu/g, twice that of iron oxide), while the iron oxide coating provides contrast for the nanoparticles to be observed using magnetic resonance imaging (MRI) so that therapy can be effectively monitored and targeted *in vivo*. Both the quasi-static magnetic properties and the heating behavior under an alternating magnetic field of the nanocomposite particles are compared to those

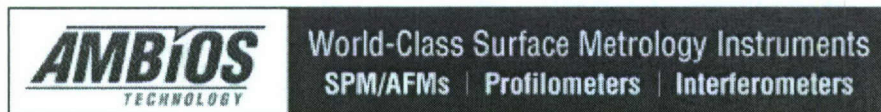


of dextran-coated, iron oxide nanoparticles under identical conditions. It will be shown that the Fe/Fe oxide nanocomposite particles not only showed superior heating behavior, but also showed good MRI contrast. Preliminary *in vivo* studies on mouse models directly injected with nanoparticles will also be presented. Supported by the NanoCancer Working Group at Dartmouth College, the Norris Cotton Cancer Center Prouty Pilot Project Program and NIST grant 60NANB2D0120.

11:30 AM \*115.9

**Magnetic Sifters and Nanoparticles for Molecular Biology and Medicine.** Shan X Wang<sup>1</sup>, Chris M Earhart<sup>1</sup>, Wei Hu<sup>1</sup>, Robert J Wilson<sup>1</sup>, Sebastian J Osterfeld<sup>1</sup>, Robert L White<sup>1</sup> and Nader Pourmand<sup>2</sup>; <sup>1</sup>Materials Science and Engineering, Stanford University, Stanford, California; <sup>2</sup>Stanford Genome Technology Center, Stanford University, Stanford, California.

Magnetic nanoparticles conjugated with biomolecules or recognition moieties are finding wide applications in medicine, most notably in magnetic separation and magnetic resonance imaging. In this context, we are developing a micromachined magnetic sifter and magnetic nanoparticles aimed for sample preparation applications in molecular biology and medicine. Current magnetic separation schemes fall into two categories: 1) columnar, macroscopic flow devices with externally applied magnetic field gradients, and 2) planar, microscopic flow devices with micropatterned magnetic elements. Columnar flow schemes offer high-throughput, but the large dimensions result in small field gradients insufficient for catching small (<100 nm) magnetic nanoparticles. The micropatterned magnetic elements in planar flow devices generate high magnetic field gradients, which can capture small particles, but the planar flow of the device severely limits throughput. We have fabricated a novel microfabricated sifter consisting of arrays of micron sized slits etched through a silicon wafer. A magnetic film is deposited on the wafer, producing high magnetic field gradients, comparable in magnitude to gradients in planar flow devices. As the solution flows through the die, magnetic particles are captured by the magnetic material surrounding the slits. The large number of slits allows for processing of large volumes of liquid, and the dies can be simply attached to a syringe or tube. These features combine the high-throughput advantage of columnar, macroscopic flow devices with the high field gradient advantage of planar flow devices. Initial experiments show separation efficiencies of ~ 30% for one pass through the sifter. Design issues and novel magnetic nanoparticles aimed at improving the capture efficiency and throughput will also be discussed. This work was supported by grants from NIH (1U54CA119367-01) and DARPA/Navy (N00014-02-1-0807), and Stanford Graduate Fellowship (Earhart).

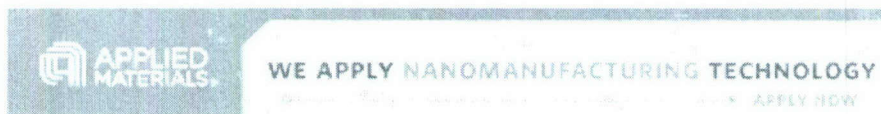


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