# Thursday Morning, November 3, 2011

**Magnetic Interfaces and Nanostructures Division**
**Room: 105 - Session MI-ThM**

## Emerging Magnetic Characterization and Results

**Moderator:** A.N. Caruso, University of Missouri-Kansas City

8:00am **MI-ThM1 The X-ray View of Ultrafast Nano Magnetism**, ***H.A. Durr***, SLAC National Accelerator Laboratory **INVITED**

Polarized soft x-rays have been used over the past 20 years to obtain fascinating new insights into nanoscale magnetism. The separation of spin and orbital magnetic moments, for instance, enabled detailed insights into the interplay of exchange and spin-orbit interactions at the atomic level. X-ray and photoelectron imaging techniques have revolutionized our understanding of magnetism of the ULTRA SMALL. In addition the now available polarized soft x-ray pulses with only few ps down to 100 fs duration allow us to observe the magnetic interactions at work in real time, i.e. they open the door to study ULTRA FAST magnetism. The ultimate goal of such studies is to understand how spins may be manipulated by ultrashort magnetic field, spin polarized current or light pulses. In this talk I will give an overview of achievements and the current status of probing magnetism of the ultra small and ultra fast using x-rays from synchrotrons [1-3] and more recently from x-ray free electron lasers.


[1] I. Radu, K. Vahaplar, C. Stamm, T. Kachel, N. Pontius, H. A. Durr, T. A. Ostler, J. Barker, R. F. L. Evans, R. W. Chantrell, A. Tsukamoto, A. Itoh, A. Kirilyuk, Th. Rasing, A. V. Kimel, *Transient ferromagnetic-like state mediating ultrafast reversal of antiferromagnetically coupled spins*, Nature **472**, 205 (2011).

[2] M. Wietstruk, A. Melnikov, C. Stamm, T. Kachel, N. Pontius, M. Sultan, C. Gahl, M. Weinelt, H. A. Dürr, U. Bovensiepen, Hot-Electron-Driven Enhancement of Spin-Lattice Coupling in Gd and Tb 4f Ferromagnets Observed by Femtosecond X-Ray Magnetic Circular Dichriosm,, Phys. Rev. Lett. **106**, 127401 (2011)

[3] C. Boeglin, E. Beaurepaire, V. Halté, V. Lopez-Flores, C. Stamm, N. Pontius, H. A. Dürr, J.- Y. Bigot, *Distinguishing the ultrafast dynamics of spin and orbital moments in solids*, Nature **465**, 458 (2010).


8:40am **MI-ThM3 Spectroscopy of Magnetic Thin Films**, ***S.N. Gilbert, N.H. Tolk***, Vanderbilt University

Recent studies of magnetic thin films and spintronic devices will be presented. Time-resolved Kerr Effect measurements of ferromagnetic/antiferromagnetic interfaces as a function of film layer thickness and antiferromagnetic spin orientation will be discussed. Magnetic and time-resolved spin characterization of novel spintronic devices and materials will also be shown.

9:00am **MI-ThM4 Detection and Control of Electronic Phase Competition in Complex Oxides**, ***T.Z. Ward***, Oak Ridge National Laboratory **INVITED**

Electronic phase separation is present in many complex material systems and has been linked to colossal magnetoresistance, high $T_c$ superconductivity, and multiferroicity. Here, nanometer to micron sized regions of vastly different electronic and magnetic properties can coexist and compete within single crystal materials. We will discuss recent work on fabricating single crystal wires of electronically phase separated manganites to a size comparable to the domains of the electronic phases residing in the material; thereby allowing finite emergent regions to dominate device characteristics. This has given us a means to probe, observe and exploit properties which are *hidden* in unconfined systems. Transport measurements on simple confined structures reveal new properties such as ultrasharp jumps in resistivity, a reemergent metal-insulator transition, and discreet resistive hopping that are unseen in larger samples. We have found that these properties are also tunable through doping, strain, electric field and magnitude of confinement. This ability to control key elements of the underlying complex electronic correlations and observe the resulting changes in a material's behavior help answer questions about the fundamental physics that rule emergent phenomena in complex materials while opening the door to new device functionality.

9:40am **MI-ThM6 Room-Temperature Spin-Polarized Scanning Tunneling Microscopy of Topological Antiferromagnetic Nanopyramids on $Mn_3N_2$(001) Surfaces**, ***K. Wang****, *A.V. Chinchore, W. Lin, A.R. Smith*, Ohio University

Antiferromagnets play a critical role in spintronic applications such as pinning layers in magnetic memories. The development of spin-polarized scanning tunneling microscopy and spectroscopy (SP-STM/STS) has shown its unprecedented power in resolving the local spin and domain structures of antiferromagnetic surfaces down to atomic level.[1-6] While most efforts have been made on imaging metal surfaces at cryogenic temperatures, only a few have been devoted to the study of room-temperature magnetic systems.[4-6] Here we apply SP-STM/STS to study the local spin and magnetic properties of a technologically driven material system which exhibits layer-wise antiferromagnetism with a very high Néel temperature (>900 K)[7]. $Mn_3N_2$(001) thin films have been grown on MgO(001) substrates using ultra high vacuum plasma-assisted molecular beam epitaxy and transferred *in situ* to a home-built room-temperature SP-STM[8] for magnetic imaging. Results have shown that the surface exhibits a *topological spin pyramid* structure with alternating single Mn- and double MnN- layers, where the magnetism is strongly correlated with the surface topography. Using SP-STM with *dI/dV* mapping, different layers can be clearly distinguished due to their different conductance. These differences in the conductance are a result of not only the different chemical environments, but also the spin ordering and the broken symmetry at the surface. We will show that it is possible to separate the contributions from both the electronic and the magnetic structure by applying a small magnetic field. The field rotates the tip magnetization axis causing concomitant change in the magnetic sensitivity while keeping the electronic structure unchanged. The demonstrated ability of direct imaging at room-temperature of the surface antiferromagnetic terraces allows further (ongoing) studies on the interplay between structural defects such as anti-phase domain boundaries and the formation of intriguing antiferromagnetic domains. We gratefully acknowledge support from the Department of Energy and the National Science Foundation.


1. R. Wiesendanger, Rev. Mod. Phys. **81**, 1495 (2009)
2. M. Bode *et al*, Nature Materials **5**, 477 (2006)
3. S. Heinze *et al*, Science **288**, 1805 (2000)
4. R. Wiesendanger *et al*, Science **255**, 583 (1992)
5. T. Kawagoe *et al*, Phys. Rev. Lett. **95**, 207205 (2005)
6. H. Yang *et al*, Phys. Rev. Lett. **89**, 226101 (2002)
7. A. Leineweber *et al*, J. Mater. Chem. **10**, 2827 (2000)
8. K. Wang *et al*, Rev. Sci. Instrum. 82, 053703 (2011).


10:40am **MI-ThM9 Growth Strategies for Mn Doping of Ge Quantum Dots: An STM Study of Reactions, Bonding and Phase Formation**, ***C.A. Nolph****, *K.R. Simov, P. Reinke*, University of Virginia

Manganese doped, magnetic germanium quantum dots are predicted to be important building blocks for the future of spintronic devices. The combination of quantum confinement and carrier mediated ferromagnetism make these structures particularly interesting. The goal of this work is to understand and control the Mn environment within the Si(100), Ge wetting layer and Ge quantum dot (QD) systems and understand how it influences the magnetic properties. Samples were investigated primarily using scanning tunneling microscopy followed by magnetic analysis using a vibrating sample magnetometer and one sample with x-ray magnetic circular dichroism. An important materials question is the competition to form secondary phases in this system at elevated temperatures, particularly Mn5Ge3 and Mn11Ge8 which are both ferromagnetic (TC = 294 – 296 K). We investigate three routes for Mn doping of Ge QDs : (1) The investigation of the stability and evolution of Mn nanostructures on a Si(100)-(2x1) reconstructed surface as a function of annealing temperature up to temperatures typical for Ge QD growth. At an annealing temperature of approximately 316°C, Mn adatoms move into Si sub-surface sites and we observe an electronic effect consistent with acceptor dopants. (2) The use of a surface driven approach where Mn is deposited on the Ge QD surface and forms well-defined islands on the QD and wetting layer surface. We observed the behavior of the Mn islands during STM measurement with increasing annealing temperatures and how the islands evolved via ripening and migration across the surfaces. In addition the structure and bonding of the Mn islands specifically on the Ge {105} facets will be discussed. (3) The co-deposition of Ge and Mn throughout the Ge QD growth process. For route (3) the highest Mn concentration is 23% which results in only minor

***** Falicov Student Award Finalist

perturbations in the Ge QD growth (fewer and smaller Ge QDs), albeit secondary phases form on the surface. Lower concentration samples (5% and 8% Mn) yielded high quality quantum dots and no observable secondary phases on the surface. We presume that when secondary phases form, the majority of the Mn deposited is consumed to form the secondary phases. The competition to form secondary phases is investigated further utilizing scanning auger microscopy to map Mn and low energy electron microscopy to study the growth sequence as a function of Mn concentration. Magnetism results from one particular sample (Mn0.05Ge0.95 QD) indicate a ferromagnetic material with a Curie temperature above room temperature. We'd like to acknowledge our funding support from NSF CHE-0828318 and DMR-0907234.

11:00am **MI-ThM10 Novel Iron-Induced Structures on Gallium Nitride (0001) and (000-1) Studied Using Scanning Tunneling Microscopy and First Principles Theory**, ***W. Lin***, Ohio University Nanoscale and Quantum Phenomena Institute, *H.A.H. Al-Brithen*, Ohio University Nanoscale and Quantum Phenomena Institute and KAIN, King Saud Univ., Saudi Arabia, *K.K. Wang, A.V. Chinchore, M. Shi, Y. Liu, N. Takeuchi, A.R. Smith*, Ohio University Nanoscale and Quantum Phenomena Institute

There is much interest in the field of spintronics in which magnetic phenomena are combined with electronic properties to form a new class of materials with added device functionality. An essential area is that of magnetic nanostructures on the surface of semiconductors. Gallium nitride represents one of the most important next generation semiconductors. The possibility for long spin lifetimes in GaN make it attractive as a spintronic material as well.[1] From this perspective, it is important to explore the epitaxial growth of ferromagnetic layers such as Fe at the surface of GaN. New results for the growth of Fe-induced structures on wurtzite GaN will be presented in this talk.

These investigations are carried out using a custom-designed, home-built molecular beam epitaxy/scanning tunneling microscopy (MBE/STM) facility. Growth of iron on GaN is carried out using an Fe effusion cell and at a substrate temperature which is carefully selected in order to produce the highest quality atomically-smooth Fe-induced structures. It is found that the Fe-induced structures on Ga-polar GaN(0001) strongly depends on the presence of the pseudo-1×1 surface structure as a starting surface, and that under the correct conditions a clear 6×6 reconstructed island structure grows outward from the GaN step edges, as revealed in scanning tunneling microscopy images. First-principles theoretical calculations have been carried out which suggest a low-energy model for the 6×6 structure consisting of Fe atoms embedded within the pseudo-1×1 layer and with Ga adatoms at the top.

The results for N-polar GaN(000$\underline{1}$) are quite different. In this case, deposition of Fe onto a Ga-rich surface results in the formation of uniform-height Fe-induced islands having a 4×2 zigzag row structure. The zigzag rows orient along the high symmetry [11$\underline{2}$0] directions of the surface.

Efforts are also underway to investigate the chemical stoichiometry, and electronic and magnetic properties of these Fe-induced structures and to explore the evolution of these monolayer films as additional Fe and/or Ga is added to the surface.

This work has been supported by the U.S. Department of Energy, Office of Basic Energy Sciences (Grant No. DE-FG02-06ER46317). Additional support from the National Science Foundation (Grant No. 0730257) is also acknowledged.

Y.L. is now at Los Alamos National Laboratory, Los Alamos, NM.

N.T. was a visiting Presidential Scholar from the Universidad Nacional Autónoma de México during 2010-11.

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11:20am **MI-ThM11 Scanning Tunneling Microscopy and Spectroscopy Performed on Single Mn Monolayer on Wurtzite (000-1) GaN**, ***A.V. Chinchore***, *K.K. Wang, A.R. Smith,* Ohio University, *V. Ferrari, A. Barral*, University of Buenos Aires, Argentina

The III-V diluted magnetic semiconductors (DMS) are a new class of materials with promising applications in spintronics.[1] The low solubility of transition metal atoms into III-V semiconductor host has been a key concern in the successful development of DMS. This low solubility however was used to advantage by Lu et.al. to develop an ideal magnetic/semiconductor bi-layer [2]. Wang et.al. recently reported high density 2D Mn-Ga stripe phases on Ga-Polar GaN(0001) surface, with interesting atomic spin arrangement. [3] The N-Polar GaN(000$\underline{1}$) 1×1 structure offers an added advantage over the Ga-Polar structure, as the Mn atoms deposited on this surface are in closer proximity to the N atoms favoring the GaMnN bonding.

We have conducted a series of experiments aimed at understanding the behavior, electronic and magnetic properties of Mn atoms on N-Polar GaN(000$\underline{1}$) 1×1 surface. The experiments were conducted in a custom built MBE-STM system with *in-situ* sample transfer ability. The growth is monitored with reflection high energy electron diffraction (RHEED). The standard GaN(000$\underline{1}$) 1×1surface was prepared and was exposed to sub monolayer doses of Mn at various temperatures. It was observed that the behavior of Mn atoms on GaN(000$\underline{1}$) 1×1surface is highly sensitive to the substrate temperature ($T_s$). The low temperature Mn deposition, $T_s \sim 100$ °C, led to the formation of a metastable 3×3 structure which transformed to a more stable $\sqrt{3} \times \sqrt{3}$ R30° structure, when the sample is heated to $T_s \sim 120$ °C, as confirmed by RHEED. It was observed that the $\sqrt{3} \times \sqrt{3}$ R30° structure is stable up to 750 °C. The temperature dependent behavior of the structures suggests that the Mn atoms are *physisorbed* while forming the metastable structure and they are *chemisorbed* in the case of the stable $\sqrt{3} \times \sqrt{3}$ R30° structure. The STM measurements performed on the Mn 3×3 structure showing the metastable nature of the structure are presented as well are the STM and STS results showing the characteristics of $\sqrt{3} \times \sqrt{3}$ R30° surface. RHEED simulations confirming the surface atomic arrangement for the structure are presented. The theoretical calculations are performed using the first principles and the Tersoff-Hamann simulation method. The results indicate that the Mn atoms push the Ga atoms laterally in the surface ad-layer forming bonds directly with the bilayer N atoms. The funding from NSF and DOE for the project is greatly acknowledged.

**References.**

[1] T. Dietl et.al. Science 287, 1019 (2000).

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[3] K. Wang et.al. Phys. Rev. B 83, 165407 (2011)

11:40am **MI-ThM12 Designing of Engineered Multiferroic Composites by Radical Enhanced Atomic Layer Deposition**, ***J.H. Choi***, *T.E. Quickel, S. Tolbert, J.P. Chang*, University of California Los Angeles

Multiferroic materials induced polarization under external magnetic field H, or induced magnetization under external electric field E. Magnetoelectric (ME) phenomena in multiferroic materials holds considerable promises because of their potential applications in spintronics, such as magneto-electric sensors, magneto-capacitive devices, and electrically driven magnetic data storage. The ultimate goal for practical device application of multiferroic materials is dependent on how to create strong ME coupling between different types of ferroic order. The strictive interaction between the piezoelectricity of the ferroelectric (FE) phase and the magnetostriction of the ferromagnetic (FM) phase lead to produce larger ME coefficients than single phase multiferroic materials. Thus, the research has been directed towards designing engineered multiferroic composite materials in the form of horizontal multilayer (2-2), vertical superstructures (3-1) or other nanoparticle composite structures (3-0) in a precise controlled manner.

In this work, the $BiFeO_3$ (BFO) and $Pb(ZrTi)O_3$ (PZT) thin film were synthesized by radical enhanced atomic layer deposition (RE-ALD). RE-ALD is a gas-phase technique in which precursor vapors are pulsed alternately into the reaction chamber and the thin film growth proceeds through surface reactions in a self limiting manner. The advantages of ALD include excellent conformality, simple and accurate thickness control and good uniformity on large areas. In order to demonstrate conformal deposition of engineered multiferroic materials in the form of 3-0 or 2-2 configuration, PZT and BFO was deposited onto a mesoporous $CoFe_2O_4$ (CFO) substrate by RE-ALD.

The mesoporous CFO films were found to be fully filled by ALD PZT and BFO. The composition and crystal structure of the PZT-CFO and BFO-CFO systems were confirmed by X-ray Photon Spectroscopy and X-ray Diffraction (XRD), respectively. More detail crystal structure were investigated by synchrotron XRD and extended x-ray absorption fine structure spectroscopy (EXAFS). The magnetic and ferroelectric properties for the PZT-CFO or BFO-CFO systems were characterized by a superconducting quantum interference device (SQUID) magnetometer and piezoresponse force microscopy (PFM). Magnetic properties such as coercive magnetic field ($H_c$) and saturation moment ($M_s$) were systematically analyzed on composite systems and the pure CFO substrate. In addition, The P-E loops for PZT-CFO and BFO-CFO thin films were measured at room temperature and the saturation polarization ($P_s$) and coercive field ($E_c$) were investigated with respect to thickness and crystal plan.

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