Wednesday Afternoon, October 20, 2010

Magnetic Interfaces and Nanostructures
Room: Zuni - Session MI-WeA

Spintronic Devices and Proximity Effects
Moderator: R.A. Lukaszew, College of William and Mary

2:00pm **MI-WeA1 A New Twist on Spin Devices**, ***S. Wolf***, University of Virginia **INVITED**

The use of a spin polarized current to rotate the magnetization direction of a ferromagnetic has a number of important implications for novel magnetic devices. Spin torque can switch the resistivity of a magnetic tunnel junction, create spin waves over a very wide range of frequencies, and move magnetic domain walls. I will describe some of the recent advances in Spin Torque Magnetic Random Access Memory (STT-RAM), spintronic nano-oscillators and flux shuttle memory. In addition I will describe a very novel logic array based on electrical control of magnetism called a Reconfigurable Array of magnetic Automata which uses the ferroelastic strain on a magnetic nanopillar to rotate the direction of magnetization. I will show how this can be used to perform logic at very low power approaching zeptojoules per switch..

2:40pm **MI-WeA3 Thermal Stability and Switching Distributions in Nanoscale Spin Torque Transfer Random Access Memory Devices**, ***S.E. Russek****, R. Heindl, W.H. Rippard, M.R. Pufall, T. Cecil*, NIST-Boulder

Thermal stability and switching distributions of MgO magnetic tunnel junction (MTJ) devices, that are being developed for spin-torque-transfer random access memory (STT-RAM), have been modeled using single domain simulations. The simulations incorporate realistic current-voltage characteristics, a field-like torque term and thermal heating. These elements are required to allow the single domain model to fit data from standard STT-RAM devices. Simulations were performed with a stochastic thermal field with 10,000 repetitions for each value of applied current and pulse duration. For a typical STT-RAM device with dimensions of 50 nm x 150 nm, at room temperature, with a 10 ns pulse width, the write error rate (WER = 1- switching probability) falls off at a rate of 40 mV/decade. To achieve a write error rate below 10-9, which is a typical value for current memory, the switching voltage must be 360 mV above the intrinsic switching voltage. The direction of the spin polarizer was systematically varied and it was found that switching probability decreases as the polarizer is moved off the device easy axis. The fall off in WER with pulse amplitude remained roughly constant.

The simulations are compared to data from devices consisting of a Co40Fe40B20 free layers, 1.1 nm MgO tunnel barrier, and a synthetic antiferromagnetic fixed layer. The average resistance area product (RA) and tunneling magnetoresistance (TMR) are RA=5 Ohm micrometer2 and TMR=150%, respectively. The devices were patterned using e-beam lithography and ion beam etching into ellipsoids of sizes ranging between 50 nm x 150 nm to 100 nm x 300 nm (all with aspect ratios 1:3). The devices were imbedded in a high frequency coplanar wave guide structure to allow high-speed switching and high-frequency thermal ferromagnetic resonance (FMR) measurements. The high speed switching measurements confirmed that simple thermally activated switching modelscannot accurately fit the measured data. The single domain simulations, with a field like torque term and thermal heating, can replicate several key features of the measured switching distribution. The thermal FMR data, however, often show a complex mode structure indicating that the real devices deviate considerably from simple single domain behavior.

These results indicate that slow fall off of the WER may be a key problem for STT-RAM technology. Within the single domain model, the slow fall off of the WER is intrinsic. To obtain a more rapid fall off in the WER, micromagnetic design concepts must be employ to prevent the device from accessing low torque configurations during the switching process.

3:00pm **MI-WeA4 Growth and Magnetism of Mn-nanostructures Embedded in a Group IV Semiconductor Matrix**, ***K.R. Simov***, University of Virginia, *C.A. Jenkins, M. Liberati,* Lawrence Berkeley National Laboratory, *P. Reinke*, University of Virginia

The magnetic doping of the group IV semiconductors Si and Ge with Mn is coveted as valuable component in novel spintronics devices. Their magnetic doping is hampered by the low solubility of Mn in both elements, and the formation of silicide and germanide phases which modify or suppress the magnetic response of the material. We therefore investigate Mn-nanostructures which are synthesized on the Si(100)(2x1) surface and then capped with a layer of Si or Ge to protect the integrity of the nanomaterial. The Mn-nanostructure is therefore embedded as a delta-doped layer within a group IV semiconductor matrix.

The first section of our presentation focuses on nanostructure synthesis, in particular the growth of monoatomic Mn-wires on the Si(100)(2x1) surface, where the dimer row structure guides the wire formation. A scanning tunneling microscopic (STM) study establishes the relation between the nanostructure type and the quality of the substrate, which is expressed in the concentration of defects prior to Mn deposition. An increasing defect concentration (1.0 % to 18.2%) leads to a suppression of wire formation and the growth of ultrasmall Mn-clusters is favored, which allows for an excellent control of nanostructure type. Surface structuring through the presence of dimer vacancy lines, or narrow terraces offer an additional route to control Mn-wire formation. A Monte-Carlo based model is introduced to describe the surface processes which lead to wire-formation.

The second section of our presentation assesses the stability of the nanostructures during the growth of the Si or Ge caps. The capping of nanostructures is indispensible for preservation of the nanostructures' unique capabilities in devices, and is critical for magnetic measurements such as VSM (vibrating sample magnetometry) and XMCD (X-ray magnetic circular dichroism, Advanced Light Source, Lawrence Berkeley National Laboratory). An STM observation of the growth process of the Si and Ge caps shows that the Mn-nanostructures are indeed preserved, and we are therefore able to assess the magnetic properties of Mn-wires and ultrasmall clusters.

The third section of our presentation is devoted to the discussion of the magnetic properties of the Mn-wire and Mn-cluster structures. The role of magnetic anisotropy, the ionic and metallic contributions from the Mn-nanostructure, and the nature of the magnetic coupling within the respective nanostructure, and with the cap-material will be discussed.

The support from NSF-Chemistry and DOE are gratefully acknowledged.

4:00pm **MI-WeA7 Exchange Bias Using Ideal Antiferromagnets**, ***D. Lederman***, West Virginia University **INVITED**

Exchange bias is the interaction at the interface between an antiferromagnetic material and a ferromagnetic thin film or nanoparticle which causes the center of the ferromagnetic hysteresis loop to shift away from zero field, effectively resulting in a unidirectional anisotropy. Despite the fact that this effect was discovered approximately fifty years ago, and that it is used in magnetic sensors found in hard drives, the fundamental mechanism responsible for this interaction was poorly understood until recently. Important advances using ideal antiferromagnets (antiferromagnets with well understood and relatively simple properties) have been made during the past few years to assess or validate theories that explain exchange bias. My group has used transition metal difluoride epitaxial thin films, such as $Fe_xZn_{1-x}F_2$ and $Fe_xNi_{1-x}F_2$, which allow us to vary the magnetic disorder and anisotropy of the antiferromagnet in a controlled manner. Traditional magnetometry techniques, as well as more sophisticated experiments sensitive to the depth profile of the magnetization, such as x-ray magnetic circular dichroism (XMCD) and polarized neutron reflectivity (PNR), have allowed us to understand the interface processes responsible for the effect. I will discuss the important results from these experiments, including 1) the effects of short range order at the surface of the antiferromagnet above its Néel temperature; 2) the observation of pinned and unpinned magnetic moments at the ferromagnet/antiferromagnet interface; and 3) the effects of the magnetic anisotropy of the antiferromagnet on the temperature dependence of the exchange bias and the possibility of reversing the effect at low temperatures.

This work was supported by the National Science Foundation.

4:40pm **MI-WeA9 Spintronic Effects in Molecular Materials: The Past, Present, and Future**, ***G.J. Szulczewski***, The University of Alabama **INVITED**

In this talk I will introduce the general concepts of spintronics and highlight some of the key experimental results that have catalyzed the emerging research area known as "organic spintronics". The confluence of spin-electronics, which combines transition metal ferromagnets and inorganic semiconductors, and molecular-electronics, which combines organic semiconductors and non-magnetic metals, has lead to the evolution of organic spintronics. Furthermore, the development of organic light emitting diodes and organic photovoltaic cells has proven that molecular thin films can reliably function as the active layer in commercial products. Consequently it often envisioned that spin dependent conduction in organic-based semiconductors, rather than traditional charge transport, can be

manipulated and detected to fabricate low-power, non-volatile, multifunctional devices because electron spin coupling to orbital angular momentum and nuclear spin is weak. Recent experimental evidence is beginning to demonstrate this view is too simplistic and hyperfine coupling is very important in the hopping transport mechanism characteristic of disordered organic semiconductors.

The focus of this talk will be on the phenomena of magnetoresistance; specifically in vertical device structures with conducting electrodes used to separate an organic semiconductor layer(s). In many laboratories around the world such devices are observed to change resistance when placed in an external magnetic field. If both electrodes are magnetic and the change in the resistance corresponds to the coercive fields of the electrodes, then the magnetoresistance can be interpreted as spin-polarized injection, transport, and ejection of carriers from one ferromagnetic layer, through the non-magnetic spacer layer, and into the second ferromagnetic layer, respectively. However, when neither of the electrodes is magnetic the magnetoresistance must arise some other phenomena and there are several competing theories to describe the effects. The bulk of this talk will be devoted to reviewing case studies from the former class of devices, since there are well-accepted criteria to support the interpretation of device magnetoresistance when using magnetic electrodes. In addition I will cite examples where the interfaces of the devices have been examined by surface sensitive spectroscopy/microscopy techniques and correlated to device performance. Finally I will conclude by recommending some new experiments that could reveal more knowledge of the fundamental spintronics effects in molecular materials and suggest some possible applications.

5:20pm **MI-WeA11 Probing Induced Magnetism in Vanadium Nano-islands on Cr by Spin-polarized STM**, ***C. Clavero***, College of William & Mary, *M. Bode*, Argonne National Laboratory, *G. Bihlmayer*, *S. Blügel*, Institut für Festkörperforschung, Germany, *R.A. Lukaszew*, College of William & Mary

The growth mode and magnetism at V(001)/Cr(001) interfaces are still controversial and in recent years have attracted considerable theoretical and experimental interest since they strongly affect the properties of multilayered structures prepared with these materials. Both V and Cr are *bcc* 3*d* transition metals with approximately half-band filling. Cr exhibits antiferromagnetism along the <001> direction which converts the (001) surfaces to ferromagnetic (001) planes that couple antiferromagnetically from layer to layer. Interestingly, it has been theoretically predicted that a single V layer on Cr couples antiferromagnetically to Cr with an induced V moment of 2.1 μ_B/atom, but drastically reducing the Cr magnetic moment[1]. Previous reports using Mössbauer spectroscopy[2] applied to Cr/V multilayers have given direct experimental evidence for a reduction of the Cr magnetic moment near the interface region. In addition, recent neutron scattering experiments have shown that proximity effects in Cr/V multilayers lead to the appearance of a 50 Å magnetically dead Cr layer near the interfaces[3].

Despite the interest in V/Cr(001) interfaces, possible magnetic polarization of V by proximity to the antiferromagnetic Cr(001) substrate has not been yet fully investigated. We report on our spin-polarized scanning tunneling microscopy (SP-STM) studies on subatomic layer coverings of V on Cr(001) substrates and experimentally demonstrate antiferromagnetic coupling between V islands and the Cr(001) underlying surface. V was evaporated on Cr(001) substrates under ultra-high vacuum conditions (base pressure in the low 10-11 mbar) and at 250 ºC, temperature reported as optimum to achieve high quality multilayers with abrupt interfaces2. V coverages ranging from 0.1 to 1.5 atomic layers (AL) where explored. Antiparallel coupling between the V islands and the Cr(001) substrate is found, with the magnetic contrast disappearing when the V islands start to coalesce for increasing coverages starting at 0.9 AL. In addition, using Scanning Tunneling Spectroscopy and density functional theory calculations, it was found that during the early stages of growth the islands exhibit radial symmetry in their chemical composition, with Cr-rich composition in the center and V-rich regions at the rims. Interestingly, for higher coverages such islands coalesce evidencing an island assisted interface alloying mechanism.

References

[1.] G. Bihlmayer, T. Asada and S. Blugel, Phys. Rev. B **62** (18), 11937 (2000).

[2.] K. Mibu *et al*., J. Magn. Magn. Mat. **226-230** (Part 2), 1785-1787 (2001).

[3.] E. Kravtsov *et al*., Phys. Rev. B **76** (2), 024421 (2007).

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