Magnetic Interfaces and Nanostructures Technical Group
Room 618/619 - Session MI+EM-WeM

Spin-Dependent Tunneling and Transport

Moderator: K. Bussmann, Naval Research Laboratory

8:20am **MI+EM-WeM1 Models of Spin-dependent Tunneling**, ***S. Zhang***, University of Missouri, Rolla **INVITED**

There are a number of theoretical models of spin-dependent tunneling. Some are based on toy models and others are built on electronic structures of ideal tunnel junctions obtained from ab-initio methods. The question is whether these models are relevant to the experimental realization of the magnetotransport of magnetic tunnel junctions. We analyze these model predictions by taking into account non-ideal nature of the magnetic tunnel junctions studied to date. It is shown that most of the theoretical conclusions are not reliable in interpreting experimental data. There are at least three intrinsic mechanisms on the voltage dependence of magnetoresistance: the effect of electronic structure, inelastic tunnel channels, and spin-dependence of electric field penetrations. The last effect comes from spin-polarized electron screening. When a voltage is applied across a magnetic tunnel junction, charges and spins are accumulated at the interfaces. The conduction electrons tend to screen these charges and spins via Coulomb and exchange interactions; this leads to a spin-dependent voltage absorption by the electrodes. We calculate the voltage dependence of magnetoresistance by including this field penetration effect. When one considers magnetic tunnel junctions beyond simple trilayer structures, e.g., double barrier junctions, a number of additional complications arise. Among them, the energy and spin relaxation of tunnel electrons becomes important. We examine these processes in detail, and present the I-V characteristics and junction magnetoresistance for both two-terminal and three-terminal geometries.

9:00am **MI+EM-WeM3 High Performance Demonstration of Magnetic Tunnel Junction Random Access Memory***, ***W.J. Gallagher***, *S.L. Brown, Y. Lu, E.J. O'Sullivan, P.L. Trouilloud, D.A. Abraham, J. Bucchignano, R.H. Koch, Y.H. Lee, R. Robbertazzi, M. Rooks, J. Yoon, R.A. Wanner, S.S.P. Parkin, D. Pearson, K.P. Roche, M.G. Samant, P.M. Rice, A. Lee, R.E. Scheuerlein,* IBM **INVITED**

We describe a magnetic tunnel junction (MTJ) RAM demonstration involving the integration of 0.25 µm CMOS technology with a special research-scale magnetic tunnel junction "back end." The magnetic back end is based upon state of the art mutilayer magnetic growth technology available on a research scale. For the demonstration, the wafers were cut into one-inch squares for depositions of bottom-pinned exchange biased magnetic tunnel junctions. The samples were then processed through four additional lithographic levels to complete the circuits. Special care was required to achieve fine lithography on the one-inch pieces aligned to the underlying circuits. Both deep uv stepper lithography and e-beam lithography were utilized. Patterning of the magnetic layers involved physical removal of the magnetic material by means of ion beam milling, an etching process not commonly used in semiconductor technology. Redeposition, which accompanies ion milling and is exacerbated in dense arrays, had to be carefully controlled with combinations of angled mills in order to minimize the occurrence of junction shorts and maximize the yield of working bits. Key performance aspects demonstrated in 1 K bit arrays included reads and writes in less than 10 ns and nonvolatility. These results suggest that MTJ MRAM might simultaneously provide much of the functionality now provided separately by SRAM, DRAM, and NVRAM. . @FootnoteText@ @footnote *@ Work supported in part by DARPA contract MDA972-96-C-0014.

9:40am **MI+EM-WeM5 Pinhole Decoration in Magnetic Tunnel Junctions**, ***D. Allen***[1], *R. Schad, G. Zangari, I. Zana, D. Yang,* University of Alabama; *M.C. Tondra, D. Wang,* Nonvolatile Electronics

Magnetic tunnel junctions are of interest for their possible applications in magnetic sensors and nonvolatile memory devices. The possibility of local shortcuts in the insulating layers of magnetic tunnel junctions, known as pinholes, can cause malfunctions in these devices. The reduction of insulator thicknesses will make this problem more severe. The ability to image pinholes could lead to further development of magnetic tunnel junctions. The imaging of structures that are not directly observable with imaging is traditionally done by decoration. This can be achieved by exploiting the conductivity of the pinholes. We decorated pinholes in a 1.8nm thick Al@sub2@O@sub3@ layer by electrodeposition of copper. These copper cauliflower-like structures can be imaged by conventional microscopies. Dielectric breakdown could be a source of pinhole creation. Applying 0.5 V for electrodeposition (as used here) would exceed the breakdown threshold for weak points in the insulator. This would create pinholes at points with insulator thickness less than 0.5 nm. This is an opportunity of the method. Upon application of increasing voltage pulses prior to deposition it will allow discrimination of potential breakdown spots as a function of their thickness. The chemical conditions were tailored to avoid damaging the insulator layer or creating new pinholes. This was verified by studying surface roughness (Atomic Force Microscopy), chemical composition (X-ray Photoelectron Spectroscopy) and layering quality (X-ray Diffraction).

10:00am **MI+EM-WeM6 Novel Hybrid Magnetoelectronic Device for Magnetic Field Sensing**, ***D.M. Schaadt***, *E.T. Yu, S. Sankar, A.E. Berkowitz,* University of California, San Diego

Structures in which magnetic and electronic materials are combined offer a variety of possibilities for realization of devices with dramatically improved functionality or performance as compared to conventional devices. We have designed, characterized, and analyzed a novel hybrid magnetoelectronic device: a monolithic field-effect-transistor-amplified magnetic field sensor in which a granular Co-SiO@sub2@ tunnel magnetoresistive (TMR) thin film is incorporated into the gate of a p-channel Si metal-oxide-semiconductor field-effect transistor (MOSFET). In this structure, current flow through the TMR film leads to a buildup of electronic charge within the gate, and consequently to a transistor threshold voltage shift. For a fixed voltage applied across the TMR layer, an external magnetic field changes the TMR film resistance, and consequently the current and charge within the gate. The resulting threshold voltage shift leads to a pronounced response to the external magnetic field in the transistor current-voltage characteristics. The relative current change induced by application of a 6 kOe external magnetic field at room temperature was amplified from 5% for the current through the TMR film to 21% for the transistor subthreshold current. The absolute current response in the saturation regime increased by a factor of about 500 compared to that of the TMR film alone. These results were achieved in a non-optimized device structure; substantially better performance should be achievable with relatively straightforward improvements in device design and processing. A detailed analysis of the operation of this device and of methods for optimization of performance will be presented.

10:20am **MI+EM-WeM7 Andreev and Conduction Electron Spectroscopy of Interfacial Spin Transport**, ***R.A. Buhrman***, Cornell University **INVITED**

The enhanced interfacial conductance of an N-S contact, due to the Andreev reflection of electrons with energy below the superconducting energy gap, provides a powerful means of measuring interfacial transmission rates, as well as any net spin polarization in the non-superconducting electrode. Thus very small F-S nanocontacts can be used to quantitatively measure the interfacial transmission probability for each spin orientation. This technique can also be extended to the determination of the spin-dependent transmission rates through thin magnetic layers. We have produced F-S and N-F-S nanocontacts lithographically, and have determined the net spin-polarization of the direct current emerging from several bulk ferromagnetic films, and the spin filtering behavior of ultra-thin ferromagnetic layers. Measurements with different N electrodes illustrate the importance of the band structure mismatch in determining the degree of the spin-filtering. The bias dependence of the nanocontact interface resistance in the normal state can also be used to examine the degree to which the interface results in inelastic, spin-flip scattering processes. For certain N electrodes, very strong inelastic scattering is observed at relatively low energies. I will compare these single interface measurements with the current-perpendicular-to-the-plane magnetoresistance results that we have obtained with spin-valve and GMR nanopillar devices less than 100 nm in diameter. The low energy spin filtering measurements will also be compared with higher energy, ~ 1eV, spin filtering measurements that our group has been conducting with an STM-based magnetic microscope.

11:00am **MI+EM-WeM9 Spin-Polarization of La@sub 2/3@Sr@sub 1/3@MnO@sub 3@**, ***D.C. Worledge***, *T.H. Geballe,* Stanford University

Spin-polarized tunneling measurements using La@sub 2/3@Sr@sub 1/3@MnO@sub 3@/SrTiO@sub 3@/Al tunnel junctions are reported. The deposition technique and efforts to control the interface quality will be discussed. At sufficiently low temperatures the application of an applied

[1] **Falicov Student Award Finalist**

magnetic field splits the peaks in the dI/dV curve, allowing a measurement of the spin polarization to be made.

11:20am **MI+EM-WeM10 Electrical Spin Injection into LED Heterostructures***, **B.T. Jonker**, B.R. Bennett,* Naval Research Laboratory*; G. Kioseoglou, A. Petrou,* State University of New York, Buffalo

Optical excitation has routinely been used to create spin polarized carrier populations in semiconductor heterostructures. Surprisingly long spin lifetimes and diffusion lengths have been reported in optically pumped GaAs in studies which have addressed both semi-classical@footnote 1@ and quantum coherent regimes.@footnote 2,3@ It is very desirable to electrically inject spin polarized carriers via a ferromagnetic contact to increase the potential for practical applications. This has been an elusive goal, however, and only modest effects (@<=@ 1%) have been obtained.@footnote 4@ In an effort to investigate the efficiency of electrical spin injection into semiconductors, we have fabricated light emitting diode structures with ferromagnetic contacts. The radiative recombination of spin polarized carriers in quantum wells results in the emission of circularly polarized light, with the degree of optical polarization directly proportional to the carrier spin polarization. The samples consist of FM / InAs / AlSb / GaSb / AlSb heterostructures grown by MBE on p-GaAs(001) substrates in which the GaSb quantum well serves as the active region for radiative recombination. Standard optical lithography and chemical etch procedures were used to define mesa structures with transparent surface contacts. Measurements are performed as a function of injection current, magnetic field, and temperature. We compare results from ex situ contacts with those obtained from samples for which the ferromagnetic films are deposited in situ via MBE. @FootnoteText@ @footnote *@ This work was supported by the Office of Naval Research. @footnote 1@ D. Hagele, M. Oestreich, W.W. Ruhle, N. Nestle and K. Eberl, APL 73, 1580 (1998). @footnote 2@ A.P. Heberle, W.W. Ruhle and K. Ploog, PRL 72, 3887 (1994). @footnote 3@ J.M. Kikkawa and D.D. Awschalom, PRL 80, 4313 (1998); Nature 397, 139 (1999). @footnote 4@ Y.Q. Jia, R.C. Shi and S.Y. Chou, IEEE Trans. Magnetics 32, 4707 (1996).

11:40am **MI+EM-WeM11 Electron Spin Interferometry***, **C.H. Back**, S. Egger,* ETH Zürich, Switzerland*; J. Krewer,* Blaupunkt-Werke GmbH, Germany*; D. Pescia,* ETH Zürich, Switzerland

Quantum interference of electron waves in Fabry-Perot type solid-state resonators has been observed in a number of experiments. The applications of this phenomenon include quantum-well based semiconductor devices,@footnote 1@ accurate mapping of the band structure of solids and surfaces@footnote 2,3,4,5@ and visualizing the spatial dependence of quantum mechanical wave functions by means of Scanning Tunnelling Spectroscopy (STS).@footnote 5@ Here we use quantum interference to switch the spin state of the electrons. The spin quantum resonator consists of a Cu-film of variable thickness sandwiched between vacuum and a magnetic Co-film. Electrons are injected into the resonator from the vacuum side. The Co-film provides a spin dependent reflector. Varying the resonator thickness results in periodic switching of the spin state of the specularly reflected electrons. We apply spin interferometry to study oscillatory interlayer exchange coupling and find a divergence of the coupling period predicted by theory.@footnote 6@ We discuss the implications of spin interferometry as spin polarimeter or spin polarized source and propose that interferometric spin selection should be observable in Spin Polarized STS. @FootnoteText@@footnote 1@Corcoran, E., Diminishing Dimensions, Sci.Am. 263, p.74-83, November Issue, (1990). @footnote 2@Paggel, J.J., Miller, T., Chiang, T.-C., Quasiparticle Lifetime in Macroscopically Uniform Ag/Fe(100) quantum Wells, Phys.Rev.Lett.81, 5632-5635, (1998). @footnote 3@Ortega, J.E., Himpsel, F.J., Mankey G.J., Willis, R.F., Quantum-well states and magnetic coupling between ferromagnets through a noble-metal layer, Phys.Rev.B 47, 1540-1552 (1993). @footnote 4@Kawakami, R.K. et al., Quantum-well states in copper thin films, Nature 398, 132-134 (1999). @footnote 5@Crommie, M.F., Lutz, C.P., Eigler, D.M., Imaging standing waves in a two-dimensional electron gas, Nature 363, 524-527 (1993). @footnote 6@Edwards,D.M., Mathon, J., Oscillations in exchange coupling across a nonmagnetic metallic layer, J.Magn.Magn.Mat. 93, 85-88 (1991).

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