Magnetic Interfaces and Nanostructures
Room 2006 - Session MI+EM-ThM

Spin Injection

Moderator: A.R. Smith, The Ohio State University

8:00am **MI+EM-ThM1 Spin-Polarized Transport in Ferromagnet-Semiconductor Heterostructures***, **A.G. Petukhov**,* South Dakota School of Mines and Technology **INVITED**

The early promise of ferromagnet-semiconductor heterostructures (FMSH) and dilute magnetic semiconductors (DMS) as a basis for spintronics has led to serious challenges for both theorists and experimentalists. This talk will focus on three fundamental issues: basic physics of spin injection, multi-scale methodology for spin-dependent transport calculations and band engineering of highly efficient FMSH-based spin injectors and spin detectors. These issues are addressed using a combination of first-principles theory, analytical modeling of the underlying physics, and design and numerical simulation of spintronic devices. We will start from basic definitions of non-equilibrium spin polarizations of the current and electron density and derive some useful relations between these quantities. We will further consider a theory of spin injection within the linear-response approximation and its generalization to a non-linear case. We will formulate a self-consistent multi-scale scheme for spin-dependent transport calculations of FMSH. The scheme combines the large scale drift-diffusion equation approach and the small scale first-principles calculations of the spin-dependent transmission matrix to provide proper microscopic boundary conditions at both sides of the junction. We will demonstrate that spin polarization of electrons in nonmagnetic semiconductors near specially tailored FMSH junctions can achieve 100%. We propose several new devices based on DMS heterostructures that lead to potentially useful effects, including extremely large and tunable tunneling magnetoresistance and high-efficiency spin filtering. These prototype devices include GaMnAs/AlAs/GaMnAs tunnel junctions; double-barrier quantum well heterostructures; and spin-selective resonant interband tunneling devices in the InAs/AlSb/GaMnSb system, using ferromagnetic DMS quantum wells. This work is supported by ONR.

8:40am **MI+EM-ThM3 Epitaxial Growth, Spin Polarization, and Electrical Spin Injection from Fe(1-x)Ga(x) (001) Films on AlGaAs/GaAs(001) LEDs***, **A.T. Hanbicki**, O.M.J. van 't Erve, C.H. Li, G. Kioseoglou, M.S. Osofsky, S.-F. Cheng, B.T. Jonker,* Naval Research Laboratory

Electrical spin injection is a prerequisite for a semiconductor spintronics technology. Spin injection into GaAs from ferromagnetic metals such as Fe via Schottky barrier tunnel contacts has been demonstrated. However, the surface emitting geometry employed to facilitate a quantum selection rule based analysis of the polarized electroluminescence (EL) produced by the spin polarized light emitting diode (spin-LED) devices necessitates the use of relatively large external magnetic fields to saturate the Fe magnetization out-of-plane. We have grown epitaxial films of Fe(1-x)Ga(x) (0 < x < 0.75), a material noted for its high magnetostriction, on AlGaAs/GaAs (001) heterostructures, and summarize the structure, magnetization, spin polarization, and results for electrical spin injection into AlGaAs/GaAs. The out-of-plane saturation field and magnetization decrease rapidly with Ga content, but the point contact spin polarization remains near that of Fe for x @<=@ 0.5. Electrical spin injection from an Fe@sub 0.5@Ga@sub 0.5@ contact produces an electron spin polarization of 30% in the GaAs at 20 K, similar to that obtained from Fe contacts, but with out-of-plane saturation fields as low as 0.4 T. This work was supported by ONR. OvE current address: Philips, Eindhoven.

9:00am **MI+EM-ThM4 Remanent Electrical Spin Injection from Fe into GaAs Edge-Emitting Spin-LEDs***, **G. Kioseoglou**,* Naval Research Laboratory*; O.M.J. van 't Erve,* Philips Research Laboratories*; A.T. Hanbicki, C.H. Li, B.T. Jonker,* Naval Research Laboratory

Electron spin polarizations (P@sub spin@) of 40-70% have been obtained in GaAs due to electrical injection from Fe or FeCo contacts using surface-emitting spin-LEDs. In such LEDs, a narrow (100 Å) QW is typically used, and the heavy hole (HH) angular momentum is constrained to lie along the surface normal due to quantum confinement, requiring a similar orientation for the spin of the injected electrons. Since Fe has its magnetization easy axis in the substrate plane, a large magnetic field (>2.2 tesla) along the surface normal is required to saturate the magnetization out-of-plane. To take advantage of the small coercive fields and large remanent in plane magnetizations of Fe, the edge emitting geometry should be developed to facilitate transduction of the spin state variable between the electron spin and optical polarization. Here we demonstrate electrical spin injection from Fe into edge-emitting LEDs with relatively wide QWs (500 and 1000 Å) and compare surface and edge emission spin injection efficiencies. The edge-emitted optical polarization for the 100Å QW spin LED is zero, as expected due to hole spin orientation. For the wider QWs, the confinement energy diminishes and the magnetic field rather than the confinement defines the quantization axis. In this case the HH angular momentum can in principle lie in-plane, co-linear with the electron spin and light propagation direction, enabling a determination of P@sub spin@ via the same selection rules. We find similar spin injection efficiencies for electron spins (contact magnetization) oriented in-plane and normal to the surface. The magnitude of the edge emitted optical polarization is limited at low magnetic fields by the orientation of the HH angular momentum, which is constrained to lie partially out-of-plane due to the reduced symmetry accompanying weak localization at the QW interfaces. This work was supported by ONR.

9:20am **MI+EM-ThM5 Towards Electrical Spin Injection into a Single InAs/GaAs Quantum Dot***, **C.H. Li**, G. Kioseoglou, A.T. Hanbicki,* Naval Research Laboratory*; O.M.J. van 't Erve,* Philips Research Laboratories Eindhoven*; B.T. Jonker,* Naval Research Laboratory

We have demonstrated electrical injection of spin-polarized electrons from an Fe Schottky contact into an ensemble of InAs/GaAs self assembled quantum dots (QDs) in a spin-LED.@footnote 1@ We observed a 5% electron spin polarization from 80-300K, consistent with the suppression of DP spin scattering expected for QDs. The electroluminescence we observed is a convolution of emission from an ensemble of dots with a considerable variation in size, hence it exhibits a broad FWHM of ~50 meV. It is highly desirable to isolate emission from a single QD to further elucidate the details of electrical spin injection and consequent spin polarization in quantum dots as a function of dot size and charge state. To this end, we have developed MBE growth methods to reduce the density of dots by more than an order of magnitude (in the order of 10@super 9@/cm@super 2@ as shown by atomic force microscopy of uncapped samples), and narrowed the aperture sizes of the surface-emitting LEDs to the order of a hundred nanometers using ebeam lithography. As the density and aperture size decrease, the initially broad emission spectrum of the dot ensemble breaks into distinct narrow features attributed to single dot emission. Emission spectra exhibiting a few well-separated peaks are observed with linewidths that are spectrometer resolution-limited. With increasing bias, the number of peaks increases drastically, indicating emission from an increasing number of dots, while the linewidth of these narrow emission peaks broadens, suggesting contributions from various charge states of the dot. Progress towards electrical spin injection into a single QD, and details of the electroluminescence spectra from these single-dot spin-LEDs as a function of bias and magnetic field will be discussed at the meeting. Supported by ONR and DARPA. @FootnoteText@ @footnote 1@C. H. Li et al. APL 86, 132503 (2005).

9:40am **MI+EM-ThM6 Organic-based Materials in Spintronics***, S. Liu, P. Jeppson, J. Sandstrom, B. Anderson, D.B. Chrisey, D.L. Schulz, **A.N. Caruso**,* North Dakota State University

Magnetic and non-magnetic organic-based solids provide physical, magnetic and electronic flexibility with regard to multilayer device fabrication. This flexibility manifests itself in the form of organic synthesis whereby molecular orbital localization and hybridization can be finely tuned. The use of low Z materials in environments where spin coherence is vital will be discussed relative to spin orbit coupling and hyperfine interaction as well as a comparison between organic and inorganic density of states and their type of existence at the Fermi level for conductors. Organic based magnets provide optimal conditions, from their pi-pi* splittings, to allow for photomagnetic and other novel phenomena not observed easily with inorganic materials. Results from our work on the room temperature Mn(II)chalcogenocarboxylate system will be discussed and indicate promise toward an organic based spin-injector. Overall, it has been shown that organics do and will play a large role in standard electronics, such that the addition of the spin degree of freedom from magnetic organic-based materials is inevitable.

10:00am **MI+EM-ThM7 Characterization of Ferromagnetic Metal/Organic Semiconductor Interfaces in Organic Spin Valves***, **G.J. Szulczewski**, J. Tang, W. Xu, L. Navar, R. Schad, A. Gupta,* University of Alabama

In the past several years there has been a growing interest in combining ferromagnetic and molecular materials to create organic-based spintronic devices, such as light-emitting diodes and spin-valves. In a vertical device structure one of the processing steps is deposition of a ferromagnetic thin film onto an organic layer. In order to understand the electronic and magnetic nature of these interfaces we have vapor deposited thin films of Co, Fe, and Ni onto 100 nm films of pi-conjugated organic molecules. The molecules studied were aluminum tris(quinolate), tetraphenylporphyrin, phthalocyanine, and perylenetetracarboxylic dianhydride. Using magnetometry techniques the temperature dependent saturation magnetization and coercivity was measured as a function of ferromagnetic metal film thickness. In general several trends were observed. First, in thin ferromagnetic layers less than 3 nm the films did not exhibit a magnetic moment. Second, the Co, Fe and Ni films exhibit ferromagnetic behavior above 3 nm with a coercivity much larger than would be observed for sputter films on Si wafers. Third, the coercivity of Ni and Co films depends on the roughness and functional groups in the molecules more than Fe films, which is attributed to the higher chemical reactivity of Fe atoms. Based on these observations we choose Co films as the top electrode in the fabrication of organic-spin valves because it less reactive than Fe and has a higher coercivity than Ni. Spin-valves were made by depositing Co films onto porphyrin and phthalocyanine organic layers which were first deposited onto La@sub0.67@Sr@sub0.33@MnO@sub3@ substrates. At 80 K the magnetoresistance was measured to be about 20%. The magnetoresistance was found to decrease rapidly with both increasing temperature and voltage bias. The role of the ferromagnetic/organic interfaces on spin-valve performance will be discussed.

10:20am **MI+EM-ThM8 Interface Magnetization Precession and Switching in Fe/AlGaAs (001)*, G. Luepke,*** College of William and Mary **INVITED**

Efficient spin-polarized electron injection is a prerequisite for the development of semiconductor-based spintronic devices. Several recent experimental studies have reported successful electrical spin injection from ferromagnetic metals into III-V semiconductor light emitting diodes (LEDs) using a variety of tunnel barriers. However, further improvement requires a detailed understanding of interface magnetic properties.@footnote 1@ In this study, we have measured the reversal process of the Fe interface layer magnetization in Fe/AlGaAs heterostructures using magnetization-induced second harmonic generation (MSHG), and compared it with the bulk magnetization as obtained from magneto-optic Kerr effect (MOKE).@footnote 2@ The switching characteristics are distinctly different - single step switching occurs at the interface layer, while two-jump switching occurs in the bulk Fe for the magnetic field orientations employed. The different switching processes lead to a deviation angle of 40-85o between interface and bulk magnetization. This behavior may result from reduced exchange interaction in the direction normal to the interface and different magnetic anisotropies at the heterojunction. To study the magnetization dynamics at the interface, we use time-resolved MSHG to investigate the coherent magnetization precession. The results are directly compared with the bulk spin precession as obtained from time-resolved MOKE.@footnoe 3@ The different switching characteristics are further revealed in the precession dynamics at low fields. The field dependence of precession frequency provides a quantitative analysis of magnetic anisotropy and magnetostatic energy of the interface layer. @FootnoteText@ @footnote 1@J. M. D. Teresa et al., Science 286, 507 (1999); B. T. Jonker, Proc. IEEE 91, 727 (2003). @footnote 2@H.B. Zhao et al., Phys. Rev. Lett. 95, 137202 (2005). @footnote 3@H.B. Zhao et al., Appl. Phys. Lett. 86, 152512 (2005).

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