Magnetic Interfaces and Nanostructures
Room: C1 - Session MI+EM-WeA

Magnetism and Spin Injection in Semiconductors
Moderator: Y.D. Park, Seoul National University, South Korea

2:00pm **MI+EM-WeA1 Anomalous Nernst Effect in $Ga_{1-x}Mn_xAs$ Ferromagnetic Semiconductors**, ***J. Shi***, University of California, Riverside **INVITED**

The origin of the anomalous Hall effect (AHE) in ferromagnets has been a subject of long-standing debate. Dilute magnetic semiconductors (DMS) provide an excellent test ground for clarifying the issues. In our study, we engineered a series of GaMnAs thin films with different doping levels and with perpendicular magnetic anisotropy which allows us to investigate both electrical and thermoelectric transport properties at zero magnetic field. Both Seebeck and Nernst coefficients (S_xx and S_xy) were measured simultaneously with the longitudinal and transverse resistivities (rho_xx and rho_xy). In addition to an usually large spontaneous or anomalous Nernst effect (ANE), we also found that both AHE and ANE arise from the same physical origin. When the temperature is varied, although the sign of AHE (rho_xy) remains unchanged, the sign of ANE (S_xy) switches at an intermediate temperature below Tc. Furthermore, we found that the same Mott relation which links the electrical conductivity and thermoelectric coefficients works very well for the anomalous transport. A simple Mott relation analysis rules out the extrinsic skew-scattering mechanism immediately with the sign change in S_xy. A further quantitative analysis of the overall temperature dependence yields exponent n=2 in rho_xy ~ rho_xx^n, indicating that the intrinsic spin-orbit effect is likely responsible for both AHE and ANE.

2:40pm **MI+EM-WeA3 Local Structure of Cr in the Epitaxial Ferromagnetic Semiconductor Cr-doped Ga_2Se_3/Si (001)**, ***E. Yitamben****, *T.C. Lovejoy, A. Pakhomov,* University of Washington, *S. Heald,* Argonne National Laboratory, *F.S. Ohuchi, M.A. Olmstead*, University of Washington

The III-VI compound Ga_2Se_3 is an intrinsic vacancy semiconductor which not only can be grown epitaxially on silicon, but, once doped with a transition metal, presents interesting potential for application in spintronics devices, since we have found it to be ferromagnetic at room temperature. Unlike III-V or II-VI materials, the intrinsic vacancies in Ga_2Se_3 create both multiple sites for dopant incorporation, raising the possibility of separate control of magnetic and carrier doping, and anisotropic band-edge states, which may increase both the Curie temperature and the magnetic anisotropy. This work presents experimental investigations of Cr-doped Ga_2Se_3 epitaxially grown on Si(100):As that probe interactions among structure, carriers and magnetism in this new class of dilute magnetic semiconductors.

Inclusion of a few atomic percent Cr into the Ga_2Se_3 lattice results in laminar semiconducting films that are ferromagnetic at room temperature, with a magnetic moment of 4 μ_B per Cr in 6 nm films, and 40% lower in 20 nm films. X-ray absorption and photoemission measurements reveal Cr in an octahedral environment; X-ray and low energy electron diffraction reveal a cubic structure with lattice constant close to that of the underlying silicon. This is surprising, since both the vacancies and Ga cations occupy tetrahedral sites in pure Ga_2Se_3.

Above ~6%, scanning tunneling microscopy (STM) reveals the formation of islands within trenches whose shape and size depend on the Cr concentration and whether or not a Ga_2Se_3 buffer layer is deposited first. The islanded films also exhibit room temperature ferromagnetism, though with about half the magnetic moment per Cr. Unlike low concentration films, they are metallic rather than semiconducting.

Acknowledgments: This work is funded by the NSF Grant DMR-0605601, NSF NER-0508216

3:00pm **MI+EM-WeA4 Ferromagnetism in Gd- and Si-co-implanted GaN**, *R. Davies, B. Gila,* ***C. Abernathy****, S.J. Pearton, C. Stanton*, University of Florida

Ion implantation has been studied as a magnetic ion incorporation method in semiconductor materials for spintronic applications due to excellent control over the amount of the implanted ion and the resultant magnetic properties of the implanted material. GaN thin films grown via metal-organic chemical vapor deposition (MOCVD) were co-implanted with Gd^+ ions with an energy of 155 keV and dose of 2.75 × 10^{10} cm^{-2} and Si^{4+} ions with energies of 5 keV and 40 keV and corresponding doses of 8 × 10^{11} cm^{-2} and 3.6 × 10^{12} cm^{-2}. Before annealing, x-ray diffraction measurements revealed that the implanted GaN thin films exhibited no secondary phase formation or clustering effects attributable to Gd. Superconducting quantum interference device (SQUID) magnetometer measurements indicated that a Gd- and Si-co-implanted GaN thin film exhibited about an order of magnitude higher magnetic moment than a Gd-implanted GaN thin film. Both of these thin films displayed ferromagnetic ordering and Curie temperatures above room temperature. The co-implanted GaN thin film also demonstrated a larger magnetic moment than a Gd- and Si-co-doped GaN thin film grown via molecular beam epitaxy (MBE) while possessing a smaller Gd concentration. The orientation of the applied magnetic field with respect to the thin film surface was seen to have an effect on the measured magnetic properties of the thin films. This orientation dependence may help elucidate the relationship between the defects produced by the implantation process and the ferromagnetic ordering exhibited by these materials.

4:00pm **MI+EM-WeA7 Structural and Electronic Properties of EuO and Gd-doped EuO Films Prepared Via Pulsed Laser Deposition**, *X. Wang, K. Fox, W. Wang,* ***J. Tang****,* University of Wyoming, *M.J. An, K. Belashchenko, P.A. Dowben*, University of Nebraska-Lincoln

Methods to prepare EuO thin films reported in the literature include reactive thermal evaporation of Eu in the presence of oxygen gas and molecular beam epitaxy (MBE). We have successfully prepared single phase polycrystalline and epitaxially grown EuO and Gd-doped EuO via pulsed laser deposition (PLD) using metal targets. This opens a new route to the preparation of this interesting material with high quality. Samples prepared in vacuum exhibit the typical M(T) curve for a ferromagnet and have a Curie temperature of 70 K. When the samples were grown under ultrahigh purity H_2 flow, they show the "double-dome" feature characteristic of oxygen deficient EuO. Tc as high as 150 K has been observed for EuO. The increased Curie temperature is attributed to the magnetic coupling enhanced by the 4f-5d coupling between the Eu moments and doped electrons. Our results reaffirm that oxygen vacancies alone can substantially increase the Tc. Calculations on the phase diagram (for Gd+EuO), the effects of oxygen vacancies and associated band structures and density of states will be presented.

4:20pm **MI+EM-WeA8 Magnetic Molecules on GaN: A Low Temperature STM Investigation**, ***K. Clark****, D. Acharya, V. Iancu, E. Lu, A. Smith, S.-W. Hla*, Ohio University

Spin electron interactions involving magnetic molecules and semiconductor surfaces are of great interest for the development of molecular spintronic devices. Due to its wide range of applications, GaN (0001) surface has received a special attention for the development of novel electronic devices. Here, we studied electronic and structural properties of TBrPP-Co molecules deposited on a freshly grown nitrogen polar GaN (0001) surface using a scanning tunneling microscopy and spectroscopy at 4.6 K under an ultra-high-vacuum condition. The TBrPP-Co molecule has a spin-active cobalt atom caged at the center of porphyrin unit and four bromo-phenyl groups are attached to its four corners. On GaN(0001), the molecules bind the surface via two molecular conformations: saddle and planar. In saddle conformation, the central part of the molecule is bent by lifting the two pyrrole units of the porphyrin macrocycle. STM images shows various self-assembled clusters of molecules on GaN(0001) surface. Within the self-assembled molecular clusters, the molecules are aligned either parallel or 90 degree rotated to each other. In the presentation, we will discuss the spin-electron coupling of this molecule-surface system. This work is supported by the Ohio University BNNT, NSF-PIRE: OISE 0730257, NSF-EMT: CCF-0622158, and the United States Department of Energy, DE-FG02-02ER46012 grants.

4:40pm **MI+EM-WeA9 Electrical Injection, Detection and Modulation of Spin Currents in Silicon**, ***O.M.J. van 't Erve****, C. Awo-Affouda, A.T. Hanbicki, M.A. Holub, C.H. Li, P.E. Thompson, B.T. Jonker*, Naval Research Laboratory **INVITED**

The electron's spin angular momentum is one of several alternative state variables under consideration on the International Technology Roadmap for Semiconductors for processing information in the fundamentally new ways. Significant progress has recently been made on spin injection into the technologically important semiconductor, Si, using vertical device structures. Here we will present the electrical injection, detection and magnetic field modulation of lateral diffusive spin transport through silicon using Fe/Al2O3 surface contacts. The tunnel contacts are used to create and

* Falicov Student Award Finalist

analyze the flow of pure spin current in a silicon transport channel. A nonlocal detection technique has been used to exclude spurious contributions from AMR and local Hall effects. The nonlocal signal shows that a spin current can be electrically detected after diffusive transport through the silicon transport channel and the signal depends on the relative orientation of the magnetization of the injecting and detecting contacts. Hanle effect measurements up to 125 K demonstrate that the spin current can be modulated by a perpendicular magnetic field, which causes the electron spin to precess and dephase in the channel during transport. By changing the bias on the injector contact we can either inject or extract spin from the Silicon channel. Here we will show using Hanle and lateral spin-valve measurements that we can change the polarization of the spin accumulation by going from the injection regime to the extraction regime and we will compare the efficiency of spin-injection versus spin extraction.

The realization of efficient electrical injection and detection using tunnel barriers and a simple device geometry compatible with "back-end" Si processing should greatly facilitate development of Si-based spintronics.

This work was supported by ONR and core NRL programs.

5:20pm **MI+EM-WeA11 Order From Chaos: α-Fe(001)/GaAs(001)**, ***J.G. Tobin**, S.W. Yu,* Lawrence Livermore National Laboratory*, S.A. Morton,* Lawrence Berkeley National Laboratory*, G.D. Waddill,* Missouri University of Science and Technology*, J.D.W. Thompson, J.R. Neal, M. Spangenburg, T.H. Shen*, University of Salford, UK

For many years, the technological possibilities of spintronic or magneto-electronic devices [1], particularly when coupled with potentially pure spin sources such as half-metallic ferro-magnets, [2] have engendered great interest. Despite the limitations encountered in such potential sources [3], there is still ample reason to pursue such concepts. This is because, in part, even with sources that operate below 100% polarization, technologically important devices should emerge. [1] However, the challenges of device integration remain significant even for cases with lowered expectations, because often the physical realities of intermixing, disorder and alloying can creep into the attempts to fabricate structures based upon ideal conceptual designs. Within this context, ferromagnetic-semiconductor interfaces are potentially important for the future applications of spintronic devices. One possibility for a room temperature spin injector is Fe/GaAs. The growth of Fe upon GaAs(001) has been studied with Photoelectron Spectroscopy (PES), including Spin-Resolved PES . Despite evidence of atomic level disorder such as intermixing, [4] an over-layer with the spectroscopic signature of α-Fe(001), with a bcc real space ordering, is obtained. The results will be discussed in light of the possibility of using such films as a spin polarized source in device applications. Lawrence Livermore National Laboratory is operated by Lawrence Livermore National Security, LLC, for the U.S. Department of Energy, National Nuclear Security Administration under Contract DE-AC52-07NA27344. Work that was performed by UMR personnel was supported in part by the Office of Basic Energy Science at the U.S Department of Energy. Work that was performed by LLNL personnel was supported in part by the Office of Basic Energy Science at the U.S Department of Energy and Campaign 2 of WCI at LLNL. We would also like to thank J.A.D. Matthew, D. Greig, A.E.R. Malins, E.A. Seddon, and M. Hopkinson for their help with this project.

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5:40pm **MI+EM-WeA12 Enhancement of Spin Injection Efficiency by Interface Modification for Fe and $Fe_{31}Co_{69}$ Thin Films on GaAs(001)**, ***S.F. Alvarado**, G. Salis, A. Fuhrer, L. Gros, R.R. Schlittler*, IBM Zurich Research Laboratory, Switzerland

We report on a detailed study of the influence of ferromagnet/semiconductor interface modifications on the electrical spin injection efficiency of Fe and $Fe_{31}Co_{69}$ thin film electrodes into the GaAs(001) surface. These modifications are induced by: a) Varying the As/Ga surface concentration of GaAs(001); and b) Post-growth annealing of the ferromagnetic thin films. Electrical spin injection experiments are carried out in a non-local device geometry at temperatures between 2.5 and 300 K. Devices were fabricated by means of either optical, e-beam, or nanostencil lithography. Non-local spin signals in the range of 2V/A at a temperature of 5K have been detected between two strip electrodes, one 2 and the other 6 µm in width, 60 µm long, separated 3 µm from each other. The spin-polarization characteristics of the devices are observed to strongly depend on substrate surface preparation and annealing treatment of the metal/semiconductor devices. The latter has a very strong influence on the magnitude of the non-local spin polarization signal, which we observe to increase by about two orders of magnitude after annealing steps from 120 °C up to 290 °C.

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