Magnetic Interfaces and Nanostructures
Room 316 - Session MI+SC-FrM

Semiconductor Spin Injection

Moderator: S.A. Chambers, Pacific Northwest National Laboratory

8:20am **MI+SC-FrM1 Ferromagnetic Nano Fe-Germenide Particles in MBE-grown Ge-Fe***, **R. Goswami**,* Geo-Centers Inc.*; G. Kioseoglou, A.T. Hanbicki, B.T. Jonker, G. Spanos,* Naval Research Laboratory

Ferromagnetic-semiconductors (FMSs) have attracted considerable attention due to the coexistence of semiconductor properties and long-range ferromagnetic (FM) order in these materials. Recently, ferromagnetic order was reported in alloy thin films based on Ge, which provides a simple host lattice to explore the fundamental origins of FM order. A relatively high Curie temperature,120 K, has been experimentally observed in a Ge-3.3at.% Mn film grown epitaxially on GaAs. It has been theoretically predicted very recently that Ge with Fe atoms in the lattice will be ferromagnetic semiconductors and the Curie temperature will increase as a function of Fe concentration. To date, relatively little attention has been paid to understanding the fine scale microstructural evolution within Ge-Fe thin films. It is well known that the microstructure plays a vital role in dictating the ferromagnetic properties. Fe-Ge contains different phases with magnetic properties ranging from ferromagnetic Fe to antiferromagnetic FeGe@sub2@. The purpose of the present investigation is to elucidate the phase transformations and overall microstructural evolution in epitaxial Ge- 4at.% Fe thin films deposited on (100) GaAs substrates at three different temperatures, 150°, 250° 400 ° C, in order to better understand magnetic properties in these materials. The equilibrium phases at this composition (4%Fe) are Ge with negligible amount of Fe and antiferromagnetic FeGe@sub2@. We have observed for all cases that nano-particles of ferromagnetic- Fe@sub3@ Ge@sub2@ form uniformly in a crystalline Ge-matrix. The particle size was observed to decrease with the substrate temperature. We demonstrate that a supersaturated Ge-Fe solid-solution forms initially from the vapor phase resulting in the solid state precipitation of this metastable ferromagnetic- germanide. This work was supported by the Office of Naval Research and DARPA.

8:40am **MI+SC-FrM2 Epitaxial Ferromagnet on Ge(111)***, **C. Zeng**,* The University of Tennessee*; J.R. Thompson,* The University of Tennessee and Oak Ridge National Laboratory*; L.C. Feldman,* Vanderbilt University and Oak Ridge National Laboratory*; S.C. Erwin,* Naval Research Laboratory*; H.H. Weitering,* The University of Tennessee and Oak Ridge National Laboratory

The difficulty of injecting spin-polarized electrons into a semiconductor is a major bottleneck in spintronics research. There are two ways to realize spin injection. One of these is to fabricate a ferromagnetic-metal/semiconductor heterostructure; the other is to use a dilute magnetic semiconductor (DMS) as the spin aligner. The former method does not work well, mainly because of the large conductivity mismatch between the ferromagnetic metal and semiconductor. The latter method is limited by the low Curie temperature, T@sub c@ of DMS. We have developed a novel interface with good potential for spin injection, namely an epitaxial ferromagnetic Mn@sub 5@Ge@sub 3@ film on Ge(111). The Mn@sub 5@Ge@sub 3@ films are fabricated by depositing Mn and subsequent annealing, or by codeposition of Mn and Ge. Mn@sub 5@Ge@sub 3@(001)//Ge(111) epitaxy relationship is verified by X-ray diffraction results, due to the small lattice mismatch. STM images display (@sr@3x@sr@3)R30° honeycomb structure, which perfectly agrees with the theoretical image of the Mn terminated Mn@sub 5@Ge@sub 3@ (001) surface. RBS and ion-channeling experiments confirmed the stoichiometry and epitaxy of the film. Magnetic measurements reveal a T@sub c@ of about 295 K. The easy axis is in-plane which is most likely due to the shape anisotropy. The multiplet splitting of the Mn 3s core level in XPS indicates an average magnetic moment of 2.6 µ@sub B@ per Mn atom, which is in almost perfect agreement with the spin-resolved band structure calculations and SQUID measurements. This research was sponsored by the Laboratory Directed Research and Development Program of Oak Ridge National Laboratory, managed by UT-Battelle, LLC, for the U.S. Department of Energy under Contract No. DE-AC05-00OR22725.

9:00am **MI+SC-FrM3 Tunnel Spin Injection from a Ferromagnetic Metal into a Semiconductor Heterostructure***, **A.T. Hanbicki**, O.M.J. van 't Erve, R. Magno, G. Kioseoglou, C.H. Li, R.M. Stroud, B.T. Jonker,* Naval Research Laboratory*; G. Itskos, R. Mallory, M. Yasar, A. Petrou,* SUNY at Buffalo **INVITED**

Significant effort has been made to incorporate ferromagnetic metals into semiconductor spintronic devices because they offer high Curie temperatures, low coercive fields, and a ready source of spin polarized electrons. Recently it has been shown that the key to efficient spin injection from a metal into a semiconductor heterostructure is a sufficient interface resistance.@footnote 1@ Tunnel barriers have been a common way of satisfying this criterion, and there are a number of recent experimental successes with Schottky contacts, thin metal oxides, and AlAs. We will review the state of the art of spin injection from an Fe Schottky contact into an AlGaAs/GaAs spin-LED. A Schottky barrier at the Fe/AlGaAs interface can serve as an effective tunnel contact if the doping profile of the semiconductor near the interface is engineered to produce a narrow depletion width. In this system, we have successfully injected polarized electrons and obtained electron spin polarizations ranging from 13% to 32% in the GaAs QW,@footnote 2@ where quantum selection rules directly link the measured circular polarization and the electron spin population. We report here recent efforts to characterize transport properties and the physical structure of this interface, and correlate them with the measured spin polarizations. To determine the dominant transport mechanism, we have analyzed the transport process using the Rowell criteria. The parabolic G-V curves and the temperature dependence of the zero-bias resistance demonstrate that single step tunneling is the dominant transport mechanism. The I-V data show a clear zero-bias anomaly and phonon signatures providing further evidence for tunneling. Preliminary data suggest that roughness and Fe segregation at the spin injecting interface suppresses spin injection. @FootnoteText@ This work was supported by the DARPA SpinS program and ONR@footnote 1@E.I. Rashba, PRB 62 (2000)@footnote 2@A.T. Hanbicki, et al., APL 80 (2002); APL 82 (2003).

9:40am **MI+SC-FrM5 Spin Injection Across (110) Interfaces: Fe/GaAs(110) Quantum Well Spin-LEDs***, **C.H. Li**, A.T. Hanbicki, G. Kioseoglou, O.M.J. van 't Erve, B.T. Jonker,* Naval Research Laboratory*; G. Itskos, R. Mallory, M. Yasar, A. Petrou,* SUNY Buffalo

Spin-LEDs can be used to reliably measure spin injection efficiency via the quantum selection rules subject to the limits imposed by the ratio of spin to radiative lifetimes. However, to date they have been implemented only in (001) oriented GaAs or InGaAs quantum wells (QWs), where the spin lifetime is shorter, resulting in an underestimate of spin injection efficiency. Recent work has shown that the spin lifetime is longer in (110) GaAs QWs, and increases with temperature.@footnote 1@ In this study we investigate spin injection in (110) oriented spin-LED QW structures to take advantage of this, and to explore the effects of band structure and the non-polar interface on spin injection. AlGaAs/GaAs LEDs have been grown on (110) substrates by molecular beam epitaxy at 450 oC and an As/Ga flux ratio of 20. Atomic force microscopy shows excellent surface morphology with a RMS roughness less than 0.5 nm. Photoluminescence is dominated by the QW excitonic emission with a linewidth of 8 meV. Initial electroluminescence results using a tailored Fe Schottky tunnel barrier injector show that a 10% spin polarization in the GaAs QW has been achieved due to injection across the Fe/AlGaAs(110) interface. The temperature dependence of the polarization, as well as comparison with (001) oriented samples and first principles theory will be presented. @FootnoteText@ Supported by DARPA, ONR, and NSF. @FootnoteText@@footnote 1@Y. Ohno et. al., PRL 83, 4196 (1999).

10:00am **MI+SC-FrM6 Electrical Spin Injection from Ferromagnetic Metal/Tunnel Barrier Injectors into AlGaAs/GaAs Quantum Well Structures***, **X. Jiang**,* Stanford University*; R. Shelby,* IBM Almaden Research Center*; R. Wang,* Stanford University*; R. Macfarlane,* IBM Almaden Research Center*; G. Solomon, J. Harris,* Stanford University*; S. Parkin,* IBM Almaden Research Center

Electrical injection of highly spin-polarized electrons into semiconductors is an essential component for the operation of spintronic devices. In this talk, we present a study of electrical spin injection into semiconductors from injectors comprised of ferromagnetic metals and tunnel barriers. An AlGaAs/GaAs quantum well structure is used to optically detect the spin-polarization of the injected electrons in the semiconductor. Large polarization of the electroluminescence from the quantum well is observed. The bias dependence and temperature dependence of the electroluminescence polarization will be discussed. This work is supported by DARPA.

10:20am **MI+SC-FrM7 Efficient Electrical Spin Injection in GaAs: A Comparison Between Different Spin Sources*, P. Van Dorpe*, *V.F. Motsnyi, Z. Liu, W. Van Roy, G. Borghs, J. De Boeck,* IMEC, Belgium **INVITED**

Electrical spin injection in semiconductors remained elusive for a long time. Recently however, break-throughs have been accomplished in the field. It appeared that tunnel injection of spin polarized electrons from ferromagnetic metals provides an efficient way for spin injection, even at room temperature. We will quantitatively compare different spin sources for spin injection in GaAs, based on tunnel injection from ferromagnetic materials. The injected spin polarization is assessed in a (Al,Ga)As-based spin-LED, using the Oblique Hanle Effect@footnote 1@ as the analysis technique. The first material combination that we successfully applied for spin injection is a CoFe/AlOx based tunnel injector where the AlOx provides a stable tunnel barrier between the ferromagnetic material and the GaAs. We have shown injected spin polarizations which exceed 24% at 80K and 12% at room temperature.@footnote 2@ A second spin source we examined uses the native Schottky barrier between GaAs and an epitaxially grown ferromagnetic metal as tunnel barrier. NiMnSb, MnAs and MnSb have been used and will be compared for their spin injection properties. Finally the results of electron spin injection from a (Ga,Mn)As-based Zener diode will be discussed. The spin polarized holes in (Ga,Mn)As are transferred to electrons in GaAs by Zener tunnelling and create a spin polarization in GaAs of at least 50% at LHe temperature. The results on electrical spin injection regularly show an interesting dependence on the applied bias. This dependence will be shown and discussed in terms of doping and band structure. @FootnoteText@@footnote 1@V.F. Motsnyi et al, Appl. Phys. Lett. 81, 265 (2002) @footnote 2@P. Van Dorpe et al, Jpn. J. Appl. Phys., Part 2 42, L502 (2003) Acknowledgements : SPINOSA (IST-2001-33334), FENIKS(GR5D-CT-2001-00535).

11:00am **MI+SC-FrM9 Electrical Spin Injection from a Ferromagnetic Metal Into a Semiconductor: Schottky vs Al@sub 2@O@sub 3@ Tunnel Barriers*, O.M.J. van 't Erve*, *A.T. Hanbicki, C.H. Li, G. Kioseoglou, B.T. Jonker,* Naval Research Laboratory*; G. Itskos, R. Mallory, M. Yasar, A. Petrou,* SUNY Buffalo

Efficient injection of spin-polarized electrons from a metal into a semiconductor requires a high resistance interface contact such as a tunnel barrier.@footnote 1@ The natural Schottky tunnel barrier which forms at the Fe/AlGaAs interface provides highly efficient spin injection, and a polarization of more than 32% has been measured in a GaAs quantum well detector.@footnote 2@ The pseudo-triangular shape and high interface doping level of the Schottky tunnel contact are factors which are quite different from those encountered for the canonical rectangular barrier typically formed from Al@sub 2@O@sub 3@. It is therefore of interest to compare the characteristics and performance of an Al@sub 2@O@sub 3@ tunnel barrier with the Fe/AlGaAs Schottky barrier in essentially identical MBE-grown device structures. The Al@sub 2@O@sub 3@ barrier is formed on top of an AlGaAs/GaAs spin-polarized light-emitting diode (spin-LED) by multi-step in situ natural oxidation of thin evaporated Al layers. A ferromagnetic metal layer is evaporated on top of this tunnel barrier and provides the spin-polarization of the injected electrons. We measure the spectral features, intensities and polarization of the electroluminescence from the surface emitting spin-LEDs, and compare these directly with similar data for the Fe Schottky contact and with literature to obtain insight into various aspects of the spin injection process. @FootnoteText@ This work was supported by the DARPA SpinS program, ONR, and NSF. @footnote 1@ E. I. Rashba, Phys. Rev. B 62, R16267 (2000).@footnote 2@ A.T. Hanbicki et al, Appl. Phys. Lett. 82 (9 June 2003).

11:20am **MI+SC-FrM10 Electrical Spin Injection from CdCr@sub 2@Se@sub 4@ into AlGaAs/GaAs Spin-LED*, G. Kioseoglou*, *A.T. Hanbicki, C.H. Li, O.M.J. van 't Erve, R. Goswami, G. Spanos, B.T. Jonker,* Naval Research Laboratory*; R. Mallory, M. Yasar, G. Itskos, A. Petrou,* SUNY at Buffalo

Ferromagnetic semiconductors (FMS) provide an opportunity to control spin dependent behavior and study spin injection and transport in semiconductor heterostructures. Much of the effort has focused on III-Mn-V p-type FMS, where the ferromagnetism is mediated by holes. Since electron transport is the basis for high frequency and low power operation, an n-type FMS grown epitaxially on a device quality substrate is especially attractive. Recent work demonstrated epitaxial growth of n-type CdCr@sub 2@Se@sub 4@, a chalcogenide spinel FMS, on GaAs(001) and GaP(001).@footnote 1@ The measured conduction band offsets indicate a staggered band alignment conducive to electron transport from the CdCr@sub 2@Se@sub 4@ into the AlGaAs.@footnote 2@ We present here spin polarized electron injection from CdCr@sub 2@Se@sub 4@ into an AlGaAs/GaAs LED structure. The circular polarization due to spin injection from the CdCr@sub 2@Se@sub 4@ reaches a maximum value of 6% at B = 0.5T, and mimics the hard axis magnetization determined by SQUID magnetometry measurements. In contrast to previously studied ZnMnSe and Fe contacts in which injection of predominantly m@sub j@ = -1/2 electrons was observed, for CdCr@sub 2@Se@sub 4@ the majority of the injected electrons are in the m@sub j@ = +1/2 state. TEM reveals that the existing interfaces are highly defected, a factor known to limit spin injection.@footnote 3@ Efforts to increase the spin injection efficiency are focused on improving the interface, the contact resistance and electrical properties of CdCr@sub 2@Se@sub 4@. Ga, an n-type dopant in CdCr@sub 2@Se@sub 4@, was introduced in a @delta@-doping configuration, and results on new LED structures with improved electrical characteristics and interface morphology will be presented. @FootnoteText@ This work was supported by DARPA SpinS program, ONR, and NSF. @footnote 1@Y.D. Park et al., Appl. Phys. Lett. 81, 1471 (2002). @footnote 2@H.B. Zhao et al, Appl. Phys. Lett. 82, 1422 (2003). @footnote 3@R. Stroud et al, Phys. Rev. Lett. 89, 166602 (2002).

11:40am **MI+SC-FrM11 Chemical Intermixing and Spin Injection in Fe/AlGaAs Schottky Barrier SpinLEDs*, R.M. Stroud*, *A.T. Hanbicki, G. Kioseoglou, O.M.J. van Erve, C.H. Li, B.T. Jonker,* Naval Research Laboratory*; G. Itskos, R. Mallory, M. Yasar, A. Petrou,* SUNY Buffalo

Injected spin polarizations ranging from 13% to 32% have been measured for Fe/AlGaAs Schottky barrier spin-polarized light emitting diodes spinLEDs.@footnote 1@ Transmission electron microscopy studies of these devices show evidence for diffusion of the Fe into the underlying AlGaAs. High-resolution images indicate an expansion of the AlGaAs (100) plane spacing near the interface by up to 15% and a change in contrast. The Fe diffusion is confirmed by energy-dispersive x-ray spectroscopy and Z-contrast imaging. The thickness of the intermixing region estimated from lattice images inversely correlates with the injected spin polarization, ranging from 0.8 nm +/- 0.3 nm for the 32% spin polarization sample up to 1.6 nm +/- 0.3 nm for the 13% spin polarization sample. Spin scattering in this intermixing region may explain the reduction in the injected spin polarization. This work was supported by ONR and the DARPA SpinS program. @FootnoteText@ @footnote 1@Hanbicki, et al., APL 80 (7): 1240-1242 (2002).

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