Wednesday Morning, October 4, 2000

Magnetic Interfaces and Nanostructures
Room 206 - Session MI+EL-WeM

Magnetic Semiconductors and Hybrid Structures I
Moderator: B. Jonker, Naval Research Laboratory

8:20am **MI+EL-WeM1 Characterizations of MBE Grown Single Crystal Ferromagnetic Ni@sub 2@MnGa Thin Films on (001) Ga@sub 1-x@In@sub x@As***, J.W. Dong*[1]*, J.Q. Xie, L.C. Chen, M.T. Figus, S. McKernan, C.J. Palmstrom,* University of Minnesota

Minimization of spin flip scattering at the interface of ferromagnetic metal/semiconductor is expected with the use of high quality epitaxially grown ferromagnetic metal/semiconductor heterostructures with minimal interfacial reactions. The Heusler alloy Ni@sub 2@MnGa is ferromagnetic at room temperature and has the cubic L2@sub 1@ Heusler structure with lattice parameter 3% larger than that of GaAs. We have demonstrated MBE growth of 900 Å-thick single crystal Ni@sub 2@MnGa on (001) GaAs with a 6 monolayer-thick Sc@sub 0.3@Er@sub 0.7@As interlayer, which acts as a template layer and a diffusion barrier. Reflection high energy electron diffraction, X-ray diffraction, and transmission electron microscopy (TEM) studies confirm the single crystal structure of the Ni@sub 2@MnGa films and indicate that the growth is pseudomorphic on GaAs substrates. These results suggest an epitaxially stabilized tetragonal phase of Ni@sub 2@MnGa with a = b = 5.65 Å, c = 6.12 Å, which has not been found in the bulk. High resolution cross section TEM image shows that the interface between Ni@sub 2@MnGa films and the Sc@sub 0.3@Er@sub 0.7@As interlayer is atomically abrupt. The Rutherford backscattering channeling minimum yield of 6.5% further confirms the high quality of the Ni2MnGa films. At room temperature, magnetic measurements using a vibrating sample magnetometer show that the films are ferromagnetic with a coercivity of ~50 Oe, a saturation magnetization of ~250 emu/cm@super 3@, and a weak in-plane magnetic anisotropy. Using a superconducting quantum interference device magnetometer, the Curie temperature of the films is found to be ~340 K. Our results indicate that Ni@sub 2@MnGa/GaAs can form high quality ferromagnetic metal/semiconductor heterostructures that might be used for spin injection measurements. In this talk, the effect of interlayer and strain on the structural and magnetic properties of Ni@sub 2@MnGa on Ga@sub 1-x@In@sub x@As substrates will be discussed.

8:40am **MI+EL-WeM2 Molecular Beam Epitaxial Growth of Ferromagnetic Ni@sub 2@MnGe on GaAs(001)***, **J. Lu**, J.W. Dong, J.Q. Xie, D. Carr,* University of Minnesota*; V. Godlevsky,* Rutgers University*; C.J. Palmstrom,* University of Minnesota

A number of Heusler (L2@sub 1@) structures such as Ni@sub 2@MnX (X = Ga, In, Sn, Sb) are ferromagnetic shape memory alloys. The ferromagnetic Heusler alloys show promise as single crystal ferromagnetic spin polarized injecting contacts to semiconductors. In this work, epitaxial thin films of the Heusler alloy Ni@sub 2@MnGe have been for the first time grown on GaAs(001) substrate by molecular beam epitaxy (MBE). A two step growth procedure was used which included alternate layer epitaxy at 200°C of a thin Ni@sub 2@MnGe template layer followed by codeposition at 250°C. A (2x2) surface reconstruction was observed by in-situ reflection high energy electron diffraction. X-ray diffraction studies show that the Ni@sub 2@MnGe film is epitaxially grown on GaAs(001) with the crystallographic relationship: (001)@sub Ni2MnGe@//(001)@sub GaAs@, (110)@sub Ni2MnGe@//(110)@sub GaAs@ . X-ray diffraction was used to determine both the out of plane and in plane lattice parameters. These confirmed that the film had a tetragonal structure, with a = 5.65 ±0.02 Å c = 5.897 Å, and c axis perpendicular to film surface, suggesting pseudomorphic growth on the GaAs surface. The magnetic properties were measured using superconducting quantum interference device magnetometry (SQUID). The coercivity of the film is ~50 Oe, and the saturation magnetization Ms is ~ 200 emu/cm3. The Curie temperature was 330 ± 10 K. In this talk, the magnetic and structural properties of Ni@sub 2@MnGe/GaAs heterostructures as a result of growth procedures and composition will be discussed. Results from Rutherford backscattering and transmission electron microscopy studies will be correlated with the magnetic properties.

9:00am **MI+EL-WeM3 Demonstration of Electrical Spin Injection: The Spin-LED@footnote 1@***, **Y.D. Park**, B.R. Bennett, B.T. Jonker,* Naval Research Laboratory*; H.-D. Cheong, G. Kioseoglou, A. Petrou,* SUNY, Buffalo

Electrical spin injection into a semiconductor is a prerequisite for realizing the potential of semiconductor-based spintronic devices. This has been an elusive goal, however, and only modest effects (@<=@ 1%) have been obtained. We report here highly efficient electrical spin injection from a magnetic contact into a GaAs quantum well-based light emitting diode (LED) heterostructure (a spin-LED@footnote 2,3@) in which the spin injection efficiency exceeds 50%. Radiative recombination of spin polarized carriers in quantum wells results in the emission of circularly polarized light. The degree of optical polarization is proportional to the carrier spin polarization, enabling a direct, quantitative measure of the spin injection efficiency. The samples consist of ZnSe/ZnMnSe/AlGaAs/GaAs/AlGaAs heterostructures grown by MBE on p-GaAs(001) substrates, where the semimagnetic semiconductor ZnMnSe serves as a source of spin-polarized electrons which are injected via an applied bias voltage into the GaAs quantum well. Standard optical lithography and chemical etch procedures were used to define surface emitting LED mesa structures. The measured circular polarization of the electroluminescence (EL) exceeds 50%, and demonstrates that highly efficient spin transport occurs across the ZnMnSe/AlGaAs interface despite the large 0.5% lattice mismatch. Data are reported as a function of injection current, magnetic field, and temperature. The EL lineshape consists of multiple components whose relative polarization provide insight into spin relaxation mechanisms. We compare results from ex situ and in situ contacts, and with those obtained for carefully lattice matched systems.@footnote 4@. @FootnoteText@ @footnote 1@ This work was supported by the Office of Naval Research. @footnote 2@ US patent #5,874,749 (filed 6/93; awarded 2/99) @footnote 3@ Jonker, et al., submitted for publication. @footnote 4@ Fiederling, et al., Nature 402, 787 (16 December 1999).

9:20am **MI+EL-WeM4 Ferromagnetism and Spin Related Phenomena in Semiconductor Heterostructures***, **H. Ohno**,* Tohoku University, Japan **INVITED**

Alloys between non-magnetic III-V semiconductors and Mn have been grown by molecular beam epitaxy and shown to exhibit ferromagnetism at reduced temperatures. These alloys, (Ga,Mn)As, (In,Mn)As, and (Ga,Mn)Sb are quasi-lattice matched to their host semiconductors and thus offer new and unique opportunities to combine ferromagnetism and high quality III-V heterostructures being widely used in frontiers of semiconductor physics and also in commercially available devices. This talk covers the following topics: (1) Preparation and properties of ferromagnetic semiconductors, particularly (Ga,Mn)As, where transition temperature can be as high as 110 K for 5% Mn concentration.@footnote 1@ (2) The origin of carrier-induced ferromagnetism based on a mean field theory using kp approximation.@footnote 2@ (3) Ferromagnet/non-magnet tri-layer semiconductor structures exhibiting inter-layer magnetic coupling and spin-dependent scattering.@footnote 3@ (4) Resonant tunneling structures with ferromagnetic emitters.@footnote 4@ (5) Spin-injection experiments using ferromagnetic semiconductor heterostructures.@footnote 5@ (6) Spin relaxation in nonmagnetic (110) GaAs quantum wells, where prolonged spin relaxation times are observed,@footnote 6@ which can be over 10 ns from room temperature down to 5 K when modulation doped. @FootnoteText@ @footnote 1@ H. Ohno, Science, 281, 951 (1998), J. Mag. Mag. Materials, 200, 110 (1999). @footnote 2@ T. Dietl, H. Ohno, F. Matsukura, J. Cibert, and D. Ferrand, Science, 287, 1019 (2000). @footnote 3@ N. Akiba, D. Chiba, K. Nakata, F. Matsukura, Y. Ohno, and H. Ohno, J. Appl. Phys., 87, 6436 (2000). @footnote 4@ H. Ohno, N. Akiba, F. Matsukura, A. Shen, K. Ohtani, and Y. Ohno, App. Phys. Lett., 73, 363 (1998). @footnote 5@ Y. Ohno, D. K. Young, B. Beschoten, F. Matsukura, H. Ohno, and D. D. Awschalom, Nature, 402, 790 (1999). @footnote 6@ Y. Ohno, R. Terauchi, T. Adachi, F. Matsukura, and H. Ohno, Phys. Rev. Lett., 83, 4196 (1999).

10:00am **MI+EL-WeM6 Properties of Mn@sub x@Ge@sub 1-x@, Cr@sub y@Ge@sub 1-y@ and Mn@sub x@Cr@sub y@Ge@sub 1-x-y@ Semiconductor Films Grown by Molecular Beam Epitaxy@footnote 1@***, **J.E. Mattson**,* Naval Research Laboratory, US*; Y.D. Park, T.F. Ambrose, A.T. Hanbicki, A. Wilson, G. Spanos, B.T. Jonker,* Naval Research Laboratory

Mn doped GaAs exhibits ferromagnetic ordering along with semiconducting behavior.@footnote 2,3@ Recent theory@footnote 4@ suggests that low concentrations of Mn (10@super 20@ cm@super -3@). We describe here the structural, magneto-transport, and magnetic properties of Ge@sub 1-x@Mn@sub x@, Ge@sub 1-y@Cr@sub y@ and

[1] **Falicov Student Award Finalist**

Ge@sub 1-y-x@Cr@sub y@Mn@sub x@ thin films (with x < 0.15, and y < 0.15) in which Mn and Cr act as acceptors. Samples were grown by MBE on GaAs(001) and Si(001) substrates at substrate temperatures ranging from 175 to 350°C and growth rates of 4-5 Å/min. For all growth conditions studied, the GeMn films show a largely diffuse RHEED pattern and lack of structural order as determined by XRD. The temperature dependence of the resistivity shows non-metallic behavior with room temperature hole concentrations as high as 3x10@super 20@cm@super -3@. The magnetic properties determined from SQUID magnetometry are similar to those of Ge@sub 8@Mn@sub 11@ bulk alloys, suggesting the formation clusters of Ge@sub 8@Mn@sub 11@ rather than a homogeneous alloy. Plan-view TEM confirms the presence of clusters. The GeCr films exhibit single crystal growth and are p-type with p

10:20am **MI+EL-WeM7 Characterizations of Fe Thin Films on GaAs (001) Grown at Cryogenic Temperatures by Molecular Beam Epitaxy*, Y. Chye*,** *P Petroff,* University of California, Santa Barbara

One of our research objectives is to fabricate hybrid structures by integrating ferromagnetic materials into semiconductors. It has been demonstrated that molecular beam epitaxy (MBE) can be used to fabricate single crystalline Fe directly upon GaAs.@footnote 1@ However, the intermixing between Fe and GaAs at the interface forms a "magnetically dead layer"@footnote 1@ which will badly affect polarized transport and thus make efficient "spintronics" devices hard to realize. In an effort to circumvent this problem, we propose to grow Fe on GaAs at cryogenic temperatures (below -100 ° C). At these temperatures, the deposited Fe atoms and the GaAs surface atoms are less likely to react with each other through interdiffusion. To implement these ideas, we grow Fe thin films on GaAs (001) semi-insulating substrates at -150 ° C in an EPI-620 MBE with a liquid-nitrogen cooled sample stage. It is indicated by the streaky RHEED pattern that single crystalline Fe is grown on GaAs. The surface morphology, interface properties, crystal structure, film orientation and magnetic behavior of the samples have been characterized by atomic force microscopy (AFM), transmission electron microscopy (TEM), x-ray diffraction, and superconductivity quantum interference device (SQUID), respectively. To examine the interdiffusion at the interface, we perform photoluminescence (PL) measurements for samples with very thin Fe films grown at different temperatures above GaAs quantum wells. Our results show that the PL peaks for the quantum wells do not significantly change for the cryogenic temperature grown samples, whereas the room temperature grown samples show a dramatically reduced luminescence efficiency and energy emission shift. These results suggest that the cryogenic temperature deposition strongly suppress the interdiffusion between the Fe and GaAs at the interface. @FootnoteText@ @footnote 1@ J. J. Krebs, B. T. Jonker, G. A. Prinz, J. Appl. Phys., 61 (1987) 2596.

10:40am **MI+EL-WeM8 Growth and Magnetic Properties of Epitaxial Fe-N Films@footnote 1@*, F. Liu,*** *S.-C. Byeon, C. Alexander, G.J. Mankey,* University of Alabama

Reported values of magnetic moments in epitaxial Fe@sub 16@N@sub 2@ films vary from 2.3 to 3.5 Bohr magnetons per atom.@footnote 2@ These discrepancies arise from the fact that the films are multiphase mixtures which decompose upon heating.@footnote 3@ To study this problem, 40 nm thick Fe-N films were produced using reactive sputtering in an ultra clean sputtering system with in situ RHEED. First, an S-terminated GaAs surface is prepared by wet chemical etching. After annealing at 450 C, a 3 nm thick Fe seed layer is deposited to promote epitaxial growth of a 20 nm thick Ag(100) buffer layer. The Fe-N film is then grown on this Ag(100) buffer. The sputtering power, Ar + N@sub 2@ pressure, and the substrate temperature were varied systematically to produce the optimal RHEED pattern. The films were capped with a 5 nm thick Ru layer for ex situ structural and magnetic analysis. XRD is used to identify the degree of N-site ordering and the unit cell volume. XPS depth profiling is used to determine the chemical composition of the Fe-N film. The structural and chemical measurements are correlated with ferromagnetic resonance and vibrating sample magnetometry measurements of the saturation magnetic moment. These results are used to clarify the origin of the "giant magnetic moment" in the ordered Fe@sub 16@N@sub 2@ phase. @FootnoteText@ @footnote 1@Funded by ARO #DAAH 04-96-1-0316 and NSF #DMR-9809423. @footnote 2@G.W. Fernando et al., Phys. Rev. B 61, 375(2000). @footnote 3@ Migaku Takahasi and H. Shoji, J. Magn. Magn. Mater. 208, 145(2000).

Author Index

Bold page numbers indicate presenter