Thursday Morning, November 6, 2003

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

New Spintronic Materials

Moderator: B.T. Jonker, Naval Research Laboratory

8:20am **MI+SC-ThM1 Materials for Spin Injection Into GaN-Based Devices***, **C.R. Abernathy**, G.T. Thaler, R.M. Frazier, A. Stewart, S.J. Pearton, F. Ren,* University of Florida*; Y.D. Park,* Seoul National University, Korea*; R. Rairigh, J. Kelly,* University of Florida*; J. Lee,* Seoul National University, Korea*; A.F. Hebard,* University of Florida **INVITED**

Future spintronic devices will likely require injection of polarized currents into semiconductor devices. Though significant work has been carried out in GaAs-based materials, the rapid advancement of GaN-based devices for visible light emission and high power electronics makes this an attractive system for investigation. Two types of spin injection layers appear most promising. One approach is to incorporate magnetic ions into the semiconductor. The introduction of Mn into GaN has been shown to produce ferromagnetism at 300K, making it one of the few DMS materials which may be technologically useful. This method may be limited by the relatively low degree of ordering and the possibility of scattering at the DMS/semiconductor interface. An alternative approach is the use of ferromagnetic layers with metallic conduction, such as MnAs. This material has been used to produce polarized injection into GaAs-based structures, though only at low temperature. Though the lattice mismatch to GaN is greater than for GaAs, the MnAs crystal structure possesses the same Group V symmetry as GaN. This may make growth of a good quality MnAs/GaN interface more achievable than for the MnAs/GaAs heterostructure. This talk will discuss the growth and characterization of both of these types of spin injection layers on GaN. Gas-source molecular beam epitaxy using either an RF nitrogen plasma source, for GaMnN, or AsH3, for MnAs, along with elemental sources for Ga and Mn have been used to deposit thin films on MOCVD GaN buffer layers. Conditions for depositing single phase material with optimum magnetic ordering will be described. The processing challenges associated with integrating these materials into standard GaN/AlGaN light emitting diodes (LEDs) will be discussed along with preliminary electroluminescence results from SpinLEDs fabricated using only low temperature processing. This work was supported by the U. S. Army Research Office (ARO-DAAD19-01-1-0701) and NSF (ECS-0224203).

9:00am **MI+SC-ThM3 Characterization of AlGaN and AlN Based Dilute Magnetic Semiconductors***, **R.M. Frazier**[1], G.T. Thaler, J. Stapleton, C.R. Abernathy, S.J. Pearton,* University of Florida*; M.L. Nakarmi, J.Y. Lin, H.X. Jiang,* Kansas State University*; R. Rairigh, J. Kelly, A.F. Hebard,* University of Florida*; J.M. Zavada,* U. S. Army Research Office*; R.G. Wilson,* Consultant

The realization of room temperature ferromagnetism in GaN@footnote 1@ has ignited interest in the development of magnetic devices based on existing wide bandgap technology. However, in order to integrate magnetic semiconductors into the existing technology, it may be necessary to tailor the bandgap through addition of Al. Thus, AlGaN and AlN are two promising candidates for investigation, but optimization of the material in terms of choice of dopant, magnetic characteristics and crystalline quality is necessary before device fabrication can be undertaken. Ion implantation has been shown to be an effective survey method for optimization of dopant type and concentration. In this study, AlGaN and AlN grown on sapphire substrates by Metal Organic Chemical Vapor Deposition have been implanted with Mn, Cr, and Co at high doses (3x10@super 16@ cm@super -2@, 250 keV). After implantation the samples were annealed at 900°C for activation. Photoluminescence of the AlGaN-based alloys showed no band-edge luminescence before or after ion implantation, but the implantation process did introduce deep emission lines. In AlN, the Co and Cr doped films showed hysteresis at 300K while the Mn doped material did not. Epitaxial AlMnN by contrast does show hysteresis at room temperature suggesting that defects may be deleterious to magnetic ordering. The effects of dopant type and host conductivity type on the magnetic and electrical properties after implantation into AlGaMnN will also be presented. The work was supported by the Army Research Office under ARO-DADD19-01-0-0701, ARO-DAAF190110701 and DAAF 19021420 and by NSF under ECS-0224203, DMR 0101856, and DMR 0101438. @FootnoteText@ @footnote 1@ G. T. Thaler, M. E. Overberg, B. Gila, R. Frazier, C.R. Abernathy, S. J. Pearton, J. S. Lee, Y. D. Park, Z. G. Khim, J. Kim, F. Ren, Appl. Phys. Lett. 80, 3964 (2002).

9:20am **MI+SC-ThM4 Growth and Characterization of GaMnN/AlN Multiple Quantum Wells***, **G.T. Thaler**, R.M. Frazier, J. Stapleton, C.R. Abernathy, S.J. Pearton, R.P. Rairagh, J. Kelly, A.F. Hebard,* University of Florida

Though a number of recent studies have reported room temperature ferromagnetism in GaMnN, some important questions remain including determining the minimum layer thickness needed for ferromagnetic ordering.@footnote 1,2,3@ In this paper, we report on the growth and characterization of a variety of multiple quantum well structures comprised of layers of GaMnN and AlN. XRD analysis of the layers showed sharp satellite peaks indicative of good interfacial quality. By contrast to the GaMnAs system, magnetic ordering was maintained even for structures with 5nm GaMnN layer thicknesses. The magnetic moment of the GaMnN/AlN layers was determined to be ~1.7 Bohr magnetons per Mn, much higher than the 1.1 Bohr magnetons per Mn obtained in 200nm GaMnN films grown under the same conditions. This increase is believed to be due in part to improved crystallinity brought about by the presence of the AlN and also due to strain induced by the smaller lattice constant of the AlN. The use of strained superlattices has been shown to increase the activation of the deep acceptor Mg in p-GaN and p-AlGaN.@footnote 4,5@ It is likely that a similar effect is increasing the concentration of Mn+2 relative to Mn+3, resulting in a higher moment than in the thicker films. Attempts to tailor the strain, and the magnetic properties, by varying the Al content in the buffer and barrier layers will be discussed, as will the potential for using these phenomena to make magnetic strain sensors. This work was supported by the Army Research Office under: ARO-DAAD19-01-1-0701 and by NSF under: ECS-0224203 and DMR 0101856. @FootnoteText@ @footnote 1@ G.T. Thaler, et al. Appl. Phys. Lett. 80, 3964 (2002). @footnote 2@ S. Sonada, et al. J. Cryst. Growth 237-239, 1358 (2002). @footnote 3@M.L. Reed, et al. Appl. Phys. Lett. 79, 3473 (2001). @footnote 4@ Y.-L. Li, et al. Appl. Phys. Lett. 76, 2728 (2000). @footnote 5@P. Kozodoy, et al. Appl. Phys. Lett. 74, 3681 (1999). .

9:40am **MI+SC-ThM5 Theory of Dilute Magnetic Semiconductors***, **P. Bruno**,* Max Planck Institute of Microstructure Physics, Germany **INVITED**

10:20am **MI+SC-ThM7 Materials Characterization and Magnetic Studies of Epitaxial Co@sub x@Ti@sub 1-x@O@sub 2-x@ Deposited on Si(001) by Molecular Beam Epitaxy***, **T.C. Kaspar**[2],* University of Washington*; T. Droubay,* Pacific Northwest National Laboratory*; A.C. Tuan,* University of Washington*; C.M. Wang, S.A. Chambers, J.W. Rogers, Jr.,* Pacific Northwest National Laboratory

For spintronic devices such as spin-FETs, efficient injection of spin-polarized electrons into a semiconductor material is necessary. Progress has been made using ferromagnetic metals to tunnel spin-polarized electrons into AlGaAs/GaAs quantum well structures. However, for devices compatible with current semiconductor technology, efficient spin injection into Si is desired. Diluted magnetic semiconductors (DMSs) that can be grown epitaxially on Si are prime candidates. The epitaxial growth will result in a high-quality interface, reducing depolarization caused by scattering at interfacial defects. Further, the conductivity of the DMS can be tuned by doping to match that of Si, greatly increasing the spin injection efficiency. While most known DMS materials have Curie points well below room temperature, anatase Co@sub x@Ti@sub 1-x@O@sub 2-x@ has been shown to have a Curie temperature of at least 700K when deposited on LaAlO@sub 3@(001). In addition, anatase is well lattice-matched to Si. To prevent interfacial reactions between the film and substrate resulting in SiO@sub 2@ and/or silicide formation, a buffer layer of epitaxial SrTiO@sub 3@ (STO) is first deposited. In this study, a STO buffer layer and Co@sub x@Ti@sub 1-x@O@sub 2-x@ film on Si(001) are deposited by molecular beam epitaxy (MBE), which has been shown previously to result in higher quality Co@sub x@Ti@sub 1-x@O@sub 2-x@ films than pulsed laser deposition (PLD). Magnetic films have been successfully deposited with Co in the +2 charge state. The growth mode of Co@sub x@Ti@sub 1-x@O@sub 2-x@ has been investigated to minimize the formation of Co-rich anatase particles on the film surface. Thorough materials characterization of the Si interface, the STO buffer layer, and the Co@sub x@Ti@sub 1-x@O@sub 2-x@ film will be presented, paying particular attention to the possibility of metallic Co atoms in the film. In addition, the electronic and magnetic properties of the structure will be presented.

[1] **Falicov Student Award Finalist**

[2] **Falicov Student Award Finalist**

10:40am **MI+SC-ThM8 Ferromagnetic Co-doped Anatase TiO_2: Are All Growth Methods Created Equal?*, T. Droubay*, *S.M. Heald,* Pacific Northwest National Laboratory*; T.C. Kaspar,* University of Washington*; C.M. Wang, S.A. Chambers,* Pacific Northwest National Laboratory

With both theoretical and experimental underpinnings, a flurry of activity has centered around new candidate diluted magnetic semiconductors (DMS) based on doping semiconducting oxides with magnetic impurities. With a Curie point of ~700K, high remanence, and high saturation, Co-doped TiO_2 in the Anatase form stands out as the most magnetically robust oxide DMS. Following the initial discovery in 2001, several groups have explored the synthesis and properties of Co-doped anatase using an array of different growth methods. While most of these techniques produced materials exhibiting room temperature ferromagnetic behavior, the resounding message learned has been to accurately determine if minority phases are present. Thin film growth of this novel oxide material has been dominated by pulsed laser deposition (PLD) and oxygen plasma-assisted molecular beam epitaxy (OPA-MBE) on $SrTiO_3$(001) and $LaAlO_3$(001). We have consistently produced epitaxial materials by OPAMBE in which the saturation moment is consistently found to be ~1.1 - 1.3 μ_B/Co at room temperature. In contrast, $Co_xTi_{1-x}O_2$ grown by PLD typically has a saturation magnetization at room temperature of 0.3 μ_B/Co. We will discuss the similarities and differences between materials produced by these two techniques highlighting morphological, electrical and magnetic properties. We will also discuss our recent post-growth annealing study of MBE grown specimens in which the magnetic properties do not change when the films are annealed in vacuum at 825K. This is particularly interesting in light of recent seemingly contradictory results of annealed PLD grown films. Shinde et al. report that Co metal inclusions in an Anatase film can be dissolved within the matrix and substituted for Ti as a result of a 1200K anneal in 1atm. argon. In contrast, Kim et al. found that Co came out of solution and formed Co metal as a result of a 700K anneal in 10^{-6} torr O_2.

11:00am **MI+SC-ThM9 Ferromagnetism in Optically Transparent Semiconducting Co Doped SnO_{2-d} Films*, R.J. Choudhary*[1]**, *S.B. Ogale, S.R. Shinde,* Univ. of Maryland*; J.P. Buban,* Univ. of Illinois at Chicago*; S.E. Lofland,* Rowan Univ.*; S.N. Kale, V.N. Kulkarni, J. Higgins,* Univ. of Maryland*; C. Lanci,* Rowan Univ.*; J.R. Simpson,* Univ. of Maryland*; N.D. Browning,* Univ. of Illinois at Chicago*; S. Das Sarma, D. Drew, R.L. Greene, T. Venkatesan,* Univ. of Maryland

Thin films of Co doped SnO_{2-d} grown by pulsed laser deposition on single crystal sapphire substrates are examined for their magnetic, structural, electrical, magnetotransport and optical properties. The films exhibit room temperature ferromagnetism with a Curie temperature close to 650 K. In addition, the films with 5 % of Co doping exhibit a giant magnetic moment of 7.5 ± 0.5 μ_B/Co. The films are highly transparent even at 27 % of Co doping. The optical bandgap shows a redshift with Co doping. Ion channeling data show a fair degree of channeling for Sn but no channeling for Co, implying Co atoms to be structurally incoherent. However, no clustering of Co can be observed in high-resolution transmission electron microscopy even up to 27 % of Co doping. The electrical resistivity shows a rapid increase with Co doping. Possible scenarios about the microscopic state of this system and the origin of ferromagnetism will be discussed.

11:20am **MI+SC-ThM10 Elaboration and Characterisation of Cobalt Doped ZnO Thin Films for Spintronic Applications*, A. Anane***, *K. Rode, J.L. Maurice, J.P. Contour,* UMP CNRS-Thales and Paris XI University, France

ZnO is a large gap II-VI semiconductor potentially interesting for UV opto-electronic applications. We have investigated the structural and the magnetic properties of cobalt substituted ZnO thin films deposited on sapphire (0001) substrates by pulsed laser deposition. The films show clear ferromagnetic behavior up to 400K, the saturation moment does not exceed 1.3 ÂµB / Co atom which far away from is expected for the ionic Co2+ (3d7). We have ruled out parasitic phases as the origin of the measured magnetism by many experimental techniques, including High resolution transmission electron microscopy, X-ray edge spectroscopy and X-ray magnetic-circular-dichroism. Preliminary transport measurements on magnetic tunnel junctions based on Zn0.75Co0.25O will be presented.

11:40am **MI+SC-ThM11 Ferromagnetism in Cobalt Doped $La_{0.5}Sr_{0.5}TiO_{3-d}$ Films*, S.R. Shinde***, *S.B. Ogale, Y.G. Zhao, J. Higgins, R.J. Choudhary,* University of Maryland*; S.E. Lofland, C. Lanci,* Rowan University*; J.P. Buban, N.D. Browning,* University of Illinois at Chicago*; S. Das Sarma,* University of Maryland*; A.J. Millis,* Columbia University*; V.N. Kulkarni, R.L. Greene, T. Venkatesan,* University of Maryland

Epitaxial films of lightly cobalt doped $La_{0.5}Sr_{0.5}TiO_{3-d}$ are shown to exhibit ferromagnetism at room temperature. A clear hysteresis loop with coercevity ~150 Oe and the Curie temperature around 450 K are observed for these (001) oriented films grown by pulsed laser deposition at oxygen pressure of 10^{-4} Torr on $LaAlO_3$ substrates. For cobalt doping up to ~2%, no inhomogeneity is observed by scanning transmission electron microscopy (S-TEM). The magnetization is found to change non-monotonically (in the range 1-3 μ_B/Co) as a function of conductivity in films deposited at different partial pressures. The films range from being opaque metallic to transparent semiconducting depending on the oxygen pressure during growth and are yet ferromagnetic at and above room temperature.

[1] **Falicov Student Award Finalist**

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