# SYMPOSIUM G

## Semiconductor Spintronics

April 13 - 15, 2004

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* Invited paper

SESSION G1:Material Properties of Dilute Magnetic Semiconductors
Chair: Bernd Beschoten
Tuesday Morning, April 13, 2004
Room 2005 (Moscone West)

**8:30 AM *G1.1**
**GaMnAs: improved materials and the emerging understanding of magnetic and magnetotransport properties.**
B. L. Gallagher, K. W. Edmonds, K. Y. Wang, R. Campion, L. Zhao and C. T. Foxon; School of Physics & Astronomy, University of Nottingham, Nottingham, United Kingdom.

By careful control of MBE growth conditions and post growth annealing procedures we have produced GaMnAs epilayers which high conductivities and Curie temperature up to 173K. We demonstrate that the improvement in material properties resulting from annealing is due to the out diffusion of interstitial Mn. The high conductivies of our material makes it possible to obtain accurate hole densities for a range of Mn compositions. We find that compensation is very low in best samples. We show that our measured Curie Temperatures, Hall conductivities and AMR are in good agreement with the mean field theory. We also find that there is no evidence of a fundamental magnetisation deficit in our material. Time permitting we will also discuss the room temperature ferromagnetism we observe GaMnN, transition metal doped oxides.

**9:00 AM G1.2**
**Nondestructive Optical Method to Check Nanometer-size Metallic Secondary Phases in Diluted Magnetic Semiconductors.**
Sung Seok A. Seo[1,2], T. W. Noh[1,2], J. D. Lim[1,3], Y. D. Park[1,3], Y. S. Kim[1], Z. G. Khim[1], Y. W. Kim[4] and S. J. Pearton[5]; [1]School of Physics, Seoul National University, Seoul, South Korea; [2]Research Center for Oxide Electronics, Seoul National University, Seoul, South Korea; [3]Center for Strongly Correlated Materials Research, Seoul National University, Seoul, South Korea; [4]School of Materials Science and Engineering, Seoul National University, Seoul, South Korea; [5]Department of Materials Science & Engineering, University of Florida, Gainesville, Florida.

Mn doped III-V diluted magnetic semiconductors (DMS) have attracted a lot of attention due to their potential applications to spin-based electronics. In spite of development of elaborate growth techniques, it is still difficult to avoid and monitor the formation of nanometer-size inter-metallic compounds, such as $Mn_xAs_y$, $Mn_xN_y$, and GaMn. Since many of the metallic secondary phases are known to be ferromagnetic with high magnetic ordering temperatures, it is essential to determine whether such ferromagnetic metallic clusters are formed or not before investigating the possible origins of DMS. Up to this, X-ray diffraction (XRD) and transmission electron microscopy (TEM) have been widely used to determine the formation of the secondary phases. However, both methods have some serious drawbacks: XRD cannot easily detect the nanometer-size phases, and TEM is destructive and its data should be interpreted with care. We demonstrated that optical spectroscopy could be a useful non-destructive method to check the formation of such metallic secondary phases. The small particle geometry of the second phases moves the plasma resonance from zero to a higher frequency region, making a strong absorption (called, the 'sphere resonance') near the optical region. For example, $Mn_4N$ inter-metallic particles in (Ga,Mn)N/$Al_2O_3$ result in a strong resonance peak at 1.2 eV.[1] This spectroscopic technique is nondestructive and simple to use. In addition, this method provides quantitative information, such as the volume fraction of the metallic phases. In this presentation, we will provide numerous examples, including $Mn_4N$ particles in (Ga,Mn)N/$Al_2O_3$ and MnAs particles in LT-GaAs/GaAs samples, and how the secondary phase particles become larger during the post-annealing process. The spectroscopic signature of possible metallic secondary phases in literature will be also discussed. [1] Seo et al., Appl. Phys. Lett., 82, 4749 (2003).

**9:15 AM G1.3**
**Structural Properties of Cr-implanted GaN.**
Martina Luysberg[1], Lothar Houben[1], Vitaliy Guzenko[2], Raffaella Calarco[2], Andre Dahmen[2] and Thomas Schaepers[2]; [1]Institute of Solid State Research, Research Center Juelich and cni-Center of Nanoelectronic Systems for Information Technology, Juelich, Germany; [2]Institute of Thin Films and Interfaces, Research Center Juelich and cni-Center of Nanoelectronic Systems for Information Technology, Juelich, Germany.

Recently, the implantation of semiconductors with ferromagnetic transition metals has become of interest with respect to the realization of spintronic devices. For the case of Cr implantation into GaN ferromagnetic behaviour at room temperature has been reported in literature. However, up to now it is an open question whether the ferromagnetic properties arise from ferromagnetic clusters or whether an ideal dilute magnetic semiconductor is formed. In our work we focus on the structural characterization of Cr implanted GaN by high-resolution transmission electron microscopy. GaN layers are deposited by metal organic vapor deposition on $Al_2O_3$ substrates. Cr ions were implanted with dose of 5E16 $cm^{-2}$ and an energy of 200keV. Subsequently, the samples were annealed at 850 °C and 700 °C for 5 min, respectively. As a result of implantation and annealing a highly defective layer extending to a depth of 230 nm is formed. Three depth regions can be distinguished : Close to the surface the densitiy of structural defects, identified by their strain contrast is considerably lower than in deeper regions. The intermediate region extending from about 30 nm to 200 nm below the surface, is characterized by a large density of planar defects parallel to the (0001) planes, some of them are identified as stacking faults in high-resolution images. In addition, local contrast variations extending over about 2 nm are observed, which appear as Moire fringes in high-resolution images and are indicative of a second phase. Finally, at the end of range, small dislocation loops, up to 6 nm in diameter are observed. Thus, besides the formation of dislocations and planar defects, we found clear evidence for clusters arising from a second phase.

**10:00 AM *G1.4**
**Control of ferromagnetic order in semiconductor heterostructures with Mn delta doping.**
Masaaki Tanaka[1,2] and Ahsan M. Nazmul[1,2]; [1]Dept of Electronic Engineering, University of Tokyo, Tokyo, Japan; [2]PRESTO Program, JST, Kawaguchi, Japan.

In this presentation, we will review the recent developments of epitaxial ferromagnetic heterostructures based on semiconductors towards spintronics. This includes the semiconductor materials and heterostructures having high ferromagnetic transition temperatures (III-V based alloy magnetic semiconductors, Mn-delta-doped magnetic semiconductors, and related heterostructures), spin-dependent transport and tunneling, and their device applications (tunneling magnetoresistance devices and three-terminal devices using spin-transport) [1]-[3]. Future issues and prospects will be also discussed. In particular, we show our magnetotransport study on ferromagnetic III-V semiconductor heterostructures with high Curie temperature (Tc). In selectively doped heterostructures (Mn-delta-doped GaAs / Be-doped AlGaAs), in which holes are supplied from the Be-doped p-AlGaAs layer to the Mn-delta-doped channel, ferromagnetic ordering was clearly observed [4]. In the heterostructure prepared with proper conditions, its Tc was as high as 172 K, higher than the Tc of InAs- or GaAs-based random-alloy magnetic semiconductors [5]. Furthermore, we show the control of ferromagnetism in the heterostructures by using gate electric field and light irradiation at relatively high temperatures ( 100 K) [6][7]. This work was supported by the PRESTO (Sakigake-21) Program of JST, the IT Program RR2002 of MEXT, Toray Science Foundation, and Grant-in-aid for Scientific Research from MEXT, Japan. References [1] M. Tanaka and Y. Higo, Phys. Rev. Lett. 87, 026602 (2001). [2] M. Tanaka and Y. Higo, Physica E13, 495 (2002). [3] S. Ohya, H. Kobayashi, and M. Tanaka, Appl. Phys. Lett. 83, 2175 (2003). [4] A. M. Nazmul, S. Sugahara, and M. Tanaka, Appl. Phys. Lett. 80, 3120 (2002). [5] A. M. Nazmul, S. Sugahara, and M. Tanaka, cond-mat/0208299 (August 2002); Phys. Rev. B67, 241308(R) (2003). [6] M. Tanaka, Invited talk at the Annual American Physical Society (APS) March Meeting 2003, paper S7.004, Austin, March 3-7, 2003. [7] A. M. Nazmul, S. Sugahara, and M. Tanaka, to be published in Physica E.

**10:30 AM *G1.5**
**Engineering Ferromagnetic Semiconductors.**
Ezekiel Johnston-Halperin[1], J. A. Schuller[2], C. S. Gallinat[2], T. C. Kreutz[2], R. C. Myers[2], R. K. Kawakami[3], H. Knotz[2], A. C. Gossard[2] and D. D. Awschalom[2]; [1]Chemistry, California Institute of Technology, Pasadena, California; [2]Center for Spintronics and Quantum Computation, University of California, Santa Barbara, California; [3]Physics, University of California, Riverside, California.

Much of the promise of the emerging field of semiconductor spintronics lies in the inherent flexibility of semiconducting materials, specifically the ability to continuously tune both their band gap energy and free carrier concentration. However, progress has been slowed by both the lack of n-type ferromagnetic semiconductors and the interdependent nature of carrier concentration and TC in these materials. Specifically, the construction of bipolar-junction based spin-transistors as proposed by Flatté et al. [1] would be significantly simplified if one were able to control the sign and magnitude of the doping in a ferromagnetic semiconductor. Here we present the synthesis of novel structures based on digital ferromagnetic heterostructures (DFH) [2] wherein we achieve electrical doping *independent* of the concentration of magnetic dopants [3]. These structures are comprised of alternating layers of sub-monolayer thickness MnAs and either Be or Si doped GaAs (p- or n-type respectively) grown by atomic layer epitaxy (ALE). The samples are characterized by superconducting quantum interference device

(SQUID) magnetometry and x-ray diffraction, revealing ferromagnetic behavior for all doping levels. Further, transport measurements reveal critical point scattering typically seen in random alloy (Ga,Mn)As as well as switching consistent with the giant planar hall effect (GPHE) [4]. Finally, fluctuations in the magnetoresistance are observed at low temperatures which suggest enhanced sensitivity to domain wall motion in these structures. Work supported by DARPA, ONR, and AFOSR. [1] M. Flatté, et al., Appl. Phys. Lett. **82**, 4740 (2003). [2] R.K. Kawakami, et al., Appl. Phys. Lett. **77**, 2379 (2000). [3] E. Johnston-Halpeirn, et al., Phys. Rev. B **68**, 165328 (2003). [4] H.X. Tang, et al., Phys. Rev. Lett. **90**, 107201 (2003).

### 11:00 AM *G1.6

**Theory of Ferromagnetism in Diluted Magnetic Semiconductors.** Allan Hugh MacDonald[1], Dimitri Culcer[1], Qian Niu[1], Alvaro Nunez[1], Nicolai Sinitsyn[2], Jairo Sinova[2,1], Tomas Jungwirth[3,1] and Yugui Yao[4,1]; [1]Department of Physics, University of Texas, Austin, Texas; [2]Physics, Texas A&M University, College Station, Texas; [3]Physics, Czech Academy of Sciences, Prague, Czech Republic; [4]Institute of Physics, Chinese Academy of Sciences, Beijing, China.

III-V semiconductors like GaAs and InAs become ferromagnetic when Mn is substituted on a small fraction of the cation sites. There has recently been considerable interest in these materials, mainly because of their possible role in semiconductor spintronics. I will review the status of efforts to understand the interrelated magnetic, optical, and transport properties of these ferromagnets. I will focus on unusual aspects of their ferromagnetism, including the inevitable role of alloy disorder in systems with diluted moments and the important role that spin-orbit interactions in the valence band of the host semiconductors play in enabling ferromagnetism at relatively high temperatures. My talk will emphasize the complementary insights that come from first-principles and phenomenological descriptions of these materials. These unusual ferromagnets provide an interesting window on some general issues in the theory of itinerant electron ferromagnetism. One important property of these ferromagnets is the strong anomalous Hall effect that they exhibit. I will argue that the anomalous Hall conductivity in these ferromagnets is a purely intrinsic effect that can be explained with reasonable accuracy in terms of the host semiconductor band structure alone. The conductivity arises from an additional contribution to the group velocity of band electrons that is induced by an electric field and is perpendicular to the field direction, sometimes referred to as the anomalous velocity. Quantitative evaluation of the anomalous velocity can account for the Hall effect, not only in DMS ferromagnets, but also in transition metals. The term spin-torque has been used to describe the influence of spin-polarized current in an inhomogeneous magnetic system on the collective magnetization orientation. Spin-torques are usually explained using a language that rests heavily on the conservation of total spin-angular- momentum, that is on appealing to a Hamiltonian that is approximately spin-rotationally invariant. Motivated by the case of DMS ferromagnetism, in which current-induced magnetization reversals have not yet been observed, I will describe a view of spin-transfer that applies equally well to systems with strong spin-orbit interactions. References: Sinova et al. PRB Volume 67, 235203. Culcer et al. cond-mat/0309475;cond-mat/0307663. APL, Volume 83,320 and other preprints available on cond-mat.

### 11:30 AM G1.7

**Exchange Interactions, Curie Temperatures and Spin-waves in Dilute Magnetic Semiconductors.** kazunori sato[1], Peter H. Dederichs[1] and Hiroshi Katayama-Yoshida[2]; [1]Institut fuer Festkoerperforschung, Forschungszentrum Juelich, Juelich, Germany; [2]Institute of Scientific and Industrial Research, Osaka University, Osaka, Japan.

The Magnetic properties of dilute magnetic semiconductors (DMS) are calculated from first-principles by mapping the ab-initio results on a Heisenberg model. The electronic structure of DMS is calculated by using the Korringa-Kohn-Rostoker coherent potential approximation (KKR-CPA) method within the local density approximation. Effective exchange coupling constants Jij's are evaluated by embedding two impurities i and j in the CPA medium and using the Jij formula of Liechtenstein et al. [1]. The Curie temperatures (Tc) of (Ga, Mn)N, (Ga, Mn)P, (Ga, Mn)As and (Ga, Mn)Sb are estimated from the calculated exchange coupling constants by using the mean-field approximation (MFA) and the random phase approximation (RPA). Both approximations give the same chemical trends, i.e., Tc is proportional to the square root of Mn concentration c for (Ga, Mn)N where the double exchange interaction dominates, on the other hand Tc is linear to c in (Ga, Mn)Sb being dominated by the p-d exchange interaction dominates. Since the extended valence hole states mediate the ferromagnetic coupling between localized Mn magnetic moments in (Ga, Mn)Sb (p-d exchange [2]), the exchange interaction is long range leading to a flat spin-wave dispersion relation. As a result, the MFA gives similar results as the RPA and becomes practically exact in the very dilute limit where the screening of the pair interaction by other impurities can be neglected. On the other hand, in (Ga, Mn)N impurity bands appear in the band gap and due to the broadening of the impurity bands the ferromagnetic state is stabilized (double exchange [3]). Since the wave function of the majority Mn d-states in the gap are well localized, the exchange interaction is short range leading to dispersive magnon bands. As a result, the MFA values deviate from the RPA values already for low concentrations and Tc in MFA is systematically higher than in RPA. [1] A. I. Liechtenstein et al., J. Magn. Magn. Mater. 67 (1987) 65. [2] T. Dietl et al., Science 287 (2000) 1019. [3] H. Akai, Phys. Rev. Lett. 81 (1998) 3002.

### 11:45 AM G1.8

**Electronic Structure and Valence of Mn impurities in III-V Semiconductors.** Thomas C. Schulthess[1,5], W. Temmeran[2], S. Szotek[2], W. H. Butler[3] and G. M. Stocks[4,5]; [1]Computer Science and Mathematics Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee; [2]Daresbury Laboratory, Warrington, United Kingdom; [3]University of Alabama, Tuscaloosa, Alabama; [4]Metal and Ceramics Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee; [5]Center for Computational Sciences, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

Substitutional Mn impurities in III-V semiconductors can acquire either a divalent or a trivalent configuration. For example, it is generally accepted that Mn in GaAs is in a (\$d$\hat{5}$+h\$) configuration with five occupied Mn d-orbitals and a delocalized hole in the valence band. In contrast, Mn in GaN is believed to be in a \$d$\hat{4}$\$ configuration with a deep impurity state that has d-character. But there have recently been some discussions about the possibility of having some Mn ion in GaN assuming a divalent (\$d$\hat{5}$+h\$) type configuration. In order to achieve carrier induced ferromagnetism, the desired state of the Mn ions in III-V semiconductors is the (\$d$\hat{5}$+h\$) configuration. We have therefore performed ab-initio calculations of the Mn valence when it substitutes Ga in various III-V semiconductor hosts. We use the self-interaction corrected local spin density (SIC-LSD) method which is able to treat localized impurity orbitals properly. In particular we find that the method is capable of predicting the (\$d$\hat{5}$+h\$) state of Mn in GaAs. For Mn in GaP and GaN the calculations predict a trivalent \$d$\hat{4}$\$ state in the idealized system. The energy differences between \$d$\hat{4}$\$ and (\$d$\hat{5}$+h\$) configurations in GaP are, however, very small. Introduction of defects or donors doe change the valence of Mn in GaP, favoring the divalent state under certain circumstances. Work supported by the Defense Advanced Research Project Agency and by the Division of Materials Science and Engineering, U.S. Department of Energy, under Contract DE-AC05-00OR22725 with UT-Battelle LLC.

## SESSION G2:Diluted Magnetic Semiconductors and Oxide Materials
Tuesday Afternoon, April 13, 2004
Room 2005 (Moscone West)

### 1:30 PM G2.1

**Investigation and discovery of novel magnetic phenomena in Mn incorporated InP, InSb and other III-V semiconductors, synthesized through controlled-ambient annealing.**
Joel Philip Hollingsworth and Prabhakar Bandaru; Mechanical and Aerospace Engineering, University of California, San Diego, La Jolla, California.

Magnetic semiconductors are of interest for emerging spintronic applications, such as the integration of electronic information processing with magnetic data storage. The preparation of these materials, such as (Ga, Mn) As with Curie temperatures (Tc) in the range of 110 K, has been mostly done by non-equilibrium molecular beam epitaxy which overcomes the low solubility limit of Mn in GaAs. In this talk, we report on alternative synthesis techniques to increase the incorporation of magnetic elements into non-magnetic III-V semiconductors, such as InP, InSb and GaAs. The aim is to discover new magnetic materials with Tc greater than/around room temperature. Furnace annealing, under excess anion (P, Sb and As) pressure together with the co-incorporation of Cr were used to increase the Mn substituting for Group III atoms. These annealing treatments were hypothesized to reduce the effect of Mn interstitials, which have been shown to reduce Tc. Novel magnetic phenomena, such as the occurrence of a ferromagnetic Tc around 60 K in Mn-containing InP and ferrimagnetism in GaAs including both Mn and Cr, were observed through SQUID magnetometry. X-ray diffraction was used to characterize phase homogeneity. We are in the process of measuring transport properties in these materials, and plan to expand this work by using the magneto-optic Kerr effect for further specificity in magnetic phase characterization. The use of facilities at the W.M. Keck Center for Interface Materials Science at UCSD is acknowledged.

**1:45 PM G2.2**
**Carrier induced ferromagnetism in II-IV-$V_2$ Chalcopyrites.**
Paul Kent[1,2] and T C Schulthess[2]; [1]University of Tennessee, Knoxville, Tennessee; [2]Oak Ridge National Laboratory, Oak Ridge, Tennessee.

Although it has been suggested[1] that high $T_c$ dilute magnetic semiconductor (DMS) materials can be realized from common III-V semiconductors, solubility of Mn is limited in these materials and high Curie temperatures have yet to be realized. As an alternative potential route to high $T_c$ materials, we have performed a systematic investigation of the II-IV-$V_2$ alloys doped with Mn, such as (Cd,Mn)$GeP_2$ and (Zn,Mn)$SnAs_2$. These "virtual III-V" chalcopyrite alloys are compatible with many existing III-V technologies, yet the Mn solubility is greatly increased, because $Mn^{2+}$ ions can readily substitute on the group II sites. Using projector augmented wave (PAW) density functional calculations we have calculated the ferromagnetic coupling (J) between various configurations and charge states of Mn atoms, including several intrinsic defects. Here we report that Zn-Sn based compounds have larger ferromagnetic interactions than in $CdGeP_2$ and $ZnGeP_2$, which have been grown by several groups. Although the magnitude of the interaction strongly depends on the Mn complexes considered, the larger effective exchange interaction in, e.g., $ZnSnAs_2$ and $ZnSnP_2$ should result in concomitantly enhanced Curie temperatures. Our results also confirm the validity of the postulated model of carrier mediated ferromagnetism in chalcopyrites[2,3]. We recommend that this class of materials should be more thoroughly investigated for potentially viable spintronics materials. Work supported by the Defense Advanced Research Project Agency and by the Division of Materials Science and Engineering, U.S. Department of Energy, under Contract DE-AC05-00OR22725 with UT-Battelle LLC. [1] T. Dietl et al. Science **408**, 944 (2000). [2] G. A. Medvedkin et al. Jpn. J. Appl. Phys. **39**, L949. (2000) [3] P. Mahadevan and A. Zunger Phys. Rev. Lett. **88**, 047205 (2002).

**2:00 PM G2.3**
**The effect of the spin-orbit coupling on the spin polarisation of half-metals.** Peter H. Dederichs[1], Phivos Mavropoulos[2] and Voicu Popescu[3]; [1]Institut fuer Festkoerperforschung, Forschungszentrum Juelich, Juelich, Germany; [2]Institut fuer Festkoerperforschung, Forschungszentrum Juelich, Juelich, Germany; [3]Department Chemie/Physikalische Chemie, University of Munich, Munich, Germany.

We have performed first-principles calculations in order to investigate the effect of the spin-orbit coupling to the existence of the spin-down band gap of half-metals and to the spin polarisation at the Fermi level. Due to spin-orbit coupling the spin is not a good quantum number, so that a spin polarisation of exactly 100% is unrealistic. As typical half-metallic systems, we have chosen the Heusler alloy NiMnSb, the ordered zinc-blende alloys CrAs, CrSb, and MnBi, and the diluted magnetic semiconductors (Ga,Mn)As and (Ga,Mn)N. We find that the majority-spin states are partly reflected into the minority band gap. The intensity of the DOS for minority electrons in this energy region depends mainly on the strength of the spin-orbit coupling: heavier sp elements result in a higher ratio of minority/majority spin DOS, thus in a lower spin polarisation at the Fermi level. We see a trend of decreasing spin polarisation P as we go from CrAs (P=99.6%) to CrSb (P=98.6%) and finally to MnBi (P=77%). In NiMnSb we find a value of P=99%. Also, it is important how deep the Fermi level lies within the gap, since majority states close to the gap edges can be easier spin-flipped than states deep in the gap. This results in a decrease of the spin polarisation to P=92% for (Ga,Mn)As where the Fermi level is very close to the valence band edge, which is p-like and exhibits strong spin-orbit coupling. We have also explained these effects by first-order perturbation theory. For transport applications in spintronics we conclude that the spin-orbit coupling is not very critical, since even in compounds with strong spin-orbit coupling (MnBi or (Ga,Mn)As) the majority DOS at the Fermi level dominates over the minority by an order of magntiude. Nevertheless in many cases a significant reduction of the spin polarisation is observed.

**2:15 PM G2.4**
**Rectifying Electrical Characteristics of $La_{0.7}Sr_{0.3}MnO_3$/ZnO Heterostructure.** Ashutosh Tiwari, NC state university, raleigh, North Carolina.

We have succeeded in fabricating a p-n junction, consisting of p-type manganite ($La_{0.7}Sr_{0.3}MnO_3$) and n-type ZnO layers grown on sapphire substrate. This junction exhibits excellent rectifying behavior over the temperature range 20-300K. Electrical characteristics of $La_{0.7}Sr_{0.3}MnO_3$ (LSMO) film in this heterostructure are found to be strongly modified by the built-in electric field at the junction. It has been shown that by applying the external bias voltage, the thickness of the depletion layer and hence the electrical and magnetic characteristics can precisely be tuned.These junctions provide an effective way to control the electrical and magnetic characteristics of giant magnetoresistive LSMO films by using the built-in electric field at the LSMO/ZnO interface. They also provide an opportunity to integrate various magnetic and magnetoresistive properties of manganites with nonlinear optical and optoelectronics applications of ZnO.

**3:00 PM G2.5**
**Epitaxial growth and magnetic properties of $Si_{1-x}Mn_x$ thin films.** Satoshi Sugahara[1,2], Kok Leong Lee[1], Tomohiro Matsuno[1] and Masaaki Tanaka[1,2]; [1]Dept. of Electronic engineering, The university of Tokyo, Tokyo, Japan; [2]PRESTO, JST, Kawaguchi, Japan.

Recently, ferromagnetic alloy semiconductors (FASs), in which the host semiconductor (SC) lattice sites are partially occupied by magnetic ions, attract considerable attention for semiconductor-based spintronics. Since the lattice mismatch between FAS and its host SC is relatively small and the crystal structure of FAS is the same as the host, high-quality magnetic heterostructures can be grown. Furthermore, the predicted high spin polarization of FAS and small conductivity mismatch enable efficient spin injection from FAS to SC. While most of the studies are concentrated on II-VI or III-V based materials so far, little work has been done on Si-based FASs. Epitaxial growth of Si-based FASs and their heterostructures on Si substrates are obviously important, since they are expected to be compatible with present Si device technology. In this paper, we report on the successful growth of $Si_{1-x}Mn_x$ thin films on Si(001) substrates by molecular beam epitaxy (MBE). Although the magnetic properties of the $Si_{1-x}Mn_x$ films depended on the growth conditions and Mn concentrations, $Si_{1-x}Mn_x$ films exhibited clear ferromagnetic ordering. Low-temperature (LT) MBE technique was employed for the growth of $Si_{1-x}Mn_x$ films in order to avoid the precipitation of Mn silicides, and also an LT-grown Si buffer layer was used to allow continuous $Si_{1-x}Mn_x$ film growth at nearly the same temperature. After the growth of a 15-nm-thick Si buffer layer on a Si(001) substrate, a 30-nm-thick $Si_{1-x}Mn_x$ film was grown at 250-400°C. The $MCs^+$-SIMS technique was used to measure the Mn concentration. When $Si_{1-x}Mn_x$ films were grown at 250°C, the epitaxial growth was observed up to the Mn concentration x of 40% from in-situ RHEED measurements. However, the surface exhibited rough morphology due to the 3-dimensional growth, and its roughness was increased with increasing x. No ferromagnetic ordering was observed for the $Si_{1-x}Mn_x$ films grown at 250°C. The 2-dimensinal growth of $Si_{1-x}Mn_x$ films was observed by increasing the growth temperature to 400°C, and the morphology and crystallinity of $Si_{1-x}Mn_x$ films were significantly improved. $Si_{1-x}Mn_x$ films with smooth surface due to the 2-dimensinal growth were obtained at $X < 12\%$. SQUID measurements revealed ferromagnetic ordering below 130K for a $Si_{0.96}Mn_{0.04}$ film (x=4%) grown at 400°C. $Si_{1-x}Mn_x$ films with higher x (more than 8%) exhibited two ferromagnetic phases; the first phase with the Curie temperature $T_c$ of 150K and a second phase with higher $T_c$ (>300 K). The origin of these ferromagnetic phases will be investigated by magneto-optical and magneto-transport measurements, such as magnetic circular dichroism (MCD) and anomalous Hall effect.

**3:15 PM G2.6**
**Synthesis, Magnetism, and Magneto-Optical Spectroscopy of ZnO Diluted Magnetic Semiconductor Quantum Dots.**
Daniel R. Gamelin, Dana A. Schwartz, Pavle V. Radovanovic, Nick S. Norberg and Kevin R. Kittilstved; Chemistry, University of Washington, Seattle, Washington.

Diluted magnetic semiconductor (DMS) nanostructures such as quantum dots (DMS-QDs), quantum wells, quantum wires, and epitaxial thin films are pivotal architectural elements in many proposed spintronics devices. This talk will present our group's recent advances in the development of direct routes for preparation of freestanding high-quality DMS quantum dots of ZnO, a target material recently shown to support high-temperature ferromagnetism in thin films. Emphasis will be placed on the application of magneto-optical spectroscopic methods (including magnetic circular dichroism and Zeeman spectroscopies) to study the electronic structural properties of ZnO DMS-QDs. Spectroscopic identification of ligand field, charge transfer, and excitonic transitions in DMSs will be presented and related to the spintronics-relevant functional properties. The use of variable-temperature variable-field magneto-optical methods to define ground state spin-orbit splittings, and the influence of such splittings on the magnitudes of semiconductor band level Zeeman splittings, will also be discussed. Finally, data addressing the influence of DMS length scales on high-TC ferromagnetic ordering will be presented.

**3:30 PM G2.7**
**Optical properties of transition metal doped ZnO Ceramics and thin films.** Ram S Katiyar, Neha Awasthi and Pijush

Bhattacharya; Department of Physics, University of Puerto Rico, San Juan, Puerto Rico.

Dilute magnetic semiconductors (DMS) are extensively investigated for their potential in combining ferromagnetic and semiconductor properties in a single material. It has been experimentally demonstrated that the 3d transition metal atoms are soluble up to several mole fraction ( 0.35) in ZnO host, which made it a promising candidate for fabrication of DMS with high Curie temperature. In this study, V, Mn and Fe doped ZnO ceramics were prepared using conventional ceramic processing. Thin films were fabricated on c-Al$_{2}$O$_{3}$ substrate using pulsed laser deposition technique and ceramic targets. The dopant concentration was varied between 1 - 10 mole percent in the targets. Substrate temperature was varied in the range of 700-800 ${̂o}$ C with an oxygen partial pressure of 1 mTorr. The hexagonal structure of ZnO was retained with transition metal doping as observed from the x-ray diffraction measurements. Raman spectroscopy showed additional modes due to transition doping in ceramic and thin films. In V doped ZnO strong peaks were observed at 264 cm${̂-1}$ and 852 cm${̂-1}$, which were not present in undoped ZnO ceramics and thin films. In the case of Mn doped ZnO, additional peaks were observed at 521 cm${̂-1}$ and 568 cm${̂-1}$. Fe doped ZnO ceramic and thin films showed additional peaks at 636, 681 and 1260 cm${̂-1}$. The intensity of these additional peaks was increased with the increase in the dopant concentrations. Optical absorption data showed shift in the ZnO bandgap with dopant concentrations. The sub-bandgap absorption was observed in the case of Mn doping. The temperature variation of additional Raman vibrational modes due to transition metal doping will be presented for different doping concentrations.

**3:45 PM G2.8**
**Chemical Control Over Long Range Magnetic Ordering in $Co^{2+}$:ZnO Thin Films.** Dana A. Schwartz, Chemistry, University of Washington, Seattle, Washington.

We report a method for chemically controlling the long range magnetic ordering of diluted magnetic semiconductor nanocrystals (DMS-NCs). The magnetic ordering is chemically controlled and fully reversible in films of $Co^{2+}$:ZnO nanocrystals. Spectroscopic studies reveal a decrease in the tetrahedral cobalt absorption intensity that quantitatively correlates with a decrease in the measured paramagnetic susceptibility. Magnetic circular dichroism experiments are used to identify the new magnetically ordered ground state and correlate it with the observed long range magnetic ordering.

**4:00 PM G2.9**
**Electronic structure and ferromagnetism of Mn implanted n- and p-type ZnO.** Leon Petit[1,2], Thomas C Schulthess[1,2], Axel Svane[3], Walter M Temmerman[4] and Zdzislawa Szotek[4]; [1]Computer Science and Mathematics Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee; [2]Center for Computational Sciences, Oak Ridge National Laboratory, Oak Ridge, Tennessee; [3]Institute of Physics and Astronomy, University of Aarhus, Aarhus, Denmark; [4]Computational Science and Engineering, Daresbury Laboratory, Daresbury, United Kingdom.

The prediction of room temperature magnetism in Mn doped ZnO has generated considerable interest in this compound, both from the experimental and theoretical point of views. In order to take into account the strong on-site correlations of the rather localized d-electrons, we use the self-interaction corrected (SIC)-LSD approximation. Within this scheme, the 3d electron manifold is considered to consist of both localized and itinerant states, both of which are treated on an equal footing, by adding a contribution for each d-electron to localize. By varying the relative proportions of localized and delocalized states, the most favourable (groundstate) configuration can be established. Our calculations show that the 3d electrons in Mn doped ZnO prefer to localize, regardless of whether there are codopants present or not. When Zn1-xMnxO is codoped with N atoms, hole states appear at the top of the (predominantly O-p) valence band. The d-manifold is exchange split into 5 localized up spins, and an empty down spin band situated above the Fermi level. The resulting ground state configuration clearly supports the Zener model of ferromagnetism in p-type Mn doped ZnO being driven by the exchange interaction between itinerant hole carriers, and localized spins, rather than the double exchange picture of itinerant ferromagnetism. Our calculation for Zn1-xMnxO codoped with respectively Ga and Sn atoms (n-type ZnOMn), result in a DOS where 5 d-electrons are localized, and an impurity band crossing the Fermi level appears just below the Zn1-xMnxO conduction band. Work supported by the Defense Advanced Research Project Agency and by the Division of Materials Science and Engineering, US Department of Energy, under Contract No. DE-AC05-00OR22725 with UT-Battelle LLC.

**4:15 PM G2.10**
**Colloidal Cobalt-Doped $TiO_2$ Nanocrystals: Nanoscale Diluted Magnetic Semiconductor Building Blocks for High-$T_C$ Ferromagnetic Materials.** J. Daniel Bryan[1] and Daniel R. Gamelin[1]; [1]Chemistry, University of Washington, Seattle, Washington; [2]Department of Chemistry, University of Washington, Seattle, Washington.

Colloidal cobalt-doped $TiO_2$ nanocrystals were prepared using an wet-chemical inverted micelle synthesis as an alternative to conventional vacuum deposition techniques. These doped nanocrystals were found to be paramagnetic when isolated by surface-passivating ligands, weakly ferromagnetic ($M_s$ 0.002 $\mu_B$/Cobalt) when aggregated, and strongly ferromagnetic ($M_s$ 0.3$\mu_B$/Cobalt) when spin-coated into films under aerobic conditions that preclude the formation of metallic cobalt. Cobalt K-edge X-ray absorption spectra suggest that cobalt is in the $Co^{2+}$ oxidation state. These results provide experimental support for the existence of an intrinsic mechanism for ferromagnetic ordering in cobalt-doped $TiO_2$ rather than ferromagnetism originating from an impurity phase such as cobalt metal. This study also raises the possibility of using colloidal diluted magnetic semiconductor nanocrystals as building blocks for new ferromagnetic semiconductor nanostructures.

**4:30 PM G2.11**
**Raman Spectroscopy of Highly Aligned and Spin Polarized Thin Films of $Sr_2FeMoO_6$.** Lesley F Cohen[1], Tong Zhang[1], William R Branford[1] and H J Trodahl[2]; [1]Physics, Imperial College London, London, United Kingdom; [2]School of Chemical and Physical Sciences, Victoria University of Wellington, Wellington, New Zealand.

Thin films with a high spin polarization at room temperature are extremely desirable for semiconductor spintronic devices. As one of the most promising candidates, half-metallic ferromagnetic oxide double-perovskite, $Sr_2FeMoO_6$ (SFMO), finds itself useful for new magnetic sensors, due to its Curie temperature of 410 - 450 K (well above room temperature) and a highly spin-polarized conduction band. Raman spectroscopy is capable of studying the vibrational modes in crystalline materials, as well as the stoichiometry and the orientational and compositional homogeneity of the thin films. However, the Raman spectrum of SFMO is relatively poorly characterized, and we report here a study of the modes in thin films. Highly aligned, undoped SFMO thin films were fabricated by a non-vacuum chemical deposition technique on $LaTiO_3$ substrates [1]. Raman spectra have been collected with a Renishaw Raman microscope, using a He-Ne laser with a wavelength of 633 nm as the excitation source. In order to avoid thermo excitation due to high power of the laser, power density of the incoming light at the sample surface was maintained at $10^4$ W/cm$^2$. Raman peaks of SFMO crystalline films are assigned to various mode symmetries by an analysis as a function of polarization and crystal orientation. One mode shows clear evidence of an asymmetric line shape, and is discussed in the terms of an interaction between phonons and electronic excitations. In addition, SFMO thin films doped with Ca and Ba (10%) are also investigated, a study that is motivated by their influence on Curie temperature and magnetoresistance.
Acknowledgements: This work is supported by UK-EPSRC grant GR/R42402 and GR/S14061.
[1] W.R. Branford, S.K. Clowes, Y.V. Bugoslavsky, Y. Miyoshi, L.F. Cohen, A.V. Berenov, J.L. Macmanus-Driscoll, J. Rager, S.B. Roy, J. Appl. Phys. 94, 4714 (2003).

SESSION G3:Spin Injection
Wednesday Morning, April 14, 2004
Room 2005 (Moscone West)

**8:30 AM *G3.1**
**Ferromagnet / semiconductor heterostructures - From electrical spin injection to new magnetologic concepts.** Klaus H. Ploog, Paul Drude Institute, Berlin, Germany.

The first successful experiments on electrical spin injection from epitaxial ferromagnetic (Ga,Mn)As and Fe layers into GaAs-based spin LED's [1,2] have fueled the search for more efficient spin injectors based on either semiconducting, metallic or half-metallic thin films. Up to now, neither the optimum spin injector materials has been found, nor the spin transport of electrons (holes) across the interface is well understood. In this talk it will be shown that in addition to the established but not fully understood spin injection studies, the unique epitaxial constraints in some ferromagnet/semiconductor heterostructures, such as MnAs/GaAs(001), offer new functionalities for advanced magnetic switching devices [3]. The MnAs-on-GaAs(001) films exhibit a small out-of-plane magnetization component. As a result, the magnetization of MnAs films can be reserved not only by an in-plane magnetic field but also by a small out-of-plane field. This unusual magnetization reversal by two independent input lines opens up a new field of application for MnAs films. By proper choice of in-plane and out-of-plane magnetic fields, the basic logic functionalities AND and OR can be realized and hence magnetism-based logic operations can be performed. We have now extended this concept to a universal, non-volatile spin-logic gate [4] which is based on a single magnetoresistive element with three input lines and one output line. [1] Y. Ohno et al. , Nature 402 (1999) 790 [2] H. J. Zhu et al. , Phys.Rev. Lett. 87 (2001) 016601 [3] C. Pampuch et al. , Phys.Rev. Lett. 91 (2003) 147203 [4] A. Ney et al. , Nature 425 (2003) 485

**9:00 AM *G3.2**
**Ballistic Spin Injection from Fe into ZnSe and GaAs.**
Peter H. Dederichs, Olaf Wunnicke and Phivos Mavropoulos; Institut fuer Festkoerperforschung, Juelich, Germany.

Based on ab-initio calculations we investigate the spin injection from Fe into ZnSe and GaAs in the ballistic limit. Our results show that for the (001) oriented interface a very high spin polarization of up to 99 percent can be achieved, while for the other investigated interfaces, (110) and (111), much smaller polarizations are obtained. The high polarization for the (001) orientation results from a symmetry mismatch between the minority Fe states and the semiconductor bands and only occurs for a perfect interface. The calculations of the ground state properties are based on density functional theory and use the screened KKR Green's function method. The conductance is calculated by the Landauer formula in a Green's function formalism. Three models are used to describe the spin injection: (i) the injection of hot electrons directly into the conduction band of the semiconductor, and the injection of thermal electrons by lowering the conduction band, (ii) without and (iii) with inserting a smooth tunneling barrier at the interface. The obtained spin polarizations, including the very high spin injection efficiency for the (001) orientation, result from the different symmetries of the Fe bands for the majority and minority electrons. For the (001) orientation, the majority band at the Fermi energy is of sp-like origin and can couple well to the conduction band of the semiconductor, but the minority bands are either not allowed to couple at all, due to symmetry reasons, or couple only very weakly. For the (111) and (110) orientations, bands with the same symmetry as the semiconductor states exist for both spin directions, resulting in a low spin polarization. In the case of a tunneling barrier, new effects can arise for the (001) orientation due to the existence of resonant interface states in the minority band. For the investigated cases they only slightly reduce the polarization, but in principle the effect could be dramatic if the resonance coincides with the Fermi level. In addition we shortly discuss the role of defects, of a finite bias voltage and of quantum well resonances in an Fe/ZnSe/Fe(001) trilayer system.

**10:00 AM G3.3**
**Dynamic Kerr Effects and Evidence for Photo-induced Magnetization in (LaCa)$MnO_3$.** S.A. McGill[1], R.I. Miller[1], O.N. Torrens[1], A. Mamchik[2], I-Wei Chen[2] and J.M. Kikkawa[1]; [1]Department of Physics  Astronomy, University of Pennsylvania, Philadelphia, PA; [2] Department of Materials Science  Engineering, University of Pennsylvania, Philadelphia, PA.

We study the magnetic dynamics of the colossally magnetoresistive manganite, (LaCa)$MnO_3$, using simultaneous pump-probe Kerr and reflectivity spectroscopy. Kerr rotation at 1.55 eV is sensitive to the ferromagnetic transition, and measurements of transient rotation around Tc contain two components with distinct rise times and opposite sign. One component is discussed in terms of pump-induced demagnetization previously inferred through transient reflectivity, while the novel, second component is discussed in the context of phase-separation and photo-nucleated magnetism. This work supported by DARPA through ONR N00015-01-1-0831, NSF through DMR-0094156, -0079909, and 0303458, the Sloan Foundation, and the Research Corporation.

**10:15 AM *G3.4**
**Dynamic Nuclear Polarization by Electrical Spin Injection.** J. Strand[1], B.D. Schultz[2], A.F. Isakovic[1], X. Lou[1], C.J. Palmstrom[2] and Paul A. Crowell[1]; [1]School of Physics and Astronomy, University of Minnesota, Minneapolis, Minnesota; [2]Department of Chemical Engineering and Materials Science, University of Minnesota, Minneapolis, Minnesota.

Spin injection from ferromagnetic metals into semiconductor quantum wells has been achieved recently by several groups using Schottky barriers as tunneling injectors. We demonstrate that the resulting spin-polarized current can be used as a "pump" for nuclear spins in $Al_xGa_{1-x}As$/GaAs quantum wells in low ($<$ 500 Oe) $in-plane$ magnetic fields. The nuclear spins are used in turn to control electron spin dynamics in the heterostructure. The magnitude of the nuclear polarization (up to  9 kG) is determined by the spin-polarized current density flowing into the semiconductor. The effective field inducing precession of the electronic spins is dominated by the hyperfine field of the nuclei, for which direct evidence is found in resonant depolarization measurements. The nuclear polarization can be partially suppressed by modulating the injection current at the NMR frequency. Many properties of the coupled electron-nuclear spin system can be fit by a simple dynamical model accounting for the magnetocrystalline anisotropy of the Fe film as well as spin relaxation and carrier recombination in the semiconductor. [1] J. Strand *etal.*, Phys. Rev. Lett. **91**, 036602 (2003); Appl. Phys. Lett. **83**, 3335 (2003).

**10:45 AM G3.5**
**Dynamical nuclear polarization in bulk GaAs due to electrical spin injection from a MnSb tunnel Schottky contact.** pol van dorpe[1,2], Wim Van Roy[1], Vasyl Motsnyi[1], Gustaaf Borghs[1] and Jo De Boeck[1]; [1]MCP-MN, Imec, leuven, Belgium; [2]ESAT, K.U.Leuven, Leuven.

It is known that spin-polarized electrons in the conduction band of GaAs create a polarization of the nuclear spins in the GaAs-lattice through cooling of the nuclear spin system by the hyperfine interaction [1]. The magnitude of this polarization depends on the localization of the electron wave function and the amount of electrons that are involved. In early experiments, a large nuclear spin polarization due to optical pumping has only been detected in compensated samples, where effective electron localization on donor sites takes place. Recently dynamical nuclear polarization has been demonstrated in GaAs quantum wells due to electrical spin injection from a Fe contact [2] and in a compensated GaAs bulk region by spin injection from a CoFe/AlOx tunnel injector [3]. In this study we have fabricated MnSb-based spin-LED's, where MnSb(1-101) has been grown epitaxially on an AlGaAs/GaAs(001) LED. The spin-polarized electrons enter the semiconductor by tunneling through the tailored Schottky barrier at the MnSb/AlGaAs interface and are analyzed using the oblique Hanle effect technique [4]. The MnSb film has a strong in-plane uni-axial anisotropy. The easy axis hysteresis loop is square with a large coercive field ( 700 Oe), which allows us to control the sign and amplitude of the oblique magnetic field without modifying the magnetic state of the injector. Although the active region is undoped, we see a drastic narrowing of the Hanle curves compared with the AlOx-based spin-LED's with an identical active region, which becomes more pronounced at higher biases. This is caused by the higher electron injection rate, as evidenced by the increased electroluminescence intensity. We were able to observe transient effects in the degree of circular polarization in several measurement configurations. In a first configuration we sweep the field from 600 Oe to 900 Oe (in-plane component) which results in a reversal of the MnSb-injector. The direction of the nuclear spin follows slowly, which results in a slowly varying effective magnetic field in the Hanle experiment, with a time scale up to 60 seconds. In a second configuration we sweep the magnetic field through zero while we leave the magnetic state of the injector unchanged. Here transient effects that can be correlated with the coupled electronic-nuclear system are also observed with a similar time scale. In a third configuration, we switched off the injection current during increasing time intervals and studied at the decay of the nuclear spin polarization during these "off-states". We found a decay time in the order of 5 to 10 minutes. Acknowledgements: SPINOSA (IST-2001-33334),FWO(W.V.R) ,IWT(P.V.D.) [1] Optical Orientation, edited by F. Meier and B.P Zakharchenya (North-Holland, Amsterdam, 1984) [2] J. Strand et al, Phys. Rev. Lett. 91, 036602 (2003) [3] V.F. Motsnyi et al, presented at SpintechII, Brugge (2003) [4] V.F. Motsnyi et al, Appl. Phys. Lett. 81, 265 (2002)

**11:00 AM G3.6**
**Strong bias dependence of electron spin injection from (Ga,Mn)As into GaAs.** pol van dorpe[1,2], Zhiyu Liu[1], Wim Van Roy[1], Vasyl Motsnyi[1], Gustaaf Borghs[1] and De Boeck Jo[1]; [1]MCP-MN, Imec, Leuven, Belgium; [2]ESAT, K.U.Leuven, Leuven, Belgium.

Currently there is great interest for electrical spin injection in semiconductors as an important step to the realization of spintronic devices. Epitaxial combinations of ferromagnetic and non-magnetic semiconductors offer high quality systems with high opportunities for spin injection. The ferromagnetic semiconductors that are nowadays intensively investigated are III-V semiconductors that are heavily doped with Mn, such as (Ga,Mn)As. Their Curie temperature (TC) is still low compared to most ferromagnetic metals but in recent developments this critical temperature has been pushed to 160 K by low temperature annealing of thin (Ga,Mn)As top layers[1,2]. The intrinsic p-type character of (Ga,Mn)As is a disadvantage for spin injection due to the low hole spin lifetime in GaAs. Recent experiments have shown that interband (Zener) tunneling from valence band electrons of (Ga,Mn)As to the conduction band of GaAs is a way to circumvent this disadvantage[3,4]. In both experiments the spin polarization was measured through the circular polarization of the light emitted from an InGaAs quantum well and injected spin polarizations of respectively 6.5% and 1% at 6 K and 5 K were found. We have investigated electron spin injection from a thin, annealed (Ga,Mn)As layer into an (Al,Ga)As-based spin-LED using the Oblique Hanle Effect-technique[5]. At 4.6 K the injected spin polarization reached 80%. The spin signal decreased with temperature and vanished at 120 K, the TC of the (Ga,Mn)As thin film. The injected polarization is very sensitive to the applied bias and disappears completely at about 0.6V above the electroluminescence threshold. To understand this behaviour, we have performed self-consistent simulations of the biased spin-LED. The simulated current-voltage characteristics show a reasonable correspondence with the measured IV-curve. From these simulations and tunneling experiments in literature [6], it follows that the electrons tunnel from a very thin ( 2nm) region at the interface between (Ga,Mn)As and GaAs. The high electric field in the p++n+ diode results in an interfacial depletion of (Ga,Mn)As. At higher bias, electrons tunnel mainly from the depleted region. Since the magnetization of (Ga,Mn)As is carrier-mediated, depletion at the interface can lead to a suppression of the interfacial exchange splitting in the valence band, which we directly probe with the spin-injection experiment. Acknowledgements: FENIKS(GR5D-CT-2001-00535), IWT (PVD), FWO(WVR) [1] K. W. Edmonds et al, Appl. Phys. Lett. 81, 4991 (2002) [2] D. Chiba et al, Appl. Phys. Lett. 82, 3020 (2003) [3] M. Kohda et al, Jpn. J. Appl. Phys. 40, L1274 (2001) [4] E. Johnston-Halperin et al, Phys. Rev. B 65, 041306 (2002) [5] V.F.Motsnyi et al, Appl. Phys. Lett. 81, 265 (2002). [6] R. Meservey and P.M. Tedrow, Physics Reports 238(4), 173-243 (1994)

**11:15 AM G3.7**
**Growth of Wide Bandgap Materials for Spin Injection from Spin Polarized Heuslers into Narrow Gap Semiconductors.**
Lesley Cohen[1], Tong Zhang[1], Steve K Clowes[1], Will R Branford[1], Yury Bugoslavsky[1] and Wim van Roy[2]; [1]Physics, Imperial College London, London, United Kingdom; [2]IMEC, Leuven, Belgium.

Spin LED structures using $AlO_x$ tunnel barriers [1] or narrow Schottky barriers [2] have to date proven to be a highly successful way for electrical spin injection from ferromagnetic metals into AlGaAs/GaAs structures. To date much less effort has taken place developing narrow gap semiconductors (NGS) such as InAs and InSb for spintronic application although they offer significant advantage in some respects over the GaAs system in terms of high electrical mobility and spin orbit coupling. Here we review the characteristics of typical wide band gap materials such as $In_{1-x}Al_xSb$, AlSb, $Al_{1-x}Ga_xSb$ as Schottky/tunnel contacts between MBE grown NiMnSb and narrow gap materials such as InAs and InSb and discuss their potential as spintronic materials for NGS technology. Acknowledgements: This work is supported by the UK- EPSRC grant GR/R42402 and the EU contract FENIKS: G5RD 2001 00535. [1] P. Van Dorpe, V. F. Motsnyi, M. Nijboer, E. Goovaerts, V. I. Safarov, J. Das, W. Van Roy, G. Borghs and J. De Boeck, Jpn. J. Appl. Phys. 42, L502 (2003). [2] A. T. Hanbicki, O. M. J. van 't Erve, R. Magno, G. Kioseoglou, C. H. Li, B. T. Jonker, G. Itskos, R. Mallory, M. Yasar and A. Petrou, Appl. Phys. Lett. 82, 4092 (2003).

**11:30 AM G3.8**
**Theory of Spin Injection into Conjugated Organic Semiconductors.** P.Paul Ruden[1] and Darryl L. Smith[2]; [1]University of Minnesota, Minneapolis, Minnesota; [2]Los Alamos National Laboratory, Los Alamos, New Mexico.

Conjugated organic semiconductors are promising candidate materials for spintronics because long spin relaxation times are expected for the relevant conduction and valence bands that originate from carbon $\pi$ and $\pi^*$ orbitals. We present a theoretical model to describe electrical spin injection from a magnetic contact into a conjugated organic semiconductor and contrast this case with that of spin injection into inorganic semiconductors. In thermal equilibrium the magnetic contact is spin polarized whereas the organic semiconductor is unpolarized. To achieve significant spin current and spin density, the organic semiconductor must be driven far out of local thermal equilibrium by an electric current. If the injecting contact has metallic conductivity, its electron distribution cannot be driven far from equilibrium by practical current densities. Thus, to achieve effective spin injection, equilibration between the conjugated organic semiconductor and the metallic contact must be suppressed. This requires an energy barrier to injection that may be due either to a large Schottky barrier or to an insulating tunnel barrier. Schottky injection barrier formation on conjugated organic semiconductors differs from that on inorganic semiconductors inasmuch as contacts made to organic semiconductors often follow near-ideal Schottky behavior, thus permitting the energy barrier to charge carrier injection to be varied over a wide range by using metals with different workfunctions. Insulating tunnel barriers to organic semiconductors based on organic molecules can be conveniently fabricated using self-assembly techniques. We describe structure design strategies to obtain efficient spin injection into conjugated organic semiconductors and compare these approaches with corresponding design strategies for spin injection into inorganic semiconductors. Methods of detecting the injected spin current and spin density in the organic semiconductor will also be addressed.

SESSION G4:Rashba Effect and Spintronic Devices
Chair: Thomas Schaepers
Wednesday Afternoon, April 14, 2004
Room 2005 (Moscone West)

**1:30 PM *G4.1**
**Sprintronics with Holes in Semiconductor Nanostructures*.**
Ulrich Zuelicke, Institute of Fundamental Sciences, Massey University, Palmerston North, New Zealand.

Strong efforts are being undertaken at present, aimed at designing components for a possible future spin-based electronics. A lot of attention is being focussed on the utilization of the intrinsic quantum-mechanical coupling between charge carriers' spin and orbital degrees of freedom. The possibility to achieve voltage control of such a spin-orbit coupling using the Rashba effect motivated a seminal proposal [1] for a spin-controlled field-effect device (spinFET). Its operational principle is based on the spin precession of conduction-band electrons after injection from ferromagnetic contacts. More recently, the interplay between Rashba spin-orbit coupling and quantum confinement in nanostructures has been explored, revealing novel and sometimes counterintuitive effects. For example, it was shown to be possible to create spin-polarized currents in nanowires without magnetic fields or ferromagnetic contacts [2]. Compared to electrons in the conduction band, hole carriers in semiconductors are usually subject to a much stronger spin-orbit coupling due to the predominantly p-type character of valence-band states. This opens up new possibilities to demonstrate, and possibly eventually manufacture, spintronic devices based on spin-orbit effects. As an example, we have developed a spin-filter design involving hole nanowires that is similar to the one discussed for electrons in Ref. [2]. It turns out that spin filtering can then be achieved for shorter wires, enabling possible demonstration of that device in GaAs heterostructures. We have furthermore explored spin precession of holes due to the Rashba effect in semiconductor heterostructures. The very different functional form of Rashba spin-orbit coupling for holes is taken into account in our realistic model of a hole-type spinFET device that involves diluted-magnetic-semiconductor contacts. We find clearly resolved conductance oscillations and provide approximate analytical expressions for their dependence on external gate voltages. [1] S. Datta and B. Das, Appl. Phys. Lett. **56**, 665 (1990). [2] M Governale, D, Boese, U. Zülicke, and C. Schroll, Phys. Rev. B **65**, 140403(R) (2002). *Work done in collaboration with M. Pala (SNS Pisa), M. Governale (SNS Pisa), and J. König (U Bochum).

**2:00 PM G4.2**
**Ballistic Spin Interferometer Using Square Loop Array.**
Yoshiaki Sekine[1], Takaaki Koga[2,1] and Junsaku Nitta[1,3]; [1]NTT Basic Research Laboratories, Atsugi, Japan; [2]PRESTO, Japan Science and Technology Agency, Kawaguchi, Japan; [3]CRESTO, Japan Science and Technology Agency, Kawaguchi, Japan.

We report an experimental realization of a spin interference device using the electric field control of the Rashba spin-orbit interaction which is caused by the structural inversion asymmetry in a quantum well. We found a good agreement on the Rashba spin-orbit parameter $\alpha$ among (1) experimental $\alpha$ values obtained from the spin interference, (2) those obtained from the weak antilocalization analyses, and (3) theoretical $\alpha$ values obtained from the $\mathbf{k}\cdot$ calculation. Recent success of the electric field control of the spin-orbit interaction has stimulated us to demonstrate the spin interference device.[1] We fabricated a ballistic spin interferometer using the EB lithography on an epitaxially grown $In_{0.53}Ga_{0.47}As$ quantum well. Each spin interferometer was etched to form a square-loop-shaped mesa whose side length $L$ is varied between 1.2 and 2.8 $\mu$m, and many spin interferometers were arrayed. These samples have a gate electrode covering the entire square loop array, which makes it possible to control $\alpha$ by the applied gate voltage $V_g$. We investigated the AAS type oscillation of the electric conductivity $\sigma$ as a function of the magnetic field $B$.[2] The experimental results showed $\sigma$ of the square-loop-arrayed sample oscillated with a period of $B$ of $h/2eL^2$, as expected theoretically, and the amplitude of the AAS oscillation oscillated as a function of $V_g$. [1] J. Nitta, T. Akazaki, H. Takayanagi, and T. Enoki, Phys. Rev. Lett. **78**, 1355 (1997); T. Koga, J. Nitta, T. Akazaki, and H. Takayanagi, Phys. Rev. Lett. **89**, 046801 (2002). [2] B. L. Al'tshuler, A. G. Aronov, and B. Z. Spivak, JETP Lett. **33**, 94 (1981).

**2:15 PM G4.3**

**Spin-Orbit Interaction in SiGe Quantum Wells.** Hans Malissa[1], Wolfgang Jantsch[1], Zbyslaw Wilamowski[3], Michael Muehlberger[1], Friedrich Schaeffler[1], Markus Draxler[2] and Peter Bauer[2]; [1]Institute of Semiconductor and Solid State Physics, JKU Linz, Austria, Linz, Upper Austria, Austria; [2]Institute of Experimental Physics, JKU Linz, Austria, Linz, Upper Austria, Austria; [3]Institute of Physics, Polish Academy of Sciences, Warsaw, Poland, Warsaw, Poland.

We investigate the electron spin resonance (ESR) of electrons in $Si_{1-x}Ge_x$ quantum well layers surrounded by $Si_{0.75}Ge_{0.25}$ barriers. Varying the composition of the quantum well from pure Si up to $Si_{0.9}Ge_{0.1}$ changes the g-factor, its anisotropy and the ESR linewidth. This effect is shown to arise from the Bychkov-Rashba field, that originates here from one-sided modulation doping. The magnitude of this type of spin-orbit interaction depends on the alloy composition of the quantum well. We determine the Rashba coefficient independently from the anisotropy of both the g-factor and the ESR linewidth. The consistent results obtained allow a quantitative modeling of these effects which may be useful for g-factor tuning for selective spin manipulation.

**2:45 PM *G4.4**

**Spin Effects of Low-dimensional Electron Gases Studied by Far-infrared Photoconductivity Experiments.** Can-Ming Hu, Institute of Applied Physics, University of Hamburg, Hamburg, Germany.

Recently, there is an explosion of interest to investigate the photo resistance related to elementary excitations of low-dimensional electron gases in semiconductors. In this talk, I will demonstrate that spin effects of low-dimensional electron gases can be nicely studied using far-infrared photoconductivity technique. For example, the spin-orbit interaction, which was about 80 years ago discovered by the atomic spectroscopy and gave birth to the very concept of spin, has been found rather difficult to be spectrally measured for low-dimensional electron gases. We solve the problem by detecting the spin-flip excitation using the photo-conductivity technique. Detailed filling-factor dependent study shows the collective nature of this excitation, in accordance to theoretical predictions that both Kohn and Larmor theorem are broken for long-wavelength excitations that change both the Landau and spin quantum numbers. As another example, we found that the long spin-relaxation time of a two-dimensional electron gas results in a novel bolometric spin effect. By reversing the spin polarization of electrons at the Fermi-level, bolometric spin effect gives rise to a substantial photo resistance change, which has the potential to be used to probe the spin-polarization nature of low-dimensional electron gases.

**3:15 PM G4.5**

**Spin-orbit coupling and magnetic spin states in cylindrical quantum dots.** Carlos Fernando Destefani[2], Sergio E. Ulloa[1] and Gilmar Eugenio Marques[2]; [1]Department of Physics and Astronomy and Nanoscale, Ohio University, Athens, Ohio; [2]Departamento de Fisica, Universidade Federal de Sao Carlos, Sao Carlos, Sao Paulo, Brazil.

The creation and manipulation of spin populations has received a great deal of attention in recent years. Conceptual developments that have motivated these efforts include the Datta-Das proposal for a spin FET based on the Rashba spin-orbit(SO) coupling of electrons in a 2DEG and the possibility of building quantum computation devices using quantum dots, for example. Full control of spin-flip mechanisms requires the understanding of two important SO effects in zincblende materials. One is the structure inversion asymmetry (SIA) caused by the 2D confinement (the so called Rashba term). The other is caused by the bulk inversion asymmetry (BIA) (or Dresselhaus term). The lateral confinement defining a QD introduces another SIA term with important effects on its magnetic spectrum. Although the importance of SO effects may depend on material and intrinsic fields, only recently their influence on the spin populations have been studied. We want to study the confined states in narrow-gap materials such as InSb, where both SIA and BIA effects are much larger than in wide-gap materials, such as GaAs. Experiments in InSb QDs have explored the FIR response in lithographic dots as well as PL features of self-assembled dots Our main interest here is to study the importance of each type of SO term on magnetic spectra of cylindrical narrow-gap QDs. Both the Rashba-SIA diagonal and non-diagonal, as well all the Dresselhaus-BIA terms are included in our study of QD spectra as function of magnetic field, dot sizes, g-factor, as well as the electron-electron interaction.

**3:30 PM G4.6**

**Electrical Properties of Thin InSb Films Grown by Molecular Beam Epitaxy.** Lesley Cohen, Tong Zhang, Anthony Bennett, William R Branford and Steve K Clowes; Physics, Imperial College London, London, United Kingdom.

Extraordinary magnetoresistance (MR) [1] found with semiconductor-metal composition has made possible the fabrication of entirely new types of macroscopic and mesoscopic sensors. To produce these devices it is desirable to have a material that has a high room temperature mobility $\mu$, as this effect at low magnetic field is proportional to $(\mu B)^2$ and a thin preferably surface active region (to increase the proximity to the magnetic bit). High mobility, thin InSb epilayers offer a possible route to satisfy these requirements. In addition this material system is interesting for spintronic applications. Recent measurement [2] of spin lifetime in n-type degenerate epilayers of InSb are encouraging, suggesting room temperature spin lifetime of the order of 300 ps. For hybrid spintronic devices, where carriers will be injected from a highly spin polarized magnetic material, there are significant device advantages if the semiconductor epilayer is thin and has high mobility (particularly if Elliott-Yafet [3] is the dominant spin relaxation mechanism). In the interest of both MR sensors and spintronic applications we have investigated the electrical and structural properties of undoped and Si doped epilayers on GaAs(100) substrates by molecular-beam epitaxy. Significant progress of electrical properties has been achieved over recent reports [4], albeit three-dimensional island growth was not suppressed. The average mobility of undoped InSb film is of 100 nm 7,000 $cm^2/Vs$ and in silicon doped InSb we have achieved a room temperature Hall mobility of 14,000 $cm^2/Vs$ in a 100 nm surface layer. The underlying mechanisms are explained by a differential two-layer model and the details, which support our observations, will be discussed in this presentation. Acknowledgements: This work is supported by the UK-EPSRC grant GR/R42402 and the EU contract FENIKS: G5RD 2001 00535. We thank QinetiQ for access to processing facilities and Toshiba Research Europe Ltd for access to magneto-transport facilities. [1] S.A. Solin, D.R. Hines, A.C.H. Rowe, J.S. Tsai, Y.A. Pashkin, S.J. Chung, N. Goel, M.B. Santos, Appl. Phys. Lett. 80, 4102 (2002). [2] P. Murzyn, C.R. Pidgeon, P.J. Phillips, J.P. Wells, N.T. Gordon, T. Ashley, J.H. Jefferson, T.M. Burke, J. Giess, M. Merrick and B.N. Murdin, C.D. Maxey, Phys. Rev. B 67, 235202 (2003). [3] R J Elliott, Phys. Rev. 96, 266 (1954); Y Yafet, 'Solid State Physics' 14 (ed. F Seitz and D Turnbull, Ac. Press, NY, 1963). [4] K. Kanisawa, H. Yamaguchi, Y. Kirayama, Appl. Phys. Lett. 76 589 (2000).

**3:45 PM G4.7**

**Nonvolatile memory and reconfigurable logic applications of spin MOSFETs.** Satoshi Sugahara[1,2], Tomohiro Matsuno[1] and Masaaki Tanaka[1,2]; [1]Dept. of Electronic engineering, The university of Tokyo, Tokyo, Japan; [2]PRESTO, JST, Kawaguchi, Japan.

Recently, novel integrated circuits based on spintronic concepts attract much interest for nonvolatile memory and reconfigurable logic devices. A spin MOSFET [1] is expected to be suitable for such spintronic integrated circuits as the building block for memory cell and logic gates, since they not only perform digital operation but also store digital data. In this paper, we propose and numerically simulate a novel nonvolatile memory cell and reconfigurable logic gates configured by the spin MOSFET. A spin MOSFET consists of a MOS gate structure and ferromagnetic contacts for the source and drain, which possesses good compatibility with the well-established Si-MOSFET technology. Its high performance can be obtained by using a half-metallic ferromagnet (HMF) as source/drain contacts. When the magnetization configuration of the HMF source/drain is parallel (antiparallel), highly spin-polarized carriers injected from the HMF source to the channel are transported into (blocked by) the HMF drain. As a result, the output current (or transconductance) depends on the magnetization configuration of the HMF source/drain. A single spin MOSFET itself acts as a nonvolatile memory cell, leading to an ultimately small cell size and thus an extremely high degree of device integration. By flipping the magnetization of the half-metallic source or drain, binary data can be stored, and this binary data can be sensed by the magnetization-configuration-dependent output characteristics. Fast readout operation with excellent fault tolerance can be realized by the large magnetocurrent ratio and high transconductance of the spin MOSFET. Reconfigurable logic gates can be realized by combining the spin MOSFET with multiple-input neuron MOS technology [2]. We show that by using the spin MOSFET as a driver or an active load, E/E, E/D and CMOS inverters with a two-input neuron MOS structure act as a reconfigurable NAND/NOR gate, whose logic functions are switched by flipping the magnetization of the spin MOSFET. The number of reconfigurable logic functions can be increased by adding the small number of spin MOSFETs and conventional MOSFETs to this NAND/NOR gate. Reconfigurable symmetric Boolean functions (AND, OR, XOR, NAND, NOR, XNOR, "0" and "1") for two-input variables can be realized by only ten transistors including four spin MOSFETs. The operation of these reconfigurable logic gates was confirmed by HSPICE simulations using a simple device model for the spin MOSFET. [1] S. Sugahara and M. Tanaka, submitted to Appl. Phys. Lett. and cond-mat/0310623. [2] T.

Shibata and T. Ohmi, IEEE Trans. Electron Dev. ED-40 (1993) 750

**4:00 PM G4.8**
**Theory of Electrically Controlled Resonant Tunneling Spin Devices.** David Ting[1] and Xavier Cartoixa[2]; [1]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California; [2]Department of Physics, University of Illinois at Urbana-Champaign, Urbana,, Illinois.

We report device concepts that exploit spin-orbit coupling for creating spin polarized current sources using nonmagnetic semiconductor resonant tunneling heterostructures, without external magnetic fields. The current spin polarization of these devices is electrically controllable, and potentially amenable to high-speed spin modulation. The concepts originated with the resonant tunneling spin filter proposed by Voskoboynikov et al. [1]. It consists of an asymmetric resonant tunneling diode (aRTD) where quantized states are spin-split by the Rashba effect [2], and achieves spin filtering by exploiting the phenomenon that the spin of a resonantly transmitted electron aligns with that of the quasibound state traversed [1,3]. Attaining significant spin filtering using this approach is challenging because of the intrinsic properties of the spin-split quantum well states: the $\mathbf{k}_{||}$-dependent spin splitting is typically small and vanishes at the zone center, and states with opposite $\mathbf{k}_{||}$ within a given spin-split subband have opposite spins so that there is no net spin when averaged over the subband. We have developed strategies for overcoming these challenges, and proposed a number of new concepts for designing heterostructure based spin devices. The resonant interband tunneling spin filter [4] exploits large valence band spin-orbit interaction to provide strong spin selectivity, without suffering from fast hole spin relaxation. Spin filtering efficiency is also enhanced by the reduction of tunneling through quasibound states near the zone center. The asymmetric resonant tunneling diode (aRITD) improves spin-filtering efficiency significantly ($> 60\%$ current spin polarization) over the aRTD. The bi-directional spin pump [5] is designed specifically to take advantage of the special spin configuration described by the Rashba effect in asymmetric quantum wells. It induces the simultaneous flow of oppositely spin-polarized current components in opposite directions through spin-dependent resonant tunneling, and can thus generate significant levels of spin current with very little net electrical current across the tunnel structure, a condition characterized by a greater-than-unity current spin polarization. Finally, we show that the efficiency of resonant tunneling spin devices can be improved when the effects of structural inversion asymmetry (SIA) and bulk inversion asymmetry (BIA) are combined properly, and incorporated into devices design. [1] A. Voskoboynikov, S. S. Lin, C. P. Lee, and O. Tretyak, J. Appl. Phys. 87, 387 (2000). [2] Y. A. Bychkov and E. I. Rashba, J. Phys. C - Solid State Phys. 17, 6039 (1984). [3] E. A. de Andrada e Silva and G. C. La Rocca, Phys. Rev. B, 59, 15583 (1999). [4] D. Z-Y. Ting and X. Cartoixà, Appl. Phys. Lett. 81, 4198 (2002). [5] D. Z-Y. Ting and X. Cartoixà, Appl. Phys. Lett. 83, 1391 (2003).

**4:15 PM G4.9**
**Four Terminal Carbon Nanotube Sensor for Magnetic Field Measurements.** Buzz Wincheski[1], Min Namkung[1], Phillip Williams[2] and Jan Smits[3]; [1]NASA LaRC, Hampton, Virginia; [2]National Research Council, Hampton, Virginia; [3]Lockheed Martin Engineering and Sciences Corporation, Hampton, Virginia.

Previous theoretical and experimental work has shown the existence of spin coherent transport through carbon nanotubes. Magnetic field measurements based upon this phenomenon are enabled by contacting nanotubes with ferromagnetic electrodes. In a two terminal device, spin polarized electrons are injected into the nanotube through contact with a ferromagnetic electrode and out of the tube through contact with a second ferromagnet. It has been shown that the transmission probability through the tube is then dependent upon the relative alignment of the magnetic field direction of the two electrodes. Unfortunately, contact resistance effects can mask those of the spin coherent transport. In this work, contact resistance effects are minimized through a four terminal approach. Using this method, standard metallic electrodes are used to align and trap single wall carbon nanotubes in specific areas of the device substrate through AC-dielectrophoresis. A second lithography layer is then used to deposit ferromagnetic contacts between the first set of electrodes and across the aligned tubes. Electrons transmitted through the carbon nanotube become spin polarized as they pass under the first ferromagnetic electrode. Electron scattering is then minimized if the moment of the now polarized electrons matches that of the second ferromagnetic electrode. Experimental measurements performed by applying a constant current across the outer electrodes while monitoring the voltage drop between the two ferromagnetic contacts show magnetoresistive effects similar to current-in-plane giant magnetoresistive (GMR) sensors. Theoretical and experimental results on the performance of the four terminal carbon nanotube magnetic field sensors are presented and compared with two terminal devices.

**4:30 PM G4.10**
**Spin and Charge Transport in Molecular Wires.**
Vladimir Burtman, Di Wu, Alexandre Sosso Ndobe, Xiaomei Jiang, Jing Shi and Valy Zeev Vardeney; Physics Dept., Univ. of Utah, SLC, Utah.

We report magneto-resistance studies of self-assembled monolayers (SAM) composed of solid solution mixtures of conductive molecular wires (1,4 benzenedimethanehiol, BDT) and dielectric spacers (1-pentanethiol, PT). The SAMs were chemisorbed on a pre-deposited ferromagnetic cobalt electrode film and capped with a top cobalt thin film that was evaporated in a vertically crossed configuration respect to the bottom electrode. The device area was about 1 $mm^2$ and multiple devices were simultaneously fabricated on the same chip We found that the molecular junction resistance of the fabricated spin-valve devices could be tuned in the range between 0.1 kOhm to 100 GOhm by controlling the wires-to-spacer ratio, r. The coercive fields, Hc of the two cobalt electrodes are different and are of order 100 Gauss. For $r < 10^{-4}$, the molecular wires are separated from each other and the device conductance, $\sigma$ obeys the additive superposition rule, where the single molecular conductance adds in parallel, namely $\sigma$  N $\times\sigma_0$, where sigma$\sigma_0$ is the single molecule conductivity and N is the number of single molecules captured in a device. I-V characteristic is highly nonlinear with resistance of the order of 10 Gohm in this r regime. The differential conductance vs. V showed saturation at about 1 volt, in agreement with previous measurements of single molecule transport in BDT. We also found that the magneto-resistance is negligiby small in this r regime and no spin-valve effect could be measured. The null result for BDT single molecule spin-valve contradicts recent measurements of Schoön et al. using nickel electrodes and similar molecules. At $r > 10^{-2}$ molecular 2D aggregates are formed within the SAM, which give rise to an new additional broad absorption band that is red-shifted respect to the single molecule absorption band. The aggregation process shifts the molecular configuration, and the intrinsic properties of the molecular wires change from that characteristic of isolated molecules to those characteristics of a 2D macromolecular structure with additional in-plane ordering in the direction of molecular stacks. This enables in-plane charge delocalization among the aromatic $\pi$-electrons and the formation of a new pair of HOMO-LUMO levels that are closer to the Fermi energy of the Co electrodes. In this r regime we found that the conductivity dependence on r becomes strongly non-linear, and the device resistance goes down dramatically to reach  100 ohm at r  1. In addition we also measured a spin-valve magnetoresistance hysteresis with $\Delta R/R$  1% at LN2 temperature. These findings indicate the formation of an effective redox self-exchange within the in-plane macromolecular aggregates, where the charge delocalization within the aggregate controls both the electrical conductivity and the spin transfer process between the two cobalt counter electrodes.

**4:45 PM *G4.11**
**Non-Linear Theory of Critical Currents for Magnetization Reversal by Spin Transfer.** Thierry R Valet, Yiming Huai, Paul Nguyen and Mahendra Pakala; Grandis Inc., Milpitas, California.

The magnetization dynamics in pillar shaped (pinned F)/N/(free F) trilayers at low temperature, in presence of spin transfer torque and applied field, is systematically studied within the framework of non-linear bifurcation theory. It is demonstrated that previously derived[1-4] critical current expressions for the onset of linear instability of the parallel (P) or antiparallel (AP) magnetic configurations, so far interpreted as switching currents in the so-called low field regime, does not in fact correspond to critical current values for irreversible magnetization reversal. They can be instead always associated to a reversible bifurcation to a limit cycle (precessional state), that can be identified as a generic Hopf bifurcation[5]. Experimentally observed irreversible magnetization reversals are shown to occur through an homoclinic bifurcation taking place at higher current amplitude. New analytical expressions for the true critical currents for magnetization reversal are obtained using a variational approach allowing to track the dynamics in the nonlinear region far from the P and AP states. The new expressions, together with the associated dynamic phase diagram, are shown to be in excellent agreement with numerical solutions of the generalized Landau-Lifschitz-Gilbert equation. The expected modifications of the low temperature dynamic phase diagram in presence of thermal activation are addressed, thanks to a newly formulated Fokker-Planck equation taking advantage of the weakly dissipative character of the dynamics. Using this newly established critical current theory, we show that the experimentally observed strong field dependence of the magnetization reversal critical currents, and distinct dissymmetry in the (Resistance vs current) hysteresis cycles, can now be accounted for in the context of single domain dynamics. Finally, the consequences for the design and operation of spin transfer based spintronic devices, specifically advanced MRAM, are discussed. [1]J. Slonczewski, J. Magn. Magn. Mater. **159**, 1 (1996). [2] J. A. Katine, F. J. Albert, R. A. Buhrman, E. B. Myers, and D. C. Ralph, Phys. Rev. Lett. **84**, 3149

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SESSION G5:Poster Session
Wednesday Evening, April 14, 2004
8:00 PM
Salons 8-9 (Marriott)

**G5.1**

**Growth of Ferromagnetic $Zn_{1-x}Mn_xO$ thin films on $Al_2O_3$ (0001) Substrates by Reactive RF Magnetron Sputtering.** Sejoon Lee[1], Cheonki Min[1], Hwa-Mok Kim[1], Hoon Young Cho[1], Tae Won Kang[1], Deuk Young Kim[1] and Youn Hwan Lee[2];

[1]Quantum-functional Semiconductor Research Center, Dongguk University, Seoul, South Korea; [2]Department of Information and Communication Engineering, Dongguk University, Kyungju, South Korea.

In this study, we have investigated the growth and the material properties of mirrorlike $Zn_{1-x}Mn_xO$ thin films on $Al_2O_3$ (0001) substrates by a reactive RF magnetron sputtering method. The material properties of $Zn_{1-x}Mn_xO$ thin films were characterized by scanning electron microscopy, atomic force microscopy, energy dispersive x-ray spectroscopy, x-ray diffractometry, cathodoluminescence spectroscopy, photoluminescence spectroscopy, and superconducting quantum interference device magnetometry. The $Zn_{1-x}Mn_xO$ thin films were formed by using a buffer layer grown at low temperature. From scanning electron microscopy measurements, it was observed that the surface morphology of $Zn_{1-x}Mn_xO$ thin films was improved with increasing the thickness of the buffer layer. In our experiment, the mirrorlike $Zn_{1-x}Mn_xO$ thin films were obtained when the films were grown at $450^oC$ with 40 nm thick buffer layer grown at $200^oC$. Since it was observed the lateral grain size measured from atomic force microscopy of the buffer layer was increased with increasing the buffer layer thickness, the formation mechanism of mirrorlike $Zn_{1-x}Mn_xO$ thin films can be considered by the relaxation effect of the c-axis preference resulting from increasing the lateral grain size of the buffer layer. The Mn incorporation in $Zn_{1-x}Mn_xO$ thin films is approximately 9%. The contents of Zn and Mn were determined by the fluorescence of Mn $ka$ and Zn $ka$ for the measurement of the energy dispersive x-ray spectroscopy. The films showed the x-ray diffraction peak at (0004) without any satellite peak, and it indicates the mirrorlike $Zn_{1-x}Mn_xO$ thin films have the single crystalline phase with hexagonal structure. For the same samples, an emission peak at 360 nm was observed for the cathodoluminescence measurement at room temperature. From measurements of temperature dependence photoluminescence, it was confirmed the dominant peak near 360 nm was attributed to the band edge emission. For the measurement of magnetic-field dependence magnetization, it is clearly observed that the $Zn_{0.91}Mn_{0.09}O$ thin films showed a hysteretic behavior originated from ferromagnetism. The easy axis for magnetization of mirrorlike $Zn_{0.91}Mn_{0.09}O$ thin films was perpendicular to the applied magnetic-field. It means that the mirrorlike films have the tensile strain due to the laterally well-merged growth because the columnar structured films grown with c-axis preference show the easy axis of in-plane resulting from the compressive strain. The transition temperature to paramagnetism from ferromagnetism was estimated about 120 K for the measurement of temperature dependence magnetization. These results imply that the mirrorlike $Zn_{1-x}Mn_xO$ thin films using 40 nm thick buffer layer grown by a reactive RF magnetron sputtering method show the characteristics of the ferromagnetic semiconductor with single crystalline phase, and it can experimently suggest that the $Zn_{1-x}Mn_xO$ thin films are feasible materials for spintronic devices.

**G5.2**

**Electronic Structure of the Diluted Magnetic Semiconductors $Pb_{1-x}Sn_xTe$:Yb.** Evgenii Skipetrov[1], Elena Zvereva[1], Olga Volkova[2], Alexandr Golubev[2] and Vasilii Slyn'ko[3]; [1]Faculty of Physics, Moscow State University, Moscow, Russian Federation; [2]Faculty of Material Science, Moscow State University, Moscow, Russian Federation; [3]Institute of Material Science Problems, Chernovtsy, Ukraine.

The galvanomagnetic properties (T=4.2-300 K, B<0.1 T) of the diluted magnetic semiconductors $Pb_{1-x}Sn_xTe$:Yb (x=0.14-0.20, $C_{Yb}$=0.05-3.0 mol.%) were studied to determine the parameters of the electronic structure and to elucidate its influence on the magnetic properties of the alloys. It was found that temperature dependencies of the resistivity and Hall coefficient $R_H$ have a "metallic" character, however the $R_H$ changes in anomalous manner: its value increases more than by order of magnitude and then passes through maximum with increasing the temperature. This obviously indicates the Fermi level to be pinned by the impurity level $E_{Yb}$ located in the valence band. As the tin content in the alloys decreases while the Yb content grows the hole concentration p decreases by more than order of magnitude indicating an approach of the ytterbium level with the valence band top. Experimental dependencies of the hole concentration on the alloy composition were used to calculate the Fermi level position in the frame of Kane's two-band model. It was assumed (1) the density of unoccupied states on the impurity level $p_{Yb}$ should coincide with magnetic ions concentration $N_{Yb3+}$ determined from the magnetic measurements; (2) the density of states function $g_{Yb}(E)$ may be approximated by a Gaussian-type curve with the impurity band width independent on the impurity content. In terms of this model the position of the ytterbium level $E_{Yb}$ in the alloys was calculated and the energy spectrum diagram under variation of the matrix composition and Yb content was constructed. It was shown that the magnetic properties of semiconductors studied depend strongly on the electronic structure of alloys, in particular on the mutual arrangement of the valence band top, Fermi level and ytterbium impurity level.

**G5.3**

**Magnetic Properties of GaN Layers Implanted by Mn, Cr or V.** Vitaliy A. Guzenko[1], Nicolas Thillosen[1], Andre Dahmen[1], Raffaella Calarco[1], Thomas Schaepers[1], Martina Luysberg[2] and Lothar Houben[2]; [1]Institute of Thin Films and Interfaces, Research Centre Juelich, Juelich, 52425, Germany; [2]Institute of Solid State Research, Research Centre Juelich, Juelich, 52425, Germany.

The growing interest in dilute magnetic semiconductors (DMS) for spintronics applications impelled many research groups to search for materials with Curie temperatures above room temperature. On the basis of recent theoretical predictions a promising candidate is GaN, doped by Mn up to concentrations of approximately 5 at.%. Recently, many groups reported on the successful fabrication of ferromagnetic GaN:Mn layers grown by molecular beam epitaxy. We followed a different approach by implanting 3d-transition metals into GaN films. GaN layers grown by MOVPE on sapphire substrates, undoped, p- or n-doped, were implanted by Mn, Cr or V ions with a dose of $5{\cdot}10^{16}$ $cm^{-2}$. The implantation energy was 200 keV. During implantation the substrate temperature was held at 350° C, in order to reduce amorphization. Subsequently, a rapid thermal annealing in nitrogen atmosphere for 5 minutes at 700° C was performed. The magnetic properties of our samples were investigated by using a SQUID-magnetometer. The magnetization as a function of magnetic field as well as the dependence on temperature revealed paramagnetic behaviour for all samples. Depending on delay and change of the magnetic field between two successive measurements a hysteresis in the magnetization could be observed in some cases. These results can be explained by the presence of clusters of a 3d-metal rich secondary phase, which is in good agreement with results obtained from structural investigations, such as transmission electron microscopy and Rutherford backscattering, performed on our samples.

**G5.4**

**Properties of ion-implanted transition metals into n+GaAs:Si and p+GaAs:C epilayers*.** J. D. Lim[1,2], K. S. Suh[1,2], C. U. Jang[1,2], H. K. Choi[1,2], J. H. Park[1,2], T. H. Kim[1,2], C. R. Abernathy[3], S. J. Pearton[3] and Y. D. Park[1,2]; [1]Center for Strongly Correlated Materials Research, Seoul National University, Seoul, South Korea; [2]School of Physics, Seoul National University, Seoul, -, South Korea; [3]Department of Materials Science & Engineering, University of Florida, Gainesville, Florida.

Ion-implantation of various magnetic transition metal (TM) impurities has allowed for rapid survey of various oxide and semiconductor systems for possible diluted magnetic semiconductors (DMS) exhibiting ferromagnetic ordering [1]. The technique also allows for co-doping of magnetic and non-magnetic impurities that would be difficult to realize with low temperature growth techniques and to possibly study magnetic properties dependence on itinerant carriers, such as in (Ga,Mn)(C,As) [2]. Ion-implantation technique along with annealing process utilizing a highly n- or p-type GaAs epilayer also allows for avenues to study various mono-transition metal-arsenides (such as CrAs, VAs, and MnAs), of which certain phases are predicted half-metals [3], in a metallic matrix as well as realizing nano-granular systems with significant magnetoresistances [4]. Here, we report on the magnetic and transport properties of Cr, Mn, and V ion-implanted p+GaAs:C as well as Cr and Mn ion-implanted n+GaAs:Si. As implanted, all samples show insulating like behavior possibly due to implantation damage and, excluding Mn implanted samples, show either paramagnetic or diamagnetic behavior. From Hall Effect measurements at room temperature, resulting carrier concentrations reflects relative position of TM impurity level in GaAs with Cr (a deep-level donor in GaAs) ion-implanted p+GaAs:C being fully compensated and n-type. Interestingly, Mn implanted samples (which exhibited the highest hole concentrations) with implantation dose less than 5 x $10^{16}$ $cm^{-2}$ transport properties mirror its magnetic properties with characteristic anomalies in resistivity corresponding to magnetization measurements as function of temperature, as well as extraordinary Hall Effect which is observed below its magnetic ordering temperature. Further annealing studies as well as resulting magnetotransport properties will be also presented. * This work is partly supported by Samsung Electronics Endowment and KOSEF through CSCMR, KIST Vision21 Program, and ARO-FE. [1] S.J. Pearton et al., J. Appl. Phys. **93**,1 (2003); S.J. Pearton et al., **286**, 1 (2003). [2] Van An Dinh *etal.*, Jpn. J. Appl. Phys. **42**, L888 (2003); T. Jungwirth *etal.*, arXiv:cond-mat/0306557; Y.D. Park *etal.*, Phys. Rev. B **68**, 085210 (2003). [3] M. Shirai, Physica E **10**, 143 (2001);B. Sanyal *etal.*, Phys. Rev. B **68**, 054417 (2003). [4] Akinaga *etal.*, Appl. Phys. Lett. **76**, 357 (2000).

### G5.5

**Optimization of sample holder materials for magnetic measurements using a commercial vibrating sample magnetometer system.** Ilaria Bossi, Neil Dilley and Stefano Spagna; Quantum Design, Inc., San Diego, California.

A major challenge associated with the measurement of small d.c. magnetic moments using a vibrating sample magnetometer (VSM) arises concerning the rejection of the magnetic signal from the sample holder. In general, the total measured magnetic moment ($m_T$) is the sum of the sample's moment ($m_s$), the sample holder ($m_{sh}$), and also any magnetic signals in the sample environment ($m_e$) : $m_T = m_s + m_{sh} + m_e$. To achieve a reasonable measurement accuracy for the sample requires that $m_s \gg m_{sh} + m_e$ . In this paper we characterize the magnetic behaviors of various sample holder materials as a function of both temperature and applied magnetic field using a recently developed VSM system as well as a SQUID magnetometer. The study shows that pure plastics with no fillers such as Kel-F, Delrin and Teflon generally exhibit the optimal magnetic behavior of weak diamagnetism at both 5 K and 300 K. We also observed that glass fiber-reinforced plastics exhibit strong paramagnetic behavior at low temperature due to the paramagnetic impurities present in the glass.

### G5.6

**Ferromagnetic behavior in Mn ion-implanted p+AlAs:C*.** Y. S. Kim[1], J. D. Lim[1,2], J. S. Lee[1], S. S.A. Seo[1,3], C. R. Abernathy[4], S. J. Pearton[4], T. W. Noh[1,3], Z. G. Khim[1] and Y. D. Park[1,2]; [1]School of Physics, Seoul National University, Seoul, -, South Korea; [2]CSCMR, Seoul National University, Seoul, South Korea; [3]ReCOE, Seoul National University, Seoul, South Korea; [4]Department of Materials Science & Engineering, University of Florida, Gainesville, Florida.

For the possible development of semiconductor spintronics III-As heterostructure devices, a wide-band gap diluted magnetic semiconductor (DMS) such as based on AlAs would be of great interest [1]. AlAs is also unique in that though a wide-band gap semiconductor, it can be readily p-doped as high as 1.1 x $10^{20}$ $cm^{-3}$[2] to possibly investigate the crossover between the observed magnetic properties arising from bound magnetic polarons (at low carrier concentration regime) and from iterant carriers mediating the ferromagnetic ordering. Here, we report on the magnetic and transport properties of Mn ion-implanted p+AlAs:C. Epitaxial p+AlAs:C films were grown on semi-insulating GaAs substrate by gas source molecular beam epitaxy (GSMBE). After growth, Mn ions were implanted at doses 3 and 5 x $10^{16}cm^{-2}$, which corresponds to nearly 3 and 5 at % (samples A, B, respectively) with energy of 250keV with the film held at 350°C to minimize amorphization during the process. From high resolution x-ray diffraction (HRXRD) measurements, no secondary phases were apparent. Magnetic properties were measured by SQUID magnetometer. Which measurements show clear hysteresis loops at 5 K for both samples. Non-zero remanent magnetization was observed up to 230K for sample A and 310K for sample B. The magnetic ordering temperature (Tc) of sample B is similar to that of bulk MnAs, although undetected from HRXRD measurements, the observed magnetic properties from sample B can be attributed to nanometer-sized MnAs precipitates. In contrast to sample B, sample A exhibit Tc 230K. Accordingly, sample A exhibit extraordinary Hall Effect (EHE) below 230 K. * This work is partly supported by Samsung Electronics Endowment and KOSEF through CSCMR, KIST Vision21 Program, and ARO-FE. [1] Liu *etal.*, J. Magn. Magn. Mat. **242 − 245**, 967 (2002); K. Takamura *etal.*, Appl. Phys. Lett. **81**, 2590 (2002). [2] C.R. Abernathy *etal.*, Appl. Phys. Lett. **65**, 2205 (1994).

### G5.7

**Rashba spin-orbit coupling in InGaAs/InP quantum wires.** Jens Knobbe, Vitaliy A. Guzenko and Thomas Schaepers; ISG-1, Research Centre Juelich, 52425 Juelich, Germany.

In semiconductor spintronics the electron spin is used as unit of information instead of its charge. A key issue for the realization of spintronic devices is the efficient control of the electron spin. In this respect the Rashba effect provides a viable way, since it allows to adjust the spin precession of electrons in a two-dimensional electron gas by applying a gate voltage. A prominent example of a spintronic device based on the Rashba effect is the spin transistor proposed by Datta and Das [1]. Following this approach, many novel device concepts have been developed, where some even offer solutions in the field of quantum computation. For the realization of most of these concepts a reduction of the electron transport to only one dimension is indispensable. In order to investigate Rashba spin-orbit coupling in one-dimensional systems, we fabricated InGaAs/InP quantum wire structures. The heterostructure was grown by metal-organic vapor phase epitaxy. The two-dimensional electron gas was located in a strained InGaAs channel layer. Either reactive ion etching or selective wet chemical etching was employed to define the geometry of the quantum wires. The nominal width of the wires varied between 400 nm and 1 $\mu$m. A clear beating pattern was observed for all of our wires, indicating the presence of Rashba spin-orbit coupling. However, compared to two-dimensional Hall bar structures the characteristic nodes in the Shubnikov-de Haas oscillations were shifted towards higher magnetic fields for narrow quantum wire structures. By depleting the electron gas by means of a gate electrode the Rashba coupling strength could be controlled. The dependence of the beating pattern in the magneto-resistance on the quantum wire confinement could be explained on the basis of a detailed model taking the effect of Rashba spin-orbit coupling on the one-dimensional magneto-subband energies into account. [1] S. Datta and B. Das, Appl. Phys. Lett. 56, 665 (1990).

### G5.8

**Spin MOSFETs for spintronic integrated circuits.** Satoshi Sugahara[1,2], Kok Leong Lee[1] and Masaaki Tanaka[1,2]; [1]Dept. of Electronic engineering, The university of Tokyo, Tokyo, Japan; [2]PRESTO, JST, Kawaguchi, Japan.

Spin transistors, which utilize two ferromagnetic layers as a spin injector and as a spin detector, are very attractive for nonvolatile memory and reconfigurable logic devices, owing to their unique output characteristics that are controlled by the relative magnetization configuration of the ferromagnetic layers. Especially, a MOSFET type of spin transistor (spin MOSFET) is promising, since its prospected large current-drive capability and power gain are necessary for such spintronic "integrated circuits". In this paper, we propose and theoretically analyze two types of the spin MOSFET consisting of a MOS gate structure and ferromagnetic contacts for the source/drain, where i) a ferromagnetic metal (FM) and ii) a half-metallic ferromagnet (HMF) are used as the contact material. The nanometer-scale channel length and the ballistic transport of spin-polarized carriers are assumed for the calculation. When the FM Schottky-contacts are used for the source/drain, the spin MOSEFT in the parallel magnetization configuration acts as a Schottky source/drain MOSFET [1]. The output (drain) current for small drain bias conditions (less than the pinch-off voltage) is reduced by changing the relative magnetization of the FM source/drain from the parallel to antiparallel configuration. This is caused by spin dependent transport similar to the tunneling magnetoresistance, and its magnetocurrent ratio depends on the spin polarization of the FM source/drain. On the other hand, an extremely large magnetocurrent ratio (more than 1000%) can be obtained for the spin MOSFET using the HMF source/drain. This is because the spin-dependent barrier structures at the HMF source and drain, which are formed by the metallic and insulating spin bands of the HMF material, enable the injection of fully spin-polarized carriers into the channel and the complete extraction (in the parallel configuration) and blocking (in the antiparallel configuration) of them from the channel. Furthermore, magnetizatin-configuration-dependent output characteristics of this spin MOSFET can be realized in the much wider range of the drain bias, compared with the case of the spin MOSFET using the FM source/drain. The both spin MOSFETs exhibit a high transconductance (more than 1 S/mm) in the parallel magnetization configuration, and they also satisfy other important requirements for spintronic integrated circuits, such as high amplification capability, low power-delay product, and low off-current. Thus, the spin MOSFETs can be used as a key device for high density nonvolatile memory and reconfigurable logic devices based on novel spintronic concepts. [1] R. Hattori and J. Shirafuji, Jpn. J. Appl. Phys. 33 (1994) 612.

### G5.9

**Spin-polarization transport analyzer and modeling dependent on gate-voltage in spin field effect transistor with 2DEG layer.** Gab-Yong Lee[1,2], Chang Woo Lee[2] and Yong Tae Kim[1]; [1]System engineering, Korea Institute of Science & Technology(KIST), Seoul, South Korea; [2]Nano & Electronic Physics, Kookmin University, Seoul, South Korea.

We proposed a novel approach to analyze the spin-polarization and drain-source current within two-dimensional electron gas(2DEG) along the spin orientation, channel lengths between two ferromagnetic contacts, and gate voltage. For simulation, our basic sample is composed of 2DEG between the ferromagnetic permalloy(NiFe) source (FM1:0.5mm) and drain (FM2:1.5mm), FM1-2DEG-FM2 device. The 2DEG is playing a part of the current carrying medium dependent on the gate voltage would provide a very high-mobility channel and free of spin-flip scattering events, which is an inverted modulation-doped InAlAs/InGaAs/InAlAs heterostructure. The 2DEG is formed in the undoped InGaAs layer of 20nm thickness. Underneath the quantum well, a 7nm thickness InAlAs carrier supplied layer is separated from the channel by an undoped 6nm thickness InAlAs space layer. The spin-polarized carries are injected and collected by FM1 and FM2. A strong internal electric field oriented perpendicular to this 2DEG presents in the heterostructure interface region in the inversion layer. This effective field has an effect on the process of spin carriers included an interface of the spin-orbit effect on the carriers in the channel moving parallel to the interface. This process will rotate them out of alignment with the magnetization of the second ferromagnetic pad(F2), decreasing the transmitted current of the device. In this device, the gate voltage can be controlled to increase or to decrease the electric field, altering the spin precess. This will control the alignment of the spin process with respect to the magnetization vector in FM2. Thus this device permits the modulation of the current passing through the device. The spin rotation in spin-field effect transistor(spin-FET) with a 2DEG is controlled by the gate voltage through Rashba spin-orbit coupling. This spin-polarization causes the variation of drain-source current, because this drain-source current depends on the gate-controlled spins of electrons reaching the drain magnetic moment(FM2) and the classical field effect control. In conclusion, the spin-polarizations have a deep influence on the drain-source current is modulated magnetically by the electric field perpendicular to the 2DEG, the channel length between F1 and F2, and the length and width of gate electrode pad. For this reasons, we need to develop more and more about the theoretical design method of optimal gate-channel length and width length between two pads (F1 and F2) in semiconductor composed of 2DEG. At the designed spin-FET, we make an appropriate equation and equivalent circuit to analyze the operating process of the spin-polarization according to each steps of gate voltage within the 2DEG. We can consider more and more simple design method and the easier physical process of spin carriers dependent on the spin-polarization in a high-mobility transistor structured with 2DEG channel.

**G5.10**

**Selective Voltage-Controlled Hole Spin in Non-Magnetic Resonant Tunneling Diodes.** Y. Galvao Gobato[1,3], A. Vercik[1], I. Camps[1], M. J. S. P. Brasil[2], A. C. R. Bittencourt[4], J. F. Estanislau[1] and Gilmar Eugenio Marques[1]; [1]Departamento de Fisica, Universidade Federal de Sao Carlos, Sao Carlos, Sao Paulo, Brazil; [2]Instituto de Fisica Gleb Wataghin- UNICAMP, Campinas, Sao Paulo, Brazil; [3]Departamento de Fisica, Universidade Federal de Santa Catarina, Florianopolis, Santa Catarina, Brazil; [4]Departamento de Fisica, Universidade do Amazonas, Manaus, Amazonas, Brazil.

In this work, we report on experimental observation of hole spin selection in GaAs/GaAlAs n-i-n double barrier resonant tunneling structures (DBRTS). The holes are photoexcitated by the 488 nm line of a Coherent Ar+ ion laser. Current-voltage (I-V) curves were measured at 2K and under magnetic fields up to 15T provided by an Oxford superconducting magnet. When subjected to an external magnetic field, spin splitting of hole levels in the quantum well leads to several peaks in the transmissivity. The complexity of the valence band structure and the strong and nonlinear Zeeman splitting of holes determine the general shape of the magneto current across the sample. These experimental results are interpreted as an evidence of tunneling transport through spin polarized hole levels of non-magnetic diodes. A model that simulates the magnetic field dependence of the I(V) characteristics of the device was developed and shows a good agreement with the experiment. The energy and magneto-states of light and heavy holes for a given Landau number N in a quantum well can be calculated as solution of the Luttinger-Kohn Hamiltonian. In the absence of electric field, each quantum well function is either symmetric(even), for m = 1,3,5,... or anti-symmetric(odd), for m = 2, 4, 6,... for zero magnetic field (or k-par=(kx, ky)]=0) applied parallel to the growth direction. Only in this case heavy-hole or ligth-hole states are pure. As the magnetic field [or k-par] increases, the Hamiltonian induces mixture of parities of different spin components of each carrier type. The presence of an electric field breaks the inversion symmetry and lifts the degeneracy of the Krammer's doublets of each carrier. The application of a magnetic field increases the separation between the spin-up and spin-down components, causing a very large Zeeman splitting of the hole states. The mixing in the valence band, determined by the combination of operators in the off-diagonal elements of the Luttinger-Kohn Hamiltonian, imposes conditions for constructing each Landau state, giving rise to a sequence of Landau levels in each spinor component. A deep look into the structure of the Hilbert space shows that there are four sets of the magneto-hole states with different Landau quantum numbers involved. Therefore, theoretical and experimental results demonstrate the possibility of devices based on tunneling through spin resolved levels, which could be used as voltage controlled hole spin filters.

**G5.11**

**Nitrogen diffusion in a magnetic tunnel junction with nitrogen-treated interface.** Jin-Tae Kim[1], Heejae Shim[1], B.K. Cho[2], J.W. Choi[1] and Y Park[1]; [1]Electromagnetic Dept., KRISS, Daejeon, South Korea; [2]Materials Science and Engineering Dept., KJIST, Kwangju, South Korea.

Magnetic tunnel junctions (MTJ) with a Fe pinned magnetic layer that was exposed to nitrogen plasma for a few tens of seconds were characterized by X-ray photoelectron spectroscopy (XPS) and auger electron spectroscopy (AES) after thermal annealing at various temperatures. The nitrogen, which initially existed in both sides of the Al and Fe layers, is found to diffuse into FeMn layer after annealing at 230 C, leaving no nitrogen in the Fe layer. The role of the diffused nitrogen is discussed in terms of the physical properties of junction.

**G5.12**

**P-type Conductivity in Cubic GaMnN Layers Grown by Molecular Beam Epitaxy.** B. L. Gallagher, S. V. Novikov, K. W. Edmonds, A. D. Giddings, K. Y. Wang, R. P. Campion, C. R. Staddon and C. T. Foxon; School of Physics and Astronomy, University of Nottingham, Nottingham, United Kingdom.

III-V dilute magnetic semiconductors offer a unique combination of electronic, magnetic, and optical properties, which promise a revolution in data storage and processing technologies, and hold prospects for quantum computation. There are theoretical predictions that cubic (zinc-blende) Ga(1-x)Mn(x)N (x > 0.05) with a high hole concentration should exhibit a Curie temperature exceeding room temperature. However p-type conductivity in GaMnN layers has never been achieved without co-doping. The aim of the current work was to experimentally check this theoretical prediction and to study Mn doping of the cubic GaN for a wide range of the Mn concentrations. Cubic GaN films doped with Mn were grown by plasma-assisted molecular beam epitaxy on GaAs (001) substrates. Some of the structures contained cubic AlN buffer layers. Auger Electron Spectroscopy and Secondary Ion Mass Spectroscopy studies clearly confirm the incorporation of Mn into cubic GaN, the Mn being uniformly distributed through the layer. X-ray diffraction studies demonstrate that the Mn-doped GaN films are cubic and do not show phase separation up to the Mn concentrations of x<0.1. P-type conductivity for the cubic GaMnN layers was achieved for a wide range of the Mn doping levels. The hole concentration measured at room temperature depends non-linearly on the Mn incorporation and varies from 10(17) to 10(19) cm(-3).

SESSION G6:Spintronic Devices and Spin Dynamics
Chair: Jay Kikkawa
Thursday Morning, April 15, 2004
Room 2005 (Moscone West)

**8:30 AM *G6.1**

**Tunnel Spin Injectors for Semiconductor Spintronics: Electrical Spin Injection from Ferromagnetic Metal/Oxide Tunnel Barrier Injectors into AlGaAs/GaAs Quantum Well Structures.** Stuart Parkin, IBM Almaden Research Center, San Jose, California.

Spin-based electronics, often referred to as "spintronics", is a research field of intense current interest, which aims to develop novel sensor, memory and logic devices by manipulating the spin states of electrons or holes in semiconducting materials. This talk will focus on electrical spin injection into semiconductors, which is a prerequisite for spintronics and, in particular, on tunnel based spin injectors operable above room temperature. Two types of spin injectors, formed from 3d transition metal ferromagnets and oxide tunnel barriers, are discussed: a three-terminal magnetic tunnel transistor (MTT)[1,2] injector and a two-terminal magnetic tunnel injector. The spin polarization of the injected current into GaAs is detected optically by measuring the circular polarization of electroluminescence from an AlGaAs/GaAs quantum well light emitting diode detector. Using an MTT injector hot electrons are injected ballistically into GaAs at energies of between 1 to 2 eV. Modest spin polarization values are found of 10 percent at 1.4K for electrons with energies of 2eV because of significant electron spin relaxation in GaAs at these high energies. Using a simpler two-terminal tunnel injector with a novel tunnel barrier much higher spin polarization values are found of up to 60 percent at 100K. The magnitude of the electroluminescence and its temperature and bias dependence is largely determined by spin relaxation within the GaAs quantum well. * work carried out in collaboration with Xin Jiang, Robert Shelby, Roger Wang, Roger MacFarlane, and James Harris || with support from DARPA. 1 S. van Dijken, X. Jiang, and S. S. P. Parkin, Appl. Phys. Lett. **83**, 951 (2003). 2 X. Jiang, R. Wang, S. v. Dijken, R. Shelby, R. Macfarlane, G. S. Solomon, J. Harris, and S. S. P. Parkin, Phys. Rev. Lett. **90**, 256603 (2003).

**9:00 AM *G6.2**
**Dynamic ferromagnetic proximity effect in photo-excited semiconductors.** Gerrit E.W. Bauer, NanoScience, TU Delft, Delft, Netherlands.

The spin dynamics of photo-excited carriers in semiconductors in contact with a ferromagnet is treated theoretically and compared with time-dependent Faraday rotation experiments [1]. We treat the observed ferromagnetic proximity effect by the same formalism that successfully describes the dynamics of the magnetization vector in metallic hybrids [2]. We expect significant effects of the real and imaginary part of the spin-mixing conductance on the dynamics of spin-accumulation in the semiconductor. The long time response of the system is found to be governed by the first tens of picoseconds in which the excited plasma interacts strongly with the intrinsic interface between semiconductor and ferromagnet in spite of the existence of a Schottky barrier in equilibrium. Quantitative explanation of the experiments requires self-consistent modelling of the combined electron and hole carrier dynamics as well as ab initio calculations of the interface scattering matrices for electrons and holes. This work was carried out in collaboration with Arne Brataas, Yaroslav Tserkovnyak, Bertrand I. Halperin, Maciej Zwierzycki and Paul J. Kelly. [1] R.K. Kawakami et al., Science 294, 131 (2001); R.J. Epstein et al., Phys. Rev. B 65, 121202 (2002); R.J. Epstein et al., Phys. Rev. B 68, 041305 (2003). [2] A. Brataas et al., Phys. Rev. Lett. 84, 2481 (2000); Eur. Phys. J. B 22, 99 (2001); Y. Tserkovnyak et al., Phys. Rev. Lett. 88, 117601 (2002).

**10:00 AM *G6.3**
**Dynamics of single-electron charge and spin in quantum dots.** Toshimasa Fujisawa, [1]NTT Basic Research Laboratories, Atsugi, Japan; [2]Tokyo Institute of Technology, Tokyo, Japan.

Dynamical behaviors of a single electron charge and spin are growing interests for quantum information technologies as well as for fundamental characteristics of an electron and spin in nanostructures. We present some recent results on coherency, dissipation and dephasing of orbital and spin states in semiconductor quantum dots. First, we discuss coherency of charge states (a pseudo-spin qubit) in a double quantum dot. Consider a two-level system consisting of one charge state, in which an excess electron occupies one energy state in one dot, and another charge state, in which the excess electron occupies another energy state in the other dot. When these two states are coupled by a tunneling barrier, coherent charge oscillations can be induced by means of non-adiabatic excitation with a high-speed voltage pulse. We successfully observed clear coherent charge oscillations. The quantum information of the qubit can be manipulated by tailoring the pulse waveform. However, the charge qubit suffers from strong decoherence, which might come from electron-phonon coupling or some fluctuations. Second, we discuss spin relaxation time in a quantum dot. We investigate energy relaxation time from an excited state to the ground state in one- and two-electron semiconductor quantum dot artificial atoms. We find that the relaxation time of the one-electron artificial hydrogen atom is 3 - 10 ns, which is understood by spontaneous emission of acoustic phonons. This process can be regarded as an allowed transition in artificial atoms. However, the relaxation time of the two-electron artificial helium atom can be longer than 200 us, which is 4 or 5 orders of magnitude longer than for the allowed transition. This transition is forbidden by total-spin conservation, but actually allowed by higher-order processes. The experiments indicate that the spin and orbital degrees of freedom are well separated in our system. This is desirable for potential applications to spin based information storage. [1] T. Hayashi, T. Fujisawa, H. D. Cheong, Y. H. Jeong, Y. Hirayama, to be published in Phys. Rev. Lett. (cond-mat/0308362). [2] T. Fujisawa, D. G. Austing, Y. Tokura, Y. Hirayama, and S. Tarucha, Nature 419, 278 (2002).

**10:30 AM G6.4**
**Prospects for Narrow Gap Semiconductors for Spintronic Applications.** Lesley Cohen[1], Tong Zhang[1], Steve K Clowes[1], K Litvinenko[2], M Merrick[2], Ben N Murdin[2], P Murzyn[3], Carl R Pidgeon[3], Phil Buckle[4] and Tim Ashley[4]; [1]Physics, Imperial College London, London, United Kingdom; [2]Physics, University of Surrey, Guildford, United Kingdom; [3]Physics, Heriot-Watt University, Edinburgh, United Kingdom; [4]QinetiQ, Malvern, United Kingdom.

Narrow gap semiconductors (NGS) are interesting for spintronic applications because of their high effective g-value, high mobility, etc. These materials are substantially less studied than the GaAs system. We have made pico-second time-resolved measurements of spin lifetimes in NGS at 300 K, using quarter wave plates to produce circularly polarized pump and probe beams. Previously, we demonstrated for intrinsic InSb that the spin lifetime, $\tau_s$, is of the order of 20 ps. We determined a remarkably long spin lifetime, $\tau_s$ 300 ps, for a near-degenerate epilayer of n-InSb ($n = 2\times10^{17}$ $cm^{-3}$) [1]. We have now found similar results for intrinsic InAs, $\tau_s$ 20 ps, (in agreement with other workers) and $\tau_s$ 1.6 ns when $n = 2\times10^{17}$ $cm^{-3}$). In more heavily doped materials the interband recombination rate is significant compared with the spin relaxation which makes interpretation of time-resolved experiments more problematic. However significant spin-imbalance of the electron population still exists after the recombination has finished since the photo-holes quickly loose their spin and can recombine with electrons of either polarization. We have extended the measurements to include higher doped samples by the introduction of a photo-elastic polarization modulator to directly extract the difference between same- and oppositely circular polarized pump-probe signal. We show that in the presence of strong n-type doping, the D'yakonov-Perel relaxation is suppressed both by the degeneracy condition and by electron-electron scattering, and that the Elliott-Yafet model then dominates for the n-type material. We describe also the growth and characterization of a range of NGS epilayers and report on the prospects for their application in spintronic devices. Acknowledgements: This work is supported by the UK- EPSRC grant GR/R42402 and the EU contract FENIKS: G5RD 2001 00535. [1] P. Murzyn, C.R. Pidgeon, P.J. Phillips, J.P. Wells, N.T. Gordon, T. Ashley, J.H. Jefferson, T.M. Burke, J. Giess, M. Merrick and B.N. Murdin, C.D. Maxey, Phys. Rev. B 67, 235202 (2003).

**10:45 AM G6.5**
**Ultrafast Relaxation and Dephasing of Hot Electron Spins in n-GaAs.** Lars Schreiber, Marcus Heidkamp, Bernd Beschoten and Gernot Guentherodt; II. Physikalisches Institut, RWTH Aachen, 52056 Aachen, Germany.

Electron spins in n-doped GaAs exhibit longest spin lifetimes (> 100 ns) near the chemical potential for doping concentrations close to the metal-insulator transition [1]. However, the relaxation and dephasing of hot electron spins, which is of fundamental interest for spintronic devices based on spin tunneling [2], is widely unexplored. Therefore, we investigate the relaxation of hot electron spins in n-GaAs for silicon doping concentrations ranging from $2\times10^{15}$ $cm^{-3}$ to $1\times10^{18}$ $cm^{-3}$ at 6 K and 100 K using an optical two color pump/probe technique utilizing two phase-locked Ti-sapphire fs-lasers. This set-up allows to coherently pump electron spins with excess kinetic energy using circularly polarized light and to monitor their intraband relaxation by measuring time-resolved Faraday and Kerr rotation for which the probe energy can be tuned independently. Ultrafast relaxation (< 10 ps) of hot electron spins into both conduction and donor band states is observed for all samples. Their subsequent dephasing, however, strongly depends on the doping concentration and the pump energy. Only for samples close to the metal-insulator transition ($n_c \cong 2\times10^{16}$ $cm^{-3}$) spin lifetimes are virtually independent of the pump energy for all temperatures. For metallic and degenerate samples, however, spin lifetimes strongly decrease with increasing pump energy. In addition, for the latter samples an ultra-fast transfer of angular momentum to the total electron sea is observed indicating a collective interaction mediated by electron-electron exchange. $ResearchsupportedbyBMBFFKZ01BM160and13N8244$ [1] J. M. Kikkawa and D. D. Awschalom, Phys. Rev. Lett. **80** (19), 4313 (1998) [2] X. Jiang *et.al.*, Phys. Rev. Lett. **90** (25), 256603 (2003)

**11:00 AM G6.6**
**Spin Lifetime Tuning in Zincblende Heterostructures and Applications to Spin Devices.** Xavier Cartoixa[1], David Z.-Y. Ting[2] and Yia-Chung Chang[1]; [1]Physics, University of Illinois at Urbana-Champaign, Urbana, IL, California; [2]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California.

One of the key parameters that must be controlled for the successful achievement of spintronic devices is the spin lifetime of the carriers. For the transport of spin-encoded quantum (single state) or classical (average over an ensemble) information, we naturally demand spin lifetimes as long as possible. If, as it is normally the case, we are to employ heterostructures in the design of our spintronic devices, we need tools that provide us with predictions about the spin lifetimes and direct us to ways of obtaining the goal of long spin lifetimes. To this purpose, we present analytical expressions for the D'yakonov-Perel' spin relaxation rates under the combined action of bulk and structural inversion asymmetry for [110] and [111] zincblende heterostructures when terms up to linear and third order in k are included in the Hamiltonian. For [110] grown heterostructures, we see that the proper axes of the spin relaxation tensor depend on the value of the Rashba coefficient, which can, of course, be modulated by the action of a gate bias. We will discuss the implications for the analysis of experimental data of this finding. Even more importantly, we see for [111] heterostructures that, under the right conditions, the lowest-order-in-k component of the spin relaxation tensor can be made to vanish for all spin components at the same time. This means that any spin, no matter its direction, can be made to have an extended lifetime in [111] heterostructures, pointing to the use of [111] heterostructures as preferred channels for spin transport and active regions in spin-LEDs. We study how the inclusion of terms of higher order in k affects these results. We finally discuss a proposal for a resonant spin lifetime transistor (RSLT) [1-3] using the spin lifetime tuning concepts presented above. In this device, a spin polarized ensemble of injected electrons reach a collector with its polarization preserved (on state) or not (off state) depending on whether an applied gate bias brings the spins within the extended (resonant) lifetime condition or not. The [001] and [110] versions of this device have restrictions on the direction of the injected spins, while the characteristics of the [111] device give the designer a supplementary degree of freedom in this aspect. [1] X. Cartoix-a, D. Z.-Y. Ting and Y.-C. Chang, Appl. Phys. Lett. 83, 1462 (2003). [2] J. Schliemann, J. C. Egues and D. Loss, Phys. Rev. Lett. 90, 146801 (2003). [3] K. Hall, W. H. Lau, K. Gundogdu, M. E. Flatte and T. F. Boggess, Appl. Phys. Lett. 83, 2937 (2003).