SYSS 1: Spins in Semiconductors

Time: Monday 9:30–13:00 Location: H1

Invited Talk SYSS 1.1 Mon 9:30 H1

Generating and manipulating spins in semiconductors — •David Awschalom — Center for Spintronics and Quantum Computation, University of California, Santa Barbara, CA 93106 USA

Spin-orbit coupling in semiconductors relates the spin of an electron to its momentum, and provides a pathway for electrically initializing and manipulating electron spins for applications in spintronics and spin-based quantum information processing. We will provide an overview of optical studies exploring spin dynamics in conventional and magnetically-doped III-V semiconductors, followed by recent experiments probing the all-electrical generation and manipulation of spins. Using magneto-optical spectroscopies with temporal and spatial resolution, new phenomena including current-induced spin polarization and the spin Hall effect have been observed in bulk semiconductors and two dimensional heterostructures. These effects have recently been exploited to electrically generate on-chip spin currents that exceed the spin diffusion length and propagate macroscopic distances in the solid state. Surprisingly, these dynamics are observed over a broad range of temperatures and persist to room temperature in II-VI materials despite no evidence for electrically-induced internal magnetic fields and notably weak spin-orbit coupling. The results reveal opportunities for tuning spin sources using quantum confinement, strain and device engineering in magnetic and non-magnetic materials.

Invited Talk SYSS 1.2 Mon 10:00 H1

Spin noise spectroscopy and spin dynamics in semiconductors — •Michael Oestreich[1], Michael Römer[1], Stefanie Döhrmann[1], Stefan Oertel[1], Daniel Hägele[1,2], and Jens Hübner[1] — [1]Leibniz Universität Hannover, Institute for Solid State Physics, Appelstraße 2, D-30167 Hannover, Germany — [2]now at: Ruhr-Universität Bochum

In the first part of our talk we will introduce spin noise spectroscopy as a nearly perturbation free method to study the electron Landé g-factor and the spin dynamics in semiconductors. Spin noise spectroscopy is an astonishing sensitive technique enabling low temperature measurements on few carrier spins. The technique avoids unintentional heating of the lattice and of free or bound carriers. Spin noise spectroscopy also avoids the creation of holes and thereby suppresses spin relaxation induced by the measurement itself.

In the second part of our talk we study the electron spin dynamics in GaAs by spin noise spectroscopy and time-resolved photoluminescence. As expected, the two techniques exhibit distinct differences in the measured low temperature electron g-factor and spin relaxation times. Very elaborate long-term time-resolved measurements yield information about the dynamics of nuclear spin polarization by optical pumping. The experiments clearly show different time scales for the dynamic nuclear polarization and in combination with temperature dependent measurements enable the determination of the pure free electron Landé g-factor with unprecedented accuracy.

Invited Talk SYSS 1.3 Mon 10:20 H1

Spin-orbit interaction in Si quantum wells — •Wolfgang Jantsch[1], Hans Malissa[1], and Zbyslaw Wilamowski[2] — [1]Johannes Kepler Universität, Linz, Austria — [2]Inst. Physics, Pol. Academy of Sciences, Warsaw, Poland

Spin-orbit interaction (SOI) in Si is by 3 orders of magnitude weaker than in typical III-V compounds. Nevertheless spin relaxation and decoherence in a modulation doped Si quantum well are dominated by SOI. The long decoherence time allows for standard ESR experiments which permit access also to other SOI effects: a dc current is shown to shift the resonance frequency up or down, depending on the relative orientation of the current and magnetic field. This effect arises from the drift velocity of the electrons which causes an additional Bychkov-Rashba field [1] via SOI. We show that due to the same mechanism, a high frequency current produces an hf magnetic field that allows spin manipulation at by orders of magnitude higher efficiency than by the microwave magnetic field in an ESR setup.

[1] Yu. L. Bychkov and E. I. Rashba, J. Phys. C 17, 6039 (1984)

Invited Talk SYSS 1.4 Mon 10:40 H1

Driven coherent oscillations of a single electron spin in a quantum dot — •Frank Koppens, Christo Buizert, Klaas-Jan Tielrooij, Ivo Vink, Katja Nowack, Tristan Meunier, Leo Kouwenhoven, and Lieven Vandersypen — Kavli Institute of Nanoscience, Delft, Netherlands

The ability to control the quantum state of a single electron spin in a quantum dot is at the heart of recent developments towards a scalable spin-based quantum computer. In combination with the recently demonstrated controlled exchange gate between two neighbouring spins, driven coherent single spin rotations would permit universal quantum operations. In this talk, I will discuss the experimental realization of single electron spin rotations in a gate-defined GaAs double quantum dot. We coherently control the quantum state of the electron spin by applying short bursts of an on-chip generated oscillating magnetic field. This allows us to observe up to eight Rabi oscillations of the electron spin in a microsecond burst. Via Ramsey-type pulse sequences we measure an apparent time-averaged coherence time which is limited by the hyperfine interaction with the nuclear spins. We erase these nuclear spin effects to a large extend via spin-echo pulse sequences and recover the intrinsic coherence time.

Invited Talk SYSS 1.5 Mon 11:00 H1

Electrical spin injection and detection in semiconductors — •Paul Crowell — University of Minnesota, Minneapolis MN , USA

In the last several years, there has been substantial progress in achieving efficient electrical spin injection from ferromagnetic metals into semiconductors. In contrast, electrical spin detection has been a more significant obstacle. I will discuss recent experiments that have addressed this difficulty, leading to a definitive demonstration of electrical spin injection and detection in lateral Fe/GaAs/Fe devices [1]. Our measurements are carried out in a non-local geometry in which the spin-dependent electrochemical potential at the detector is measured when the magnetizations of the Fe source and detection electrodes are either parallel or antiparallel. Precession and dephasing of the electron spin polarization in a transverse magnetic field are confirmed by observation of a Hanle effect in the non-local voltage. The dependence of the non-local signal on transverse magnetic field, contact separation, and temperature are in good agreement with a spin drift-diffusion model. A non-local voltage due to spin accumulation is also observed when the source electrode is under forward bias. The bias dependence of the non-local voltage, which can be compared directly with optical measurements of the spin polarization, will be discussed.

This work was carried out in collaboration with X. Lou, C. Adelmann, S.A. Crooker,E. S. Garlid, J. Zhang, S.M. Reddy, S.D. Flexner, and C.J. Palmstrøm and was supported by ONR and NSF.

[1] X. Lou *et al.*, cond-mat/0701021

Invited Talk SYSS 1.6 Mon 11:20 H1

A microscopic view of the magnetism in magnetic semiconductors *(replaces the contribution by N. Samarth)* — •Michael Flatté — Department of Physics and Astronomy, University of Iowa, Iowa City, IA 52242-1479, USA

Ferromagnetism in carrier-mediated dilute magnetic semiconductors arises from the interaction of localized spins with holes. In the ferromagnetic semiconductor GaMnAs both the localized spins and the holes come from the magnetic dopant Mn. The microscopic nature of ferromagnetism in GaMnAs can be directly probed with scanning tunneling microscopy (STM) in samples with very low concentrations of Mn ions. Theoretical predictions[1] of a very spatially anisotropic wave function for a hole bound to a Mn ion have been confirmed[2] by STM images of the hole wave function in GaAs dilutely doped with Mn. Spatial overlap of these Mn-associated hole wave functions produces an effective spin-spin interaction, and eventually ferromagnetism. The highly anisotropic wave functions lead to highly anisotropic spin-spin interaction energies[1], which have been recently observed[3] in GaAs doped atom-by-atom with Mn in precise pair configurations. Control of the hole wave function with electric fields may lead also to new ways to encode and manipulate quantum information in Mn ionic spins[4].

[1] J.-M. Tang and M. E. Flatté, Phys. Rev. Lett. 92, 047201 (2004).

[2] A. Yakunin, et al., Phys. Rev. Lett. 92, 216806 (2004).

[3] D. Kitchen, A. Richardella, J.-M. Tang, M. E. Flatté, and A. Yazdani, Nature 442, 436 (2006).

[4] J.-M. Tang, J. Levy and M. E. Flatté, Phys. Rev. Lett. 97, 106803 (2006).

Invited Talk SYSS 1.7 Mon 11:40 H1

Tailoring ferromagnetism in bulk semiconductors and quantum dots — •Igor Zutic — State University of New York at Buffalo

For dilute magnetic semiconductors to find wide application in real spintronic devices [1], their electronic and magnetic properties will require tailoring in much the same way that bandgaps are engineered in conventional semiconductors. In this talk, by using the density functional theory, we examine two examples: Mn-doped II-IV-V2 chalcopyrites [2] and Mn-doped II-VI quantum dots [3]. In the first case, we reveal a variation of magnetic properties across 64 different materials which cannot be explained by the dominant models of ferromagnetism in semiconductors. We identify a small number of novel stable chalcopyrites with excellent prospect for ferromagnetism. In the second case, we explore possibility of tailoring magnetism by controlling the electron-electron Coulomb interaction, without changing the number of particles. The interplay of strong Coulomb interactions and quantum confinement leads to enhanced inhomogeneous magnetization which persist at higher temperatures than in the non-interacting case. The temperature of the onset of magnetization can be controlled by changing the number of particles as well as by modifying the quantum confinement and the strength of Coulomb interactions.

Collaboration with S. C. Erwin (NRL), R. M. Abolfath (SUNY, Buffalo) and P. Hawrylak (NRC). Supported by the US ONR and NSF-ECCS CAREER.

[1] I. Zutic, J. Fabian, S. Das Sarma, Rev. Mod. Phys. 76, 323 (2004).

[2] S. C. Erwin and I. Zutic, Nature Mater., 3, 410 (2004).

[3] R. M. Abolfath, P. Hawrylak, and I. Zutic, cond-mat/0612489.

Invited Talk SYSS 1.8 Mon 12:00 H1

Tunnel Anisotropic Magneto Resistance - TAMR — •Laurens Molenkamp — Physikalisches Institut (EP 3), Universität Würzburg

In the ferromagnetic semiconductor (Ga,Mn)As, we have found a novel magnetoresistance effect, dubbed tunnel anisotropic magnetoresistance (TAMR), The effect is due to the strong spin-orbit coupling in the material, which results in an equally strong dependence of the density of states on magnetization direction. The effect leads to the observation of a spin valve-like behavior in tunnel structures containg a single ferromagnetic layer and also dominates the spin-valve signal obtained from structures containing two (Ga,Mn)As layers. While the effect usually amounts to severals tens of percent in amplitude, at low temperatures resistance changes of five orders of magnitude. This is caused by the fact that the system undergoes a metal-insulator transition upon reorientation of the magnetization. I will present a detailed calculation of the Mn impurity states involved in the metal-insulator transition.

At the end of the talk, I will briefly discuss some recent related work in our group. We have learned how to tailor the magnetic anisotropies of (Ga,Mn)As-based nanostructures and demonstrate a simple memory element based upon this technique.

Invited Talk SYSS 1.9 Mon 12:20 H1

Electric field controlled spintronic effects based on spin-orbit coupling — •Tomas Jungwirth — Institute of Physics ASCR, Cukrovarnicka 10, 162 53 Praha 6, Czech Republic — School of Physics and Astronomy, University of Nottingham, Nottingham NG7 2RD, UK

The history of spintronic devices is reminiscent of that of the conventional microelectronics. It has started with a simple "spintronic resistor" - an anisotropic magnetoresistance sensor, followed by diode-like spin-valve elements. Building further on the analogy with conventional electronics, adding a control by external electric fields appears as a natural route to a new generation of spintronics elements. We will introduce two concepts that allow for such a functionality - the Coulomb blockade anisotropic magnetoresistance [1] and the spin Hall effect [2]. The former phenomenon reflects the magnetization orientation dependence of the classical single-electron charging energy and offers a route to non-volatile, low-field, and highly electro- and magneto-sensitive operation. In the latter phenomenon, edge spin-accumulation is generated electrically in a nominally non-magnetic system. We will discuss our theoretical understanding of these effects in which spin-orbit coupling plays the central role.

[1] J. Wunderlich, T. Jungwirth, B. Kaestner, et al., Phys. Rev. Lett. 97, 077201 (2006)

[2] J. Wunderlich, B. Kaestner, J. Sinova, T. Jungwirth, Phys. Rev. Lett. 94, 047204 (2005); K. Nomura, J. Wunderlich, Jairo Sinova, B. Kaestner, A.H. MacDonald, T. Jungwirth, Phys. Rev. B 72, 245330 (2005).

Invited Talk SYSS 1.10 Mon 12:40 H1

Zero-bias spin separation in semiconductor heterostructures — •Sergey Ganichev — Faculty of Physics, University of Regensburg, 93040, Regensburg, Germany

We observed that spin-dependent scattering of electrons in media with suitable symmetry results in in equal and oppositely directed electron flows in the spin-up and spin-down subbands yielding a pure spin current [1]. The pure spin current does not require an electric current to flow, as in the case of the spin-Hall effect, and causes a "zero-bias" spin separation. It is show that by free carrier (Drude) absorption of terahertz radiation [2] spin separation can be achieved in a wide range of temperatures from liquid helium temperature up to room temperature. Moreover the experimental results demonstrate that simple electron gas heating by any means is already sufficient to yield spin separation due to spin-dependent energy relaxation processes of non-equilibrium carriers. In our experiments on low dimensional structures based on GaAs, InAs, SiGe and GaN the pure spin current is converted into an electric current applying a magnetic field that lifts the cancellation of the two partial charge flows. A microscopic theory of this effect is developed being in a good agreement with the experimental data.

[1] S.D. Ganichev, V.V. Bel'kov, S.A. Tarasenko, S.N. Danilov, S. Giglberger, Ch. Hoffmann, E.L. Ivchenko, D. Weiss, W. Wegscheider, Ch. Gerl, D. Schuh, J. Stahl, J. De Boeck, G. Borghs, and W. Prettl, *Nature Physics* (London) **2**, 609 (2006).

[2] S.D. Ganichev and W. Prettl, Intense Terahertz Excitation of Semiconductors, (Oxford University Press, 2006).