HL 33: Spin-dependent Transport I

Time: Tuesday 10:15–13:30 Location: POT 251

HL 33.1 Tue 10:15 POT 251

Time-resolved Kerr detection of acoustic spin transport in GaAs (110) quantum wells — •Alberto Hernández-Mínguez, Klaus Biermann, Snežana Lazić, Rudolph Hey, and Paulo V. Santos — Paul-Drude-Institut für Festkörperelektronik, Hausvogteiplatz 5-7, D-10117 Berlin, Germany

Surface acoustic waves (SAWs) provide an efficient tool for the transport of spins in semiconductor quantum wells (QWs). The SAW piezoelectric field captures photogenerated electrons and holes in spatially separated locations, thus dramatically increasing the recombination lifetime, and transports them with well-defined velocity. Previous investigations of acoustic spin transport were carried out using spatially resolved photoluminescence, which requires the radiative recombination of the carriers. In this contribution, we demonstrate an alternative spin detection approach based on microscopic Kerr reflectometry in GaAs (110) QWs, where spin dephasing mechanisms associated with spin-orbit interaction result inoperative for electron spins oriented along the growth axis. The spins are generated on the SAW path by a pump laser pulse and are detected by measuring the change δP in polarization of a probe pulse delayed by τ with respect to the pump. Spatial profiles of δP during acoustic transport show a peak at $x = v_{SAW}\tau$, thus revealing the position of the moving spin packet. Measurements under an in-plane applied magnetic field demonstrate the coherent precession of the optically generated electron spins during acoustic transport over several μm, yielding information about the relaxation processes for the acoustically moving spins.

HL 33.2 Tue 10:30 POT 251

InAs spin-filter cascades in perpendicular magnetic fields — •Hauke Lehmann, Till Benter, Jan Jacob, and Ulrich Merkt — Institut für Angewandte Physik und Zentrum für Mikrostrukturforschung, Universität Hamburg, Jungiusstraße 11, 20355 Hamburg

We have experimentally demonstrated the generation and detection of spin-polarized currents by the intrinsic spin Hall effect in two-staged spin-filter cascades fabricated from InAs heterostructures [1]. Applying an external magnetic field perpendicular to the two-dimensional electron system introduces a Lorentz force. This adds to the spin-dependent force of the intrinsic spin Hall effect a spin-independent force dragging the electrons into one of the two outputs of each filter. Thus the magnetic field leads to a change of conductances and spin polarizations in each output. The conductances at the filters' outputs depend on the magnetic field direction and strength. Thus the application of magnetic fields allows inference on the strength of the intrinsic spin Hall effect in low-dimensional semiconductor nanostructures.

[1] J. Jacob, G. Meier, S. Peters, T. Matsuyama, U. Merkt, A. Cummings, R. Akis, and D. Ferry. J. Appl. Phys. **105**, 093714 (2009).

HL 33.3 Tue 10:45 POT 251

Influence of in-plane magnetic fields on the spin-orbit coupling in InAs spin-filter cascades — •Hauke Lehmann, Till Benter, Alexander Buhr, and Jan Jacob — Institut für Angewandte Physik und Zentrum für Mikrostrukturforschung, Universität Hamburg, Jungiusstraße 11, 20355 Hamburg.

In Y-shaped three-terminal junctions of quasi one-dimensional nanowires fabricated from InAs heterostructures an unpolarized current is separated into two oppositely polarized currents by the intrinsic spin Hall effect. The spin polarization can be detected by a second filter stage [1]. Combining the intrinsic spin Hall effect with the spin precession, originating from the spin-orbit interaction, the electrons execute an oscillatory motion - the so-called zitterbewegung. This motion can be tuned by an in-plane magnetic field perpendicular to the electrons' direction of motion, which couples to the effective Rashba field. We present DC biased lock-in transport measurements at millikelvin temperatures on two-staged spin-filter cascades and compare them to simulations [2].

[1] J. Jacob, G. Meier, S. Peters, T. Matsuyama, U. Merkt, A. Cummings, R. Akis, and D. Ferry. J. Appl. Phys. **105**, 093714 (2009).

[2] P. Brusheim and H. Q. Xu, arXiv: 0810.2186v2 (2009).

HL 33.4 Tue 11:00 POT 251

Spin-orbit coupling effects in the quantum oscillatory magnetization of asymmetric InGaAs/InP quantum wells in tilted magnetic fields — •Benedikt Rupprecht[1], Christian Heyn[2], Hilde Hardtdegen[3], Thomas Schäpers[3], Marc A. Wilde[1], and Dirk Grundler[1] — [1]Lehrstuhl für Physik funktionaler Schichtsysteme, TU München, James-Franck-Str. 1, D-85747 Garching b. M. — [2]Institute of Applied Physics, Jungiusstr. 11, D-20355 Hamburg — [3]Institute for Bio- and Nanosystems (IBN-1) and JARA Jülich-Aachen Research Alliance, Research Centre Jülich GmbH, D-52425 Jülich

The measurement of the magnetic susceptibility and the de Haas-van Alphen (dHvA) effect was proposed by Bychkov and Rashba in 1984 to study the spin-orbit interaction (SOI) in a structure inversion asymmetric heterostructure and the spin splitting experienced by a two-dimensional electron system (2DES). Micromechanical cantilever magnetometry recently allowed us to measure the magnetization M of asymmetric InGaAs/InP quantum wells. We observe the expected SOI-induced beating patterns in M in both nearly perpendicular and tilted magnetic fields B. Unexpectedly we find phase and frequency anomalies in M vs B which have not been predicted and not been found in magnetotransport experiments. We compare our experimental results with simulations considering SOI, Zeeman splitting and tilted fields. We show that the surprising phase and frequency anomalies go beyond the current theoretical understanding and remain to be clarified. The work is supported via SPP 1285 "Halbleiter-Spintronik" (GR1640/3-2) and the "Nanosystems Initiative Munich" (NIM).

HL 33.5 Tue 11:15 POT 251

Spin polarized photocurrents in InAs:Mn based quantum wells — •P. Olbrich[1], C. Zoth[1], C. Drexler[1], V. Lechner[1], I. Caspers[1], V. Bel'kov[2], S. Weishäupl[1], D. Vogel[1], U. Wurstbauer[3], D. Schuh[1], D. Weiss[1], and S.D. Ganichev[1] — [1]Terahertz Center, Regensburg, Germany — [2]Ioffe Institute, St. Petersburg, Russia — [3]Columbia University, NY, USA

We report on the observation and investigation of terahertz (THz) radiation induced spin polarized currents in manganese doped InAs quantum well structures (QWs). The study is aimed to explore the spin-orbit interaction in this novel material system. The incorporation of Mn into an InAs QW leads to a 2D hole gas with interesting properties as both the g^*-factor and Rashba type of spin-orbit coupling are large. Here, we demonstrate that in Mn-doped InAs QWs the absorption of THz radiation leads to pure spin currents, which we converted into a net electric current by means of an external in-plane magnetic field. Our results, in particular the dependence of the current on the magnetic field strength and temperature, have provided a feedback to the segregation of manganese. We show that as a result of this process only in systems with Mn introduced from the substrate side the spin-dependent scattering and Zeeman effect become enhanced. This result is supported by transport measurements of the longitudinal magnetoresistance. In addition, by applying photogalvanic effects we studied the anisotropy of the band spin splitting and provide the information on the ratio between the Rashba and Dresselhaus terms in InAs:Mn QWs of various designs.

HL 33.6 Tue 11:30 POT 251

Spin polarized electric currents in semiconductor heterostructures induced by microwave radiation — •C. Drexler[1], V.V. Bel'kov[2], B. Ashkinadze[3], P. Olbrich[1], C. Zoth[1], V. Lechner[1], Ya.V. Terent'ev[2], D.R. Yakovlev[2,4], G. Karczewski[5], T. Wojtowicz[5], D. Schuh[1], W. Wegscheider[1], and S.D. Ganichev[1] — [1]THz Center, Regensburg, Germany — [2]Ioffe Institute, St. Petersburg, Russia — [3]Technicon, Haifa, Israel — [4]TU Dortmund, Germany — [5]Polish Academy of Sciences, Warsaw, Poland

We report on microwave (mw) radiation induced electric currents in semi-magnetic CdMnTe and non-magnetic InAs:Si quantum wells subjected to an external in-plane magnetic field. The current generation is attributed to the spin-dependent energy relaxation of electrons heated by mw radiation. The relaxation produces equal and oppositely directed electron flows in the spin-up and spin-down subbands yielding a pure spin current. The Zeeman splitting of the subbands in the external magnetic field leads to the conversion of the spin flow into a spin-polarized electric current, which is proportional to the Zeeman splitting energy in non-magnetic structures. As a result we demonstrate, that the presence of magnetic Mn^{2+} ions yields an additional contribution to the microwave induced current formation which is related to the giant Zeeman spin splitting [1].

[1] C. Drexler *et. al.*, *Appl. Phys. Lett.* **97**, 182197 (2010).

15 min. break

HL 33.7 Tue 12:00 POT 251

Spin and orbital mechanisms of the magneto-gyrotropic photogalvanic effect in GaAs/AlGaAs quantum wells — •V. Lechner[1], L.E. Golub[2], F. Lomakina[1], V.V. Bel'kov[2], P. Olbrich[1], S. Stachel[1], I. Caspers[1], M. Griesbeck[1], M. Kugler[1], M.J. Hirmer[1], T. Korn[1], C. Schüller[1], D. Schuh[1], W. Wegscheider[3], and S.D. Ganichev[1] — [1]University of Regensburg, Germany — [2]Ioffe Institute, St. Petersburg, Russia — [3]ETH Zurich, Switzerland

Here we report on experiments, which allow us to distinguish unambiguously between the spin-dependent [1] and most recently proposed orbital origin [2] of the THz radiation induced magneto-gyrotropic photogalvanic effect (MPGE). To achieve this goal we utilize the qualitative difference in their behavior upon a variation of the g^* factor: In contrast to the orbital effects, the MPGE resulting from the spin-related roots is proportional to the Zeeman spin splitting. To explore this difference, we utilize the fact that in GaAs/AlGaAs QWs the Zeeman splitting changes its sign at a certain QW width. Our experiments show that, for most QW widths, the MPGE is mainly driven by spin-related mechanisms, which results in a photocurrent proportional to the g^* factor [3]. In structures with a vanishingly small g^* factor, however, the MPGE is also detected, proving the existence of orbital mechanisms.

[1] V.V. Bel'kov, S.D. Ganichev, Sem. Sci. Techn. **23**, 114003 (2008),

[2] S.A. Tarasenko, arXiv cond-mat: 1009.0681v1 (2010),

[3] V. Lechner et al., arXiv cond-mat: 1011.4433v1 (2010).

HL 33.8 Tue 12:15 POT 251

Magnetogyrotropic photogalvanic effects in InSb-based quantum wells — •Sebastian Stachel[1], Cynthia Karl[1], Thomas Stangl[1], Peter Olbrich[1], Vasily Bel'kov[2], Steven K. Clowes[3], Tim Ashley[4], and Sergey D. Ganichev[1] — [1]Terahertz Center, University of Regensburg, Regensburg, Germany — [2]Ioffe Institute, St. Petersburg, Russia — [3]Advanced Technology Institute, University of Surrey, UK — [4]QinetiQ, Malvern, UK

We report on the observation of the magnetic-field induced photocurrent in n-doped InSb/InAlSb quantum wells (QWs) excited by terahertz radiation. The photocurrent behavior upon variation of the radiation polarization, magnetic field strength, B, and temperature is studied. While at a moderate magnetic field the photocurrent exhibits a linear field dependence, at high magnetic fields it becomes nonlinear and even changes its sign. The experimental results are analyzed in terms of the magneto-gyrotropic photogalvanic effect (MPGE) based on the asymmetry of optical transitions and/or asymmetric relaxation of carriers in the momentum space [1]. We demonstrate that the sign inversion of the photocurrent is caused by the interplay of two mechanisms: The spin mechanism, which yields a saturation of the current at high magnetic fields due to the large Zeeman splitting in InSb-based QWs, and the orbital mechanism, which depends linearly on B and has an opposite sign. The latter contribution dominates the total current at high magnetic fields.

[1] V.V. Belkov and S.D. Ganichev, Sem. Sci. Tec. **23**, 114003 (2008)

HL 33.9 Tue 12:30 POT 251

Remanent spin injection and spin relaxation in quantum dot light emitting diodes — •Henning Soldat[1], Mingyuan Li[1], Nils C. Gerhardt[1], Arne Ludwig[2], Frank Stromberg[3], Werner Keune[3], Heiko Wende[3], Andreas D. Wieck[2], Dirk Reuter[2], and Martin R. Hofmann[1] — [1]Lehrstuhl für Photonik und Terahertztechnologie, Ruhr-Universität Bochum, D-44780 Bochum — [2]Lehrstuhl für Angewandte Festkörperphysik, Ruhr-Universität Bochum, D-44780 Bochum — [3]Fakultät für Physik and Center for Nanointegration Duisburg-Essen (CeNIDE), Universität Duisburg-Essen, D-47048 Duisburg

The study of spin-controlled optoelectronic devices has been a field of intensive research over the past few years. We investigate spin injection in remanence into InAs quantum dot (QD) light emitting diodes (LEDs). Our samples are spin LEDs with a Fe/Tb injector with out-of-plane remanent magnetization and a MgO tunnel barrier at the ferromagnetic metal/semiconductor interface to overcome the conductivity mismatch. The active region is an ensemble of InAs QDs. Intrinsic GaAs layers of variable thickness have been implemented between this active region and the spin injector to investigate the influence of transport path length on spin polarization. We have measured the circular polarization of the LED emission in remanence. By investigating the different injection path lengths for the samples we have determined the spin diffusion length in undoped GaAs along with the spin polarization at the injector interface. Additionally, the spin injection efficiency at the MgO tunnel barrier has been investigated.

HL 33.10 Tue 12:45 POT 251

Perpendicular Spin Injection and Polarization Features in InAs Quantum Dots — •Arne Ludwig[1], Henning Soldat[2], Frank Stromberg[3], Astrid Ebbing[1,4], Anne Warland[3], Mingyuan Li[2], Nils C. Gerhardt[2], Dirk Reuter[1], Oleg Petracic[4], Martin Hofmann[2], Heiko Wende[3], Werner Keune[3], and Andreas D. Wieck[1] — [1]Lehrstuhl für Angewandte Festkörperphysik, Ruhr-Universität Bochum — [2]Lehrstuhl für Photonik und Terahertztechnologie, Ruhr-Universität Bochum — [3]Fachbereich Physik and Center for Nanointegration Duisburg-Essen, Universität Duisburg-Essen — [4]Experimentalphysik IV - Festkörperphysik, Ruhr-Universität Bochum

Self assembled InAs quantum dots (QDs) are zero dimensional multilevel systems with long spin relaxation times and thus offer great potential for spin optoelectronic research and applications.

Electrically injected spin polarization is efficiently transferred into circularly polarized photons if the injected spin is oriented perpendicularly to the growth plane. The optical polarization from an ensemble of QDs in a spin-LED is strongly magnetic field dependent due to the orbital character of the transitions of excited carriers. An unambiguous separation of spin injection and Zeeman shift is obtained by investigating the magnetic field dependence of the circular polarisation of the spin-LED emission.

Here we present and analyze perpendicular spin injection from Fe/Tb magnetic injectors at room temperature and in remanence. Polarization features of excited transitions are discussed.

HL 33.11 Tue 13:00 POT 251

Coherent electrical spin-manipulation in strained InGaAs — •Sebastian Kuhlen[1,3], Klaus Schmalbuch[1,3], Markus Hagedorn[1,3], Mihail Lepsa[2,3], Thomas Schäpers[2,3], Gernot Güntherodt[1,3], and Bernd Beschoten[1,3] — [1]II. Physikalisches Institut A, RWTH Aachen University, 52074 Aachen — [2]Institut für Bio- und Nanosysteme IBN-1, Forschungszentrum Jülich, 52425 Jülich — [3]JARA: Fundamentals of Future Information Technology, 52074 Aachen

To realize novel spintronic devices it is important to develop electrical methods both to polarize and to manipulate electron spins.

We have investigated the process of so-called current-induced spin polarization in strained n-InGaAs epilayers, which favorably does not require any ferromagnetic electrodes. An electric field is found to create a Dresselhaus-type internal magnetic field, which is perpendicular and proportional to the E-field ($100\,mT$ per $4 \cdot 10^4\,V/m$). Using electric field pulses, which convert into internal magnetic field pulses, we are able to trigger the phase of the electron spin polarization. The coherence of these spins is probed by spin precession using time-resolved Faraday rotation. Moreover, the internal field pulses can be used to turn on and turn off spin precession of optically pumped coherent spin ensembles in the absence of external magnetic fields. By changing pulse width and amplitude we achieve a full 360° control of the spin direction.

This work has been supported by DFG through FOR912.

HL 33.12 Tue 13:15 POT 251

Separation of Spin and Charge Currents by Photovoltage Measurements in n-InGaAs — •Stefan Göbbels[1,2], Philipp Schäfers[1,2], Klaus Schmalbuch[1,2], Thomas Schäpers[3,2], Mihail Lepsa[3,2], Gernot Güntherodt[1,2], and Bernd Beschoten[1,2] — [1]II. Phys. Institut A, RWTH Aachen University, 52056 Aachen — [2]JARA: Fundamentals of Future Information Technology — [3]Institut für Bio- und Nanosysteme IBN-1, Forschungszentrum Jülich, 52425 Jülich

Spin photocurrents have gained strong attention in the field of spintronics as they convert spin information into electric voltage and spin-polarized currents. Many effects yielding spin-photocurrents have been demonstrated in 2DEGs, e.g. spin-galvanic effect and magneto-gyrotropic photogalvanic effect [1]. However, no direct proof of the spin polarization of these currents has been reported yet.

We present photovoltage measurements on n-InGaAs epilayers combined with Faraday rotation spectroscopy for the detection of the spin polarization. The photovoltage consists of both a light polarization dependent and an independent component which exhibit different energy dependencies. Comparison with the spin sensitive measurements of the Faraday rotation allows us to separate spin from charge voltages.

[1] S. D. Ganichev & W. Prettl, J. Phys. Cond. Mat. 15, R935 (2003)

This work has been supported by DFG through FOR 912.