MA 63: Spin: Transport, Orbitronics and Hall Effects III

Time: Friday 9:30–13:00 Location: HSZ 403

MA 63.1 Fri 9:30 HSZ 403

Spin and anomalous Hall effect induced charge and spin currents in ferromagnetic/nonmagnetic heterostructures — •Albert Hönemann[1], Christian Herschbach[1], Dmitry V. Fedorov[2], Martin Gradhand[3], and Ingrid Mertig[1,4] — [1]Martin Luther University Halle-Wittenberg, Halle, Germany — [2]University of Luxembourg, Luxembourg, Luxembourg — [3]University of Bristol, Bristol, United Kingdom — [4]Max Planck Institute of Microstructure Physics, Halle, Germany

Transport phenomena caused by spin-orbit coupling such as spin Hall effect (SHE) and anomalous Hall effect (AHE) are highly relevant topics of current research. In ferromagnetic/nonmagnetic heterostructures, the interplay of spin-orbit and exchange interaction causes new phenomena like spin-orbit torques [1].

We use an *ab initio* approach based on a relativistic Korringa-Kohn-Rostoker method to determine the electronic structure [2] and solve the linearized Boltzmann equation to describe the electronic transport [3]. We apply these methods to a Co/Cu superlattice with different substitutional impurities delta-distributed within the individual atomic layers [4]. We investigate the AHE-induced charge current as well as the SHE-induced spin current perpendicular and parallel to the interface and report on the spatial distribution of charge and spin current with respect to the interface.

[1] Gambardella *et al.*, Phil. Trans. R. Soc. A **369**, 3175 (2011); [2] Gradhand *et al.*, PRB **80**, 224413 (2009); [3] Gradhand *et al.*, PRL **104**, 186403 (2010); [4] Hönemann *et al.*, PRB **99**, 024420 (2019);

MA 63.2 Fri 9:45 HSZ 403

Spin-dependent transport in Uranium — •Ming-Hung Wu, Hugo Rossignol, and Martin Gradhand — H. H. Wills Physics Laboratory, University of Bristol, Bristol BS8 1TL, United Kingdom

Uranium, a naturally occurring heavy metal with 5f-electrons, has been investigated for decades due to its complex properties.1 Despite its narrow 5f-bands, the hybridization with 6d-bands provides itinerant electrons, distinct from other 5f actinides. In combination with its strong spin-orbit coupling, uranium is a promising material for spintronic applications e.g. magnetic multilayer systems.2-5 Furthermore uranium crystallizes in a large variety of structures such as α (orthorhombic), β (bct), γ (bcc) and hcp phase, it shows superconductivity and is close to a ferromagnetic transition. In order to shed light on the complex physics in such systems, we focus on the spin-dependent transport of uranium for a variety of phases. In our ab initio calculations we analyze the intrinsic spin Hall effect as well as the extrinsic mechanism incorporating various impurities for bulk γ, hcp and α uranium. We discuss the effects of crystal structures and magnetic moments of impurities on the spin-dependent transport.

Reference 1.S. Adak, H. Nakotte, P. de Chatel, B. Kiefer, Phys. B 406, 3342 (2011). 2. Kevin T. Moore and Gerrit van der Laan, Rev. Mod. Phys. 81, 235 (2009). 3. R. Springell, F. Wilhelm, A. Rogalev, W. G. Stirling, R. C. C. Ward, M. R. Wells, S. Langridge, S. W. Zochowski, and G. H. Lander, Phys. Rev. B 77, 064423 (2008). 4. A. Laref, E. Şaşioglu, L. M. Sandratskii, J. Phys.: Condens. Matter 18, 4177 (2006).

MA 63.3 Fri 10:00 HSZ 403

The spin Hall effect in β-W and interstitial impurities — •O. L. W. McHugh[1], M. Gradhand[1], W. F. Goh[2], and D. A. Stewart[3] — [1]University of Bristol, UK — [2]University of California at Davis, Davis, CA, USA — [3]Western Digital Corporation, San Jose, CA, USA

One of the best metals to convert charge into spin current via the spin Hall effect (SHE) [1] is β-W. Its structural stabilization requires doping with O and N [2] atoms. In addition, increasing the impurity concentration enhances its SHA [3]. The exact mechanism of this enhancement is unknown. We present *ab-initio* calculations to investigate these impurities for both α-W (bcc) and β-W on both the intrinsic and the extrinsic mechanism. We compare the PAOFlow[4] code using the Kubo formula with the semi classical description via the Berry curvature as implemented in the KKR [5]. For further investigations in impurities, as well as structural relaxation, we rely on the PAOFlow for the intrinsic and the KKR-Boltzmann method for the extrinsic contribution. We found good agreement to experiment, highlighting that for β-W the reduction of the charge conductivity is driving the effective charge to spin conversion. Beyond stabilization, the effect of impurities is small and a quantitative analysis will be presented.

[1] C.-F. Pai *et al.*, Appl. Phys. Letters, **101**(12) (2012)
[2] J. Liu, Doctoral Theses, Columbia University, NY, USA (2016)
[3] K.-U. Demasius *et al.*, Nat. Comm., **7**, 10664 (2016)
[4] M. Nardelli *et al.*, Comp. Mat. Science **143**, 462-472 (2018)
[5] M. Gradhand *et al.*, Phys. Rev. B, **84**, 075113 (2011)

MA 63.4 Fri 10:15 HSZ 403

Spin-orbital coupled dynamics in (Fe,Ni)/W(110) from first principles — •Dongwook Go[1,2,3], Frank Freimuth[1], Jan-Philipp Hanke[1], Stefan Blügel[1], Hyun-Woo Lee[2], and Yuriy Mokrousov[1,4] — [1]Peter Grünberg Institut and Institute for Advanced Simulation, Forschungszentrum Jülich and JARA, 52428 Jülich, Germany — [2]Department of Physics, Pohang University of Science and Technology, Pohang 37673, Korea — [3]Basic Science Research Institute, Pohang University of Science and Technology, Pohang 37673, Korea — [4]Institute of Physics, Johannes Gutenberg University Mainz, 55099 Mainz, Germany

A common wisdom in spintronics is that angular momentum is carried by the spin of electrons. In current-induced spin dynamics, however, we recently showed that the orbital degree of freedom plays a fundamental role, where spin dynamics follows the orbital dynamics by the spin-orbit coupling [1]. Thus, spin and orbital degrees of freedom exhibit entangled dynamics in general. In this talk, we present our recently developed formalism that consistently describes angular momentum transfer dynamics between spin and orbital degrees of freedom of electrons, and their interaction with lattice and local magnetic moment. We apply this formalism to (Fe,Ni)/W(110), and show that the orbital current injection critically affects the magnetization dynamics when the ferromagnet is Ni, which is consistent with a recently proposed orbital torque mechanism [2]. We acknowledge fundings from DFG (SPP 2137) and SSTF (BA-1501-07). [1] Go *et al.* Phys. Rev. Lett. **121**, 086602 (2019); [2] Go *et al.*, arXiv:1903.01085 (2019).

MA 63.5 Fri 10:30 HSZ 403

Fast screening of THz current pulses in heavy metal/ferromagnet bilayers — •Wolfgang Hoppe[1], Rouven Dreyer[1], Liane Brandt[1], Tobias Kampfrath[2], Mazhar Nawaz Ali[3], and Georg Woltersdorf[1] — [1]Martin Luther University Halle-Wittenberg, Physics, Halle, Germany — [2]Freie Universität Berlin, Physics, Berlin, Germany — [3]Max-Planck Institute of Microstructure Physics, Halle, Germany

We use femtosecond optical pump pulses to generate ultrashort current pulses in heavy metal/ferromagnet bilayers. The optical excitation from an ultrafast amplified laser system injects ultrashort spin current pulses from the ferromagnet into the heavy metal layer via the spin-dependent Seebeck effect [1]. Subsequently, this spin current pulse is converted into a charge current pulse inside the heavy metal layer via the inverse spin-Hall effect (ISHE) [2]. To investigate these ultrafast current pulses there are two different approaches available. Quantitatively, the exact waveform can be measured using electrooptic sampling. Qualitatively, a probing tip connected to a 50 GHz sampling oscilloscope yields a quick method to characterize the ISHE in plain films and microstructured devices. This fast approach can be utilized to investigate the signal dependence on varying layer thicknesses, different layer materials and wedged interlayers between the heavy metal and ferromagnetic layer.

[1] A. Melnikov et. al.: doi: 10.1103/PhysRevLett.119.017202
[2] T. Seifert et. al.: doi:10.1038/nphoton.2016.91

MA 63.6 Fri 10:45 HSZ 403

Engineering the emission of spintronic terahertz emitters based on defect densities — •Laura Scheuer[1], Dennis Nenno[1], Garik Torosyan[2], Alexander Brodyanski[3], Rolf H. Binder[4], Hans C. Schneider[1], Rene Beigang[1], and Evangelos Th. Papaioannou[1] — [1]Fachbereich Physik and Landesforschungszentrum OPTIMAS, Technische Universität Kaiserslautern, Kaiserslautern, Germany — [2]Photonic Center Kaiserslautern, Kaiserslautern, Germany — [3]Institut für Oberflächen- und Schichtanalytik (IFOS) and Landesforschungszentrum OPTIMAS, Kaiserslautern, Germany — [4]College of Optical Sciences, University of Arizona, Tucson, USA

The field of THz spintronics aims to control ultrafast spin currents that could enable novel applications and devices operating in the THz range. While the generation of pulsed broadband THz radiation utilizing the inverse spin Hall effect in ferromagnetic/nonmagnetic (FM/NM) metallic heterostructures was investigated considering the influence of the layer thickness, substrate, geometry and excitation energy, the influence of the crystal structure was not yet studied. Here, we experimentally show the role of the defect density of the crystal structure. Modifying the defect density results in a change of the elastic electron-defect scattering lifetime in Fe and Pt and of the interface transmission for spin-polarized non-equilibrium electrons. Supporting the experimental findings, a theoretical model is employed, accounting for the differences in the elastic electron scattering lifetime and for the transmission of spin-polarized hot carriers at the FM/NM interface.

MA 63.7 Fri 11:00 HSZ 403

THz emission from XUV pumped spintronic tri-layer emitter: A prospective timing tool for FELs — •Naman Agarwal[1], Igor Ilyakov[2], Robert Carley[1], Jan-Christoph Deinert[2], Alexander Yaroslavtsev[1], Jia Liu[1], Loic le Guyader[1], Gabor Kurdi[3], Laura Foglia[3], Riccardo Mincigrucci[3], Emiliano Principi[3], Tobias Kampfrath[4,5], Sergey Kovalev[2], Michael Gensch[6,7], and Andreas Scherz[1] — [1]European XFEL GmbH, Schenefeld, Germany — [2]TELBE, HZDR, Dresden, Germany — [3]EIS-TIMEX, FERMI, Trieste, Italy — [4]Freie Universität Berlin, Germany — [5]Fritz-Haber-Institut, Berlin, Germany — [6]Technischen Universität Berlin, Germany — [7]DLR, Berlin, Germany

We demonstrate the strong broadband THz emission from spintronic trilayer (W/CoFeB/Pt) excited by XUV wavelengths. We discuss the possible mechanisms of generation of THz emission.

Further, in our timing diagnostics scheme, we demonstrate few-femtosecond arrival-time measurements based on single-shot electro-optic sampling(EOS) of broadband THz emission from an XUV-pumped spintronic THz emitter. Experiments were performed at the EIS-TIMEX beamline of FERMI, Italy. Using a spectral-encoding scheme for EOS, we were able to measure the arrival time with 20fs resolution, which compares well with other techniques.This technique requires very small fluence (10 uJ/cm^2), compared to other techniques(transient reflectivity) requiring 10 mJ/cm^2.We discuss possible improvements of this scheme, and how it can be combined with other scientific objectives.

15 min. break.

MA 63.8 Fri 11:30 HSZ 403

Spin dynamics driven by optical spin-orbit torque — •Ritwik Mondal, Andreas Donges, and Ulrich Nowak — Department of Physics, Universität Konstanz, Konstanz 78464, Germany

Interest in controlling spins by means of ultra-short light pulses has grown immensely due to its potential technological applications. To this end, several light-spin interaction effects can contribute to the spin dynamics, e.g., the nonrelativistic Zeeman effect. However, the relativistic light-spin coupling effects cannot be neglected if the laser power is higher. In this case, a spin precession occurs due to an additional optical spin-orbit torque (OSOT) [1]. It is believed that the OSOT originates from the relativistic spin-orbit coupling of excited non-equilibrium photo carriers that is independent of the helicity of the laser pulse [1]. Here, we examine the existence of an OSOT, a relativistic spin torque originating from the spin-orbit coupling of the applied field with the magnetic spins [2]. Our analytical calculations show that the OSOT depends on the helicity of the light and proportional to the intensity, while inversely proportional to the frequency. We compare the effects of the nonrelativistic Zeeman torque and the relativistic OSOT for magnetic systems excited by a circularly polarised laser pulse. Our results show that the optical spin-orbit torque could exert torques on the spins comparable to the Zeeman torque.

[1] N. Tesarova et. al. Nature Photonics **7**, 492 (2013)
[2] R. Mondal et. al. Phys. Rev. B **92**, 100402(R) (2015)

MA 63.9 Fri 11:45 HSZ 403

Effective damping of terahertz spin-wave modes in iron — •Liane Brandt[1], Niklas Liebing[1], Ilya Razdolski[2], Roman Verba[3], Vasyl Tyberkevych[4], Andrei Slavin[4], Georg Woltersdorf[1], and Alexey Melnikov[1] — [1]Martin Luther University Halle-Wittenberg, Institute of Physics, Halle (Saale), Germany — [2]Fritz Haber Institute of the Max Planck Society, Department of Physical Chemistry, Berlin, Germany — [3]Institute of Magnetism, Kyiv, Ukraine — [4]Oakland University, Department of Physics, Rochester, USA

Recently, we have demonstrated the excitation of perpendicular standing spin waves (PSSW) in Fe/Au/Fe tri-layers studied by the time-resolved magneto-optical Kerr effect in a back pump-front probe scheme [1]. This high-frequency spin dynamic is driven by interface-confined spin transfer torque exerted by 250 fs-short spin current pulses generated in the optically excited emitter Fe layer [2]. The frequency of the PSSWs is tuned up to 2.5 THz by continuously reducing the thickness of collector Fe layer from 17 to 1 nm.

By analyzing the effective damping of the PSSW modes we observe an increase by two orders of magnitude in effective damping with increasing wave number. While the Gilbert damping is independent on the wave number, we can describe the increase in effective damping by the k-dependent spin diffusion term. Additional effects due to interfaces, defects in the volume and spin pumping appear to be small.

[1] I. Razdolski et al., Nat. Comm. 8, 15007 (2017)
[2] A. Alekhin et al., PRL 119, 017202 (2017)

MA 63.10 Fri 12:00 HSZ 403

Monte Carlo simulation of spin dynamics and spin transport in Iron (Fe) after femtosecond laser pulse irradiation — •Johan Briones, Sebastian Weber, Sanjay Ashok, and Baerbel Rethfeld — Department of Physics and Optimas Research Center, University of Kaiserslautern, Germany

The potential use of electronic spin, rather than charge, as carrier of information has brought into consideration the importance of understanding the complex phenomena of spin transport arising after a magnetic film is excited by a femtosecond laser pulse. After laser exciting the metalic ferromagnet, modeled by a spin-dependent density of states, we trace individual electrons undergoing multiple individual scatterings using a kinetic Monte Carlo model. We analyze the spin dynamics by considering the generation of secondary electrons (electronic cascade) and the exchange scattering as a spin-flip mechanism. The simulation has been performed for Fe and we discuss the implications of our results for the spin transport.

MA 63.11 Fri 12:15 HSZ 403

Spin-Hall Nano-oscillators, optimized shape and fabrication strategies — •Stephanie Lake[1], Philipp Dürrenfeld[1], Frank Heyroth[2], and Georg Schmidt[1,2] — [1]Institut für Physik, Martin-Luther-Universität Halle-Wittenberg, 06120 Halle, Germany — [2]Interdisziplinäres Zentrum für Materialwissenschaften, Martin-Luther-Universität Halle-Wittenberg, 06120 Halle, Germany

Spin Hall nano-oscillators (SHNOs), typically a bilayer device comprised of Pt and a thin film of ferromagnetic material, exhibit auto-oscillations when spin transfer torque cancels out the damping torque applied on magnetization precession. Several publications focused on Py-based SHNOs with nanoconstrictions (NCs) show that high frequency (HF) electrical signals can be generated by taking advantage of the anisotropic magnetoresistance (AMR) effect in Py[1]. However, practical use of these HF signals is challenging due to their low power[1]. To increase power, one can improve auto-oscillations in SHNOs by manipulating its geometry and material parameters.

This work is a systematic investigation of Py-based SHNOs fabricated using different electron beam lithography (EBL) strategies to optimize shape and size of the constriction. We show simulations of the static field within NCs for geometries we want to pattern with EBL and subsequent fabrication attempts. Furthermore, we obtain the AMR ratio and Gilbert damping constant of our devices. Understanding how EBL affects SHNO characteristics will allow for future optimization.

[1]Awad, A. A. *et al.*, *Nat. Phys.* **13**, 292299 (2016).

MA 63.12 Fri 12:30 HSZ 403

Controlled nonlinear magnetic damping in spin-Hall nano-devices — •Boris Divinskiy[1], Sergei Urazhdin[2], Sergej O. Demokritov[1], and Vladislav E. Demidov[1] — [1]University of Münster, Münster, Germany — [2]Emory University, Atlanta, USA

Large-amplitude magnetization dynamics is substantially more complex compared to the low-amplitude linear regime, due to the inevitable emergence of nonlinearities. One of the fundamental nonlinear phenomena is the nonlinear damping enhancement, which imposes strict limitations on the operation and efficiency of magnetic nanodevices. In particular, nonlinear damping prevents excitation of coherent magnetization auto-oscillations driven by the injection of spin current into spatially extended magnetic regions. Here, we propose and experimentally demonstrate that nonlinear damping can be controlled by the ellipticity of magnetization precession. By balancing different contributions to anisotropy, we minimize the ellipticity and achieve coherent magnetization oscillations driven by spatially extended spin current injection into a microscopic magnetic disk. Our results provide a route for the implementation of efficient active spintronic and magnonic devices driven by spin current.

References:

[1] B. Divinskiy et al., Nature Comm. 10, 5211 (2019)

MA 63.13 Fri 12:45 HSZ 403

Spin pumping at the ferromagnetic/paramagnetic phase transition of Fe monolayers — •Evangelos Th. Papaioannou, Camillo Ballani, Christoph Hauser, and Georg Schmidt — Institut für Physik, Martin-Luther-Universität Halle-Wittenberg, D-06120 Halle, Germany

Spin pumping is a powerful method to generate pure spin currents which are a key ingredient in spintronic devices. The microscopic nature of the spin current injection close to the magnetic phase transition is of great interest for future applications of magnetic nano-devices. The effect of spin pumping close to the magnetic phase transition has been only studied so far for paramagnetic insulating- and antiferromagnetic/Pt bilayers. On the contrary here, we show the effect of spin pumping and of inverse spin Hall effect (ISHE) undergoing a ferromagnetic to paramagnetic phase transition. We use ultra-thin Fe layers in Pd /Fe(1.2-1.7 monolayers)/Pd heterostructures with controllable Curie temperature. Temperature-dependent inverse spin Hall effect voltage measurements show that the ISHE signal remains persistent over a relatively wide temperature range above the Curie temperature. We correlate our spin pumping results to the spin correlation length and to the critical exponent of the transition. We discuss how spin pumping due to local magnetic order above the Curie temperature gives new insights into the pumping mechanism and how it can be turned into a simple microwave spin battery.