List of abstracts

Spin Caloritronics 7 Conference

11-15 July 2016, Utrecht, the Netherlands

Joseph Barker (Tohoku)

Title: *Atomistic investigations of magnetic insulators*

Abstract: We have been using the formalism of atomistic spin dynamics to investigate magnetic insulators such as YIG and GdIG which are used in spincaloritronics. The approach is based on the Heisenberg Hamiltonian and we faithfully recreate the magnetic unit cell of the materials. Thermodynamical properties can be sampled using Monte Carlo methods and dynamics can be studied by using the Landau-Lifshitz-Gilbert equation with a Langevin thermostat. The formalism allows the study of material specific effects which arise due to the spin wave spectrum or multiple sublattices which exist in these ferrimagnets. We will introduce new results from several different areas of research. In the area of Spin Hall magneto-resistance (SMR) we show how canted phases close to the compensation point can lead to a negative SMR signal. We will present a simple model of phonon-mediated exchange modulation and how this leads to a frequency dependent ultrafast demagnetization. Lastly we will report on our recent progress to introduce Bose-Einstein statistics (rather than Boltzmann statistics) to atomistic spin dynamics which will allow more qualitative as well as quantitative agreement between theory, numerics and experiments going forward.

Gerrit Bauer (Tohoku)

Title: *Magnon spin(calori)tronics*

Abstract: The essence of the spin Seebeck effect is the injection of a spin current into a normal metal by an electrically insulating ferromagnet under thermodynamic non-equilibrium conditions. The transverse voltages induced by the inverse spin Hall effect is the common technique to detect these spin currents. Evidence is mounting that spin Seebeck voltages are a sensitive instrument to detect spin correlations in ferromagnets that are not accessible by other techniques. This talk will address the basic physics behind selected recent experiments on ferrimagnetic yttrium iron garnet and its heterostructures.

Felix Casanova (CIC nanoGUNE)

Title: *Spin Hall effect in heavy metals: mechanisms, optimization, and related phenomena*

Abstract: The nascent field of insulating spintronics is based on the ability of ferromagnetic insulators (FMIs) to generate, process and transport spin information over long distances. Some phenomena explored in insulating spintronics include spin pumping [1,2], spin Hall magnetoresistance (SMR) [2,3], spin Seebeck effect [2,4], spin Peltier effect [5], magnetic gating of pure spin currents [6] or spin magnon transport [7].
A fundamental building block to observe and exploit these phenomena is the spin Hall effect (SHE), which converts charge currents into transverse spin currents, and vice versa, in non-magnetic metals (NM) with strong spin-orbit coupling (SOC) [8]. This is a very convenient way to create and detect pure spin currents. Finding routes to maximize the SHE is not possible as long as it remains unclear whether the dominant mechanism in a material is intrinsic or extrinsic. This issue has particularly been controversial in Pt, the prototypical SHE metal. To solve this issue, we systematically measured and analyzed the SHE in Pt with a wide range of conductivities using the spin absorption method in lateral spin valve devices [9]. We find a single intrinsic spin Hall conductivity (σ_{SH}^{int}=1600±150 Ω^{-1}cm^{-1}) for Pt in the full range studied which is in good agreement with theory. By tuning the conductivity, we observed for the first time the crossover between the moderately dirty and the superclean scaling regimes of the SHE, equivalent to that obtained for the anomalous Hall effect. Our results explain the spread of spin Hall angle values in the literature and find a clear path to enhance this important parameter [9].
We will also present a new type of magnetoresistance in NM thin films with strong SOC [10]. The spin accumulation created at the surfaces of the film by the SHE decreases in a magnetic field because of the Hanle effect. This novel *Hanle magnetoresistance* resembles SMR, although the presence of a FMI is not required. It is an alternative, simple way to quantitatively study the coupling between charge and spin currents in metals with strong SOC.
Another building block in insulating spintronics is the spin-mixing conductance, which governs the spin transport across the NM/FMI interface [2] and also plays a key role in the performance of hybrid devices. We study the importance of the interface details by measuring SMR in different Pt/FMI systems with complex surface magnetization such as spinel $CoFe_2O_4$ [11] or perovskite $LaCoO_3$, and spin magnon transport in Pt/YIG lateral devices with and without induced magnetic frustration at the YIG surface [12].

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Gyung-Min Choi[1,2], Chul-Hyun Moon[1,3], Byoung-Chul Min[1], Kyung-Jin Lee[3], and David G. Cahill[2]

[1]Center for Spintronics Research, Korea Institute of Science and Technology, Seoul 136-791, Korea
[2]Department of Materials Science and Engineering, University of Illinois, Urbana, Illinois 61801, USA
[3]Department of Materials Science and Engineering, Korea University, Seoul 136-701, Korea

Title: *Thermal spin transfer torque in metallic ferromagnets*

Abstract: The coupling of spin and heat gives rise to new physical phenomena in nanoscale spin devices. In particular, spin transfer torque (STT) driven by passing heat currents through magnetic layers provides a new way to manipulate local magnetization. Hatami *et al.* theoretically predicted thermally-driven STT in metallic spin valves [1]; Slonczewski suggested the initiation of thermally-driven STT in ferrite/metal structures and predicted a greatly enhanced quantum efficiency compared to charge-current-driven STT [2]. These new phenomena, namely, "thermal STT" rely on the transport of thermal energy, in contrast to the transport of electrical charge, and provide a new way to manipulate magnetization [1, 2]. To fully realize the envisioned advantages of thermal STT, it is important to observe thermal STT directly and quantify its sign and magnitude. Although thermal spin injections in ferromagnetic metal (FM)/normal metal (NM) [3], ferrite/NM [4], and FM/semiconductor [5] have been achieved, direct and conclusive evidence of thermal STT has remained elusive.

Here I provide direct evidence of thermal STT in metallic spin valves with the structure Pt/FM1/Cu/FM2. Heating by the ultra-fast pump optical pulse generates spin currents in the structure by two distinct mechanisms: i) volume spin generation in the FM1 layer by ultrafast heating and associated ultrafast demagnetization of FM1 [6]; ii) interfacial spin generation at the Pt/FM1 and FM1/Cu interfaces by heat current passing through the FM1 layer [7]. The spin-dependent Seebeck effect (SDSE) of FM1 converts the heat current into spin current. Both demagnetization-driven and SDSE-driven spin generation on FM1 can diffuse to FM2 and exert STT on FM2 magnetization.

The demagnetization-driven spin generation is due to thermal transport between electrons and magnons of FM1 and angular momentum conservation of electron-magnon coupling of FM1 [6]. The demagnetization-driven spin generation is significant for only the first ~3 ps after the pump optical pulse; 3 ps is approximately the time required for electrons, magnons, and phonons of FM1 to equilibrate.

The SDSE-driven spin generation is due to thermal transport between FM and NM at FM/NM interface [7]. In contrast to ultrafast demagnetization, the heat current passing through FM1 persists for a much longer time, ~100 ps, the time required for the various layers in the structure (Pt, FM1, Cu, and FM2) to equilibrate. The amount of SDSE can be controlled by the composition of FM1, which is a spin source layer, and thickness of Cu, which is a heat sink layer.

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Vladislav Demidov (Münster)

Title: *BLS study of SOT controlled magnetic dynamics in ultra-thin YIG films*

Abstract: One of the most important advantages of the spin-orbit torque (SOT) is the possibility to implement spin-torque devices based on insulating magnetic materials, such as Yttrium Iron Garnet (YIG). In the past years, the applicability of this material was limited by the large micrometer-range thickness of high-quality YIG films. Only very recently, with the developments in preparation of high-quality nanometer-thick YIG films, the implementation of insulator-based spin-torque devices became practically feasible.

Here we present our recent experimental results on the excitation and control of magnetization dynamics in 20-nm thick YIG films by using SOT. The experiments we performed by utilizing the micro-focus Brillouin light scattering (BLS) spectroscopy with the sub-micrometer spatial resolution. We demonstrate that SOT generated due to the spin-Hall effect in the adjacent Pt film can be used to increase the propagation length of spin waves in microscopic YIG waveguides by about a factor of 10. We also discuss the regime, where the SOT completely compensates the magnetic damping in YIG resulting in the onset of magnetic auto-oscillations. We show that the SOT-induced oscillations exhibit nonlinear behaviors opposite to those previously observed in all-metallic systems. In particular, with the increase in the driving current the auto-oscillating mode exhibits nonlinear spatial self-broadening, which is likely associated with the efficient mode coupling in low-loss insulating magnetic materials.

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Olena Gomanay (Mainz)

Title: *Antiferromagnetic domain wall motion in the presence of spin-polarized current and temperature gradient*

Abstract: Antiferromagnets (AF) are promising materials for spintronic because they show fast magnetic dynamics and low susceptibility with respect to magnetic fields. Application of AF as information storage devices implies fast and reliable switching between different states. In this presentation we focus on the domain wall motion as a main mechanism of the switching. We consider combined effects of the temperature gradient and spin current on the AF domain wall motion. We demonstrate that spin current splits the effective temperatures of the magnon gas in different domains and thus induces the magnon current equivalent to the thermal one. This mechanism can add to or compete with the entropic mechanism, that results from the temperature gradient. We show that tailoring of the device geometry can enhance or suppress the effective force that sets the AF domain wall into motion.

Joseph P. Heremans, Nikolas Antolin, Stephen R. Boona, Jack Brangham, Rembert Duine, Roberto C. Myers, Arati Prakash, Yaroslav Tserkovnyak, Sarah J. Watzman, Wolfgang Windl, Fengyuan Yang, Yuanhua Zheng,

Title: *Spin in thermoelectrics: from spin-Seebeck to magnon drag*

Abstract: Lucassen et al. [Appl. Phys. Lett. 99, 262506 (2011)] pointed out that the spin Seebeck effect (SSE) is closely related to the magnon-electron drag (MED) thermopower in metals. We expand on that relation, and develop semi-quantitative models for the MED thermopower of elemental Fe, Co and Ni and the anomalous Nernst coefficient of Fe. The theories have predictive power, as we illustrate when we use them to design the thermopower of ferromagnetic alloys of transition metals and then show experimentally that the alloys have a thermopower consistent with the predictions. The magnon drag thermopower is one to two orders of magnitude larger than the diffusion thermopower in these metals, a rare example of a spin-based effect dominating over a charge-based effect. We then show, using a new differential MED-thermocouple design, that the thermopower of a 6nm-thick Pt film grown on top of YIG is strongly influenced by the presence of an FM layer underneath the Pt, in what appears to be a non-local MED effect. Revisiting the spin Seebeck effects, we present data on SSE in the Pt/YIG/GGG tri-layer films that show a non-monotonic dependence of YIG thickness. We expand this to SSE measurements on 4-layer Pt/NiO/YIG/GGG system where we show the propagation of the magnons through the NiO, and antiferromagnet. We conclude by showing SSE contributions to the anomalous Nernst coefficient of FM/NM composites.

The work is funded by the US National Science Foundation MRSEC grant # DMR-1420451 and the US Army Research Office MURI grant # W911NF-14-1-0016

Christian Hess (IFW Dresden)

Title: *Spin-heat transport in low-dimensional quantum magnets*

Abstract: Spin-caloric transport phenomena of classical magnets have recently come into focus because new paradigms and applications of spin-information transport are expected. Some years ago, a new, magnetic mode of heat transport has been discovered in low-dimensional spin-1/2 *quantum* magnets and is intensely studied since then. The magnetic heat conductivity can be exceptionally large, even at room temperature, and thereby dwarfs the phonon heat conduction. In this talk, I will review the main experimental findings on spin-1/2 chains, ladders and planes. It will be shown that important conclusions about the exotic nature of the quasiparticles of the low-dimensional quantum magnets can be drawn from the analysis of the data, in particular their thermal excitation and their scattering.

Burkard Hillebrands (Kaiserslautern)

Title: *Magnon caloritronics*

Abstract: This tutorial will be devoted to spin caloritronic effects in magnetic insulators where magnons play a leading role. In the first part I will present the basics of magnonics including excitation of coherent and incoherent magnons with a focus on the interaction between magnons and phonons. This will be illustrated by recent research on the control of magnons in thermal landscapes, on magnonic heat conveyers, and on the generation of supercurrents in a magnonic macroscopic quantum state by a temperature gradient. In the last part I will address the generation and transport of non-equilibrium diffusive magnons in magnetic insulators. I will discuss thermal spin pumping and the correspondence between spatial and temporal behavior of the magnon Seebeck effect in a magnetic insulator.

Axel Hoffmann (Argonne)

Title: *Spin current generation and detection with antiferromagnets*

Abstract: Recently it has been recognized that antiferromagnetic materials can play a more active role beyond their traditional use for providing a reference magnetization direction via exchange bias. Namely, antiferromagnets may be conduits for spin currents, as well as, actively enable spin current generation and detection. With respect to the later, we demonstrated spin current generation both via spin Hall effects in conducting antiferromagnets and spin Seebeck effects in insulating antiferromagnets. Using CuAu-I-type metallic antiferromagnets (PtMn, IrMn, PdMn, and FeMn) we showed by using spin pumping that these alloys have significant spin Hall effects, which in the case of PtMn become comparable to the ubiquitously used Pt [1]. The spin Hall angles increase for the alloys with heavier element; a behavior that is well reproduced by first-principle calculations of the spin Hall conductivities based on intrinsic spin Hall effects. Furthermore, the calculations suggest pronounced anisotropies of the spin Hall conductivities, which we tested using spin transfer torque ferromagnetic resonance measurements using epitaxially grown antiferromagnetic films [2]. We observe that indeed the spin Hall conductivity is maximized for different growth orientations (a-axis for PtMn and PdMn, and c-axis for IrMn) in accordance with the first principle calculations. In addition using spin pumping measurements with permalloy/FeMn/W trilayers, we observe that there are two distinct mechanism for transporting a spin current in the metallic antiferromagnet, which we associate with electronic and magnonic spin transport, respectively. Lastly, using epitaxial MnF_2/Pt bilayers, we observe spin Seebeck voltages with distinct features due to the well-known spin-flop transition in MnF_2 [3].
This work was supported by the U.S. DOE, Office of Science, Materials Sciences and Engineering Division, DFG, the West Virginia Higher Education Policy Commission, U.S. NSF, and the WVU Shared Research Facilities.

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Hans-Gregor Hübl (Munich)

Title: *Incoherent magnon transport in non-local devices*

Abstract: The investigation of magnon transport in solid state systems allows to differentiate between two magnonic transport regimes. For example, coherent magnon transport is best described by the wave properties of the magnons, while transport of incoherently excited magnons shows similarities to diffusive processes known from electrons or phonons. This immediately triggers the question, whether these mechanisms allow for the implementation of magnon based logic devices in analogy to their electronic counterparts.
Recently, a device for studying incoherent magnon transport in the ferrimagnetic insulator yttrium iron garnet (YIG) was introduced, consisting of a platinum injector and detector, based on the spin-Hall and inverse spin-Hall effect, respectively [1,2].
We will discuss the local and non-local magnetoresistance properties for this device, and illuminate the implementation of logic-gate operations in this class of devices.

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Se Kwon Kim (UCLA)

Title: *Thermally-activated phase slips in superfluid spin transport in magnetic wires*

Abstract: We theoretically study thermally-activated phase slips in superfluid spin transport in easy-plane magnetic wires within the stochastic Landau-Lifshitz-Gilbert phenomenology, which runs parallel to the Langer-Ambegaokar-McCumber-Halperin theory for thermal resistances in superconducting wires [1]. To that end, we start by obtaining the exact solutions for free-energy minima and saddle points. We provide an analytical expression for the phase-slip rate in the zero spin-current limit, which involves detailed analysis of spin fluctuations at extrema of the free energy. An experimental setup for a magnetoeletric circuit is proposed, in which thermal phase slips can be inferred by measuring nonlocal magnetoresistance.

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M. Kläui (Mainz)

Title: *Engineering spin transmission in ferromagnetic insulator – metal heterostructures*

Abstract: The spin Seebeck effect (SSE) allows for the generation of thermally excited spin waves and thus enables one to probe a broad frequency distribution of magnon spectra [1, 2]. The occurring spin currents can be detected in an adjacent normal metal layer with the aid of the inverse spin Hall effect (ISHE).

In ferromagnetic insulator (FMI)/normal metal (NM) bilayers the temperature dependence of the SSE has been probed as a function of FMI thickness, different interfaces and detection materials [3]. At low temperatures, an enhancement of the SSE signal is observed, including the appearance of a peak in the amplitude (Fig. 1a). This enhancement clearly depends on the FMI thickness showing that bulk properties play a role. However the temperature dependence depends also strongly on the FMI/NM interface (Fig. 1b). This surprising dependence shows that different magnon modes have a different transmission probability depending on the interface. In order to obtain a better understanding of the influence of the FMI/NM interface, transmission electron microscopy (TEM) measurements combined with elemental analysis (EELS, EDS) are performed. We show that the atomistic structure of the interface depends strongly on the NM allowing us to correlate both [3]. Finally in ferrimagnets we can engineer the magnon modes and study their transmission probabilities into the NM [4].

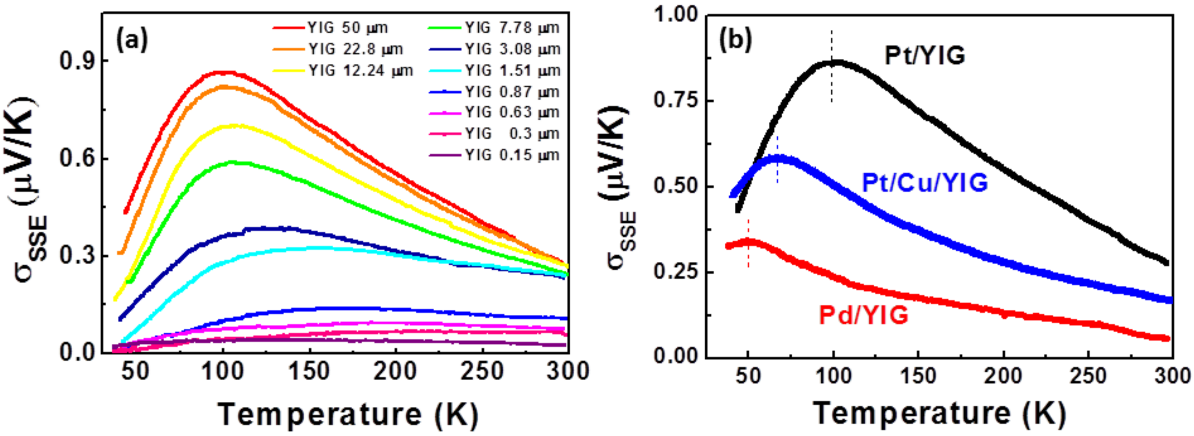

Figure 1. (a) Temperature dependent SSE coefficients (σ_{SSE}) of YIG thin films with a wide range of thicknesses. (b) Temperature dependent σ_{SSE} measured at Pt/YIG, Pt/Cu/YIG, and Pd/YIG hybrids. The thickness of YIG films is 50 μm.

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Olivier Klein (SPINTEC)

Title: *Controlling the damping inside a magnetic insulator*

Abstract: The recent discovery that spin transfer between a metal and a ferromagnet could be achieved using the spin-orbit effects [1,2] has created a great excitement in the community for two reasons: first, one could control electronically the damping of magnetic insulators, which can offer improved properties compared to metals, and here Yttrium Iron Garnet (YIG) has the lowest damping known in nature; second, the damping compensation could be achieved on very large objects, a particularly relevant point for the field of magnonics [3] whose aim is to use spin-waves as carriers of information. But most notably, none of these high-quality ultra-thin YIG films display a purely homogeneous FMR line. In such extended films, there are many degenerate modes with the main, uniform FMR mode, which through the process of two-magnon scattering broaden the linewidth. In this talk, we will demonstrate that the inhomogenous broadening decreases as the lateral size decreases due to alift the degeneracy between modes through confinement. We also show the key influence of the field orientation as well as the mode index number. By studying the dependence of the auto-oscillation threshold current at low bias field (where the inhomogeneous contribution dominates the broadening) for different disk size, we were able to demonstrate that the inhomogeneous broadening increases the threshold current. We also demonstrate that it is possible to reach full damping compensation [2] in micron-sized YIG discs of thickness 20~nm and we show clear evidence of coherent spin-orbit torque induced auto-oscillation.

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Jürgen König (Duisburg)

Title*: Unconventional superconductivity in quantum-dot systems*

Abstract: The formation of electron pairs is a prerequisite of superconductivity.
The fermionic nature of electrons yields four classes of superconducting correlations with definite symmetry in spin, space and time.
Here, we suggest double quantum dots coupled to conventional s-wave superconductors in the presence of inhomogeneous magnetic fields as a model system exhibiting unconventional pairing.
Due to their small number of degrees of freedom, tunable by gate voltages, quantum-dot systems are ideal to gain fundamental insight in unconventional pairing.
We propose detection schemes for superconducting triplet correlations, based on either Josephson or Andreev spectroscopy.

Bert Koopmans (Eindhoven)

Title: *Angular momentum transfer by femtosecond laser heating - local and non-local processes (tutorial)*

Abstract: Novel schemes for controlling the ferromagnetic state at the femtosecond time scale by pulsed laser excitation have received great current interest recently. Driving systems into the strongly non-equilibrium regime, it has been shown possible not only to quench magnetic order by femtoseond laser pulses, but also to drive systems from the anti- to ferromagnetic state, switch by circularly polarized light, and toggle-switch the ferrimagnetic state exploiting internal exchange interactions. More recently, it has been proposed that laser-induced super-diffusive spin currents over several to tens of nanometers can also be an important source of sub-picosecond magnetization dynamics. At present, the relative importance of local dissipation of angular momentum versus transfer of spin angular momentum between different regions in the laser excited material is hotly debated.

In this tutorial I will start by introducing the process of ultrafast loss of magnetic order upon fs laser heating, and discuss the local dissipation of angular momentum via Elliott-Yafet spin-flip scattering. Then I will distinguishing different mechanisms that give rise to laser-induced spin currents. Experiments on especially engineered multilayer systems that unambiguously demonstrate that -besides local dissipation- laser-induced inter-layer spin transfer does take place, will be presented. In particular I will address recent experiments that have demonstrated laser-induced *spin transfer torque* on a free magnetic layer, using a collinear multilayer configuration consisting of a free in-plane layer on top of a PMA injection layer and separated by a nonmagnetic spacer. Finally, attempts to treat both the local dissipation of angular momentum and the induced spin currents on equal footing will be discussed.

Ilya Krivorotov (UC Irvine)

Title: *Condensation of magnons driven by thermal gradients*

Abstract: A quasi-equilibrium gas of magnons can exhibit Bose-Einstein condensation at sufficiently high magnon density. The first demonstration of the magnon condensate employed microwave pumping for generation of high magnon density in a ferromagnetic insulator yttrium iron garnet (YIG) [1]. Advances in the field of spintronics create new efficient methods for magnon generation in insulating ferromagnets by pure spin currents arising from spin Hall [2] and spin Seebeck effects [3]. Recent theories predict the possibility of the magnon condensation under the action of thermal gradients applied across a ferromagnetic insulating film [4]. This talk will present experimental evidence of magnon condensation in YIG/Pt bilayer nanowires driven by the combined action of spin Hall current and thermal gradient simultaneously arising from high direct current density applied to the Pt layer. The condensate is detected via microwave signal emission from the YIG/Pt nanowire that abruptly appears above a threshold current. Sub-threshold measurements of magnetic damping via electrically detected spin wave resonance spectroscopy quantify the relative contributions of the spin Hall current and thermal gradient to the condensate formation. These measurements reveal that the thermal gradient can play the dominant role in the current-driven magnon condensation in YIG/Pt nanowire devices.

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[2] M. Collet et al., Nature Comm. 7, 10377 (2016)
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Patryk Krzysteczko (PTB)

Title: *Nanoscale detection of domain wall position by the anomalous Nernst effect*

Abstract: A number of emerging spintronic devices including racetrack memory and magnetic memristors are based on the movement of magnetic domain walls (DWs). Precise control of the positioning and motion of a single DW is paramount for their operation. One important approach for stabilising the position of a DW is to introduce artificial defects. On the other hand, the presence of intrinsic defects disturbs the smooth movement of DWs, and can jeopardise the functionality of the device.

Here, we introduce a new method for studying DW movement in nanowires with perpendicular magnetic anisotropy (PMA), based on the anomalous Nernst effect (ANE). We use sputter deposition and e-beam lithography to fabricate magnetic nanowires (NWs) with ultrathin CoFeB layers sandwiched between Pt. An additional Pt-nanoheater is placed at a distance of few microns to generate a temperature gradient across the magnetic NW. Due to ANE, a thermovoltage V_{ANE} is induced along the magnetic NW, perpendicular to both, the temperature gradient and the magnetisation of the magnetic NW: $V_{ANE} \sim M \times \Delta T$.

The thermovoltage V_{ANE} reflects the magnetisation of the entire wire. This means that not only the complete reversal of magnetisation can be detected, but also a partial reversal induced by the presence of a single DW placed at any position along the wire. V_{ANE} is thus directly proportional to the position of the DW.

We present studies of DW movement driven by uniform magnetic fields at various temperatures. Moreover, we use the tip of a magnetic force microscope to locally enhance the driving field. The latter scheme proves to be particularly powerful for studying DW movement in NWs with PMA. We discuss measurements showing DW pinning at intrinsic and extrinsic defects, and present DW position detection with a spatial resolution well below 100 nm.

Jacob Lidner (Trondheim)

Title: *Spin caloritronics with superconductors*

Abstract: It has recently been proposed and experimentally demonstrated that it is possible to generate large thermoelectric effects in ferromagnet/superconductor structures due to a spin-dependent particle-hole asymmetry. I will give an introduction to the underlying physics behind how this can be achieved in superconducting proximity structures and discuss which particular combinations of materials that may be suitable for this purpose. I will also show theoretically that when quasiparticle tunneling takes place between two thin-film superconductors in the presence of an in-plane magnetic field, the thermoelectric response is enhanced manyfold compared to when only one such superconductor is used, generating large Seebeck coefficients ($S > 1$ mV/K) and figures of merit ($ZT > 35$). Finally, I will discuss how one can induce pure spin currents thermally in superconducting structures and how these can be tuned.

Sadamichi Maekawa (JAEA)

Title: Spin Hall effects due to critical spin fluctuations

Abstract: Based on the skew scattering via collective spin fluctuations, it is proposed theoretically that the direct and inverse spin Hall effects (DSHE and ISHE) are unique tools to study spin fluctuations in metals [1].
The theoretical results are applied to the recent experiments in a weak ferromagnetic NiPd by Wei et al. [2] and a CuMnBi spin glass state by Niimi et al. [3].

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Brandon L. Giles[1], Zihao Yang[2], John Jamison[1], and **Roberto C. Myers**[1,2]

[1]*Dept. of Materials Science and Engineering*
[2]*Dept. of Electrical and Computer Engineering,*
The Ohio State University, Columbus, Ohio 43210, USA
Email: myers.1079@osu.edu

Title*: Scanning laser measurement of non-local magnon spin diffusion in YIG*

Abstract: The non-local spin-Seebeck measurement geometry isolates thermal transport from diffusive spin transport of magnons [1]. A focused laser spot thermally generates a magnon mediated diffusive spin current, which is converted to an electronic spin current in a remote Pt inverse spin Hall detector. By measuring the spin current amplitude that reaches the detector, the magnon spin diffusion process is mapped out as a function of laser position. Measurements of the spin current amplitude are fit to solutions to the two-dimensional spin diffusion equation taking into account the effect of spin-sinking allowing extraction of the magnon spin diffusion length. It is as large as 73 μm at 23 K, where laterally diffusing magnon spins are detectable at distances greater than 120 μm. This length scale is much longer than the inelastic scattering length at the same conditions (4 μm) [2], indicating that magnons, like electrons, maintain their spin information over many scattering events. Temperature dependent measurements of the magnon spin diffusion process in YIG from 300 K to 10 K will be presented and compared with all electronic non-local spin diffusion measurements in YIG [3].

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Kouki Nakata (Basel)

Title: *Magnon transport in insulating magnets: Wiedemann-Franz law, Josephson effect, and persistent quantized currents*

Abstract: Quantum-statistical mechanics provides two kinds of particles; bosons and fermions. Electrons are fermions bounded by the Pauli exclusion principle, while magnons are bosons free from it. Still, can magnons flow and propagate like electrons?
The answer is 'YES'. We [1] found the magnon counterparts of electron transport; the Wiedemann-Franz law for magnon transport, the Onsager reciprocal relation between the magnon Seebeck and Peltier coefficients, magnon Josephson effects in quasi equilibrium condensation and the quantized persistent current by Aharonov-Casher effects, and the quantum Hall effect of magnons etc.
We discuss them in detail, and clarify the differences between condensed and non-condensed magnon transport. We thus provide the universal thermomagnetic relation for magnon transport and give you a handle to electromagnetically control magnon transport [2].

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Current-induced asymmetric magnetoresistance via spin flip scattering

K. –J. Kim[1], T. Moriyama[1], T. Koyama[2], D. Chiba[2], S. –W. Lee[3], S. –J. Lee[4], K. –J. Lee[3,4], H. –W. Lee[5], & T. Ono[1*]
[1]Institute for Chemical Research, Kyoto University, Gokasho, Uji, Kyoto, 611-0011, Japan
[2]Department of Applied Physics, Faculty of Engineering, The University of Tokyo, Bunkyo, Tokyo 113-8656, Japan
[3]Department of Materials Science and Engineering, Korea University, Seoul 136-701, Republic of Korea
[4]KU-KIST Graduate School of Converging Science and Technology, Korea University, Seoul 136-713, Republic of Korea
[5]PCTP and Department of Physics, Pohang University of Science and Technology, Pohang 790-784, Korea
*ono@scl.kyoto-u.ac.jp

In ferromagnet (FM)/heavy metal (HM) bilayer structures, the interface-related spin orbit coupling (SOC) induces very intriguing phenomena such as spin Hall (SH) effect, Rashba effect and Dzyaloshinskii-Moriya interaction (DMI). Recently, studies of transport properties in FM/HM bilayers have been performed and revealed several novel magnetoresistance (MR) effects such as SH MR [1], hybrid MR [2] and anisotropic interface MR [3], unidirectional SH MR [4], all of which originate from the interfacial SOC. Such kind of MR involving in bilayer structures are of importance because it is essential for electro-magnetic device application of bilayer, as the giant magnetoresistance of a spin-valve device does.

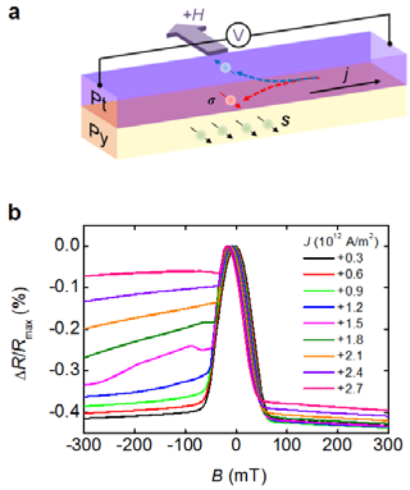

Figure 1. (a) Schematics of bilayer structure (b) Magnetoresistance as sweeping the magnetic field B for various current densities J as denoted in the figure.

Here, we report a novel MR in FM/HM bilayer structures. It is found that anisotropic magnetoresistance (AMR) versus H becomes asymmetric with respect to H = 0 under the action of spin current that is injected from HM to FM via spin Hall effect [Fig.1]. The asymmetry in AMR has unique characteristics: sign of the asymmetry reverses when the direction of either magnetic field or current is inverted, and the magnitude of the asymmetry is gradually enhanced with increasing current. The magnitude of asymmetric MR increases with increasing temperature [5].

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Thomas Palstra (Groningen)

Title: *Electrical detection of spiral spin structures in Pt/Cu2OSeO3 heterostructures*

Abstract: We report the spin-Hall magnetoresistance (SMR) sensitive to the surface magnetization of the spin-spiral material, Cu2OSeO3. We experimentally demonstrate that the angular dependence of the SMR changes drastically at the transition between the helical spiral and the conical spiral phases. Furthermore, the sign and magnitude of the SMR in the conical spiral state are controlled by the cone angle. We show that this complex behaviour can be qualitatively explained within the SMR theory initially developed for collinear magnets. In addition, we studied the spin Seebeck effect, which is sensitive to the bulk magnetization. It originates from the conversion of thermally excited low-energy spin waves in the magnet, into the spin current in the adjacent metal contact (Pt). The SSE displays unconventional behavior where not only the magnitude but also the phase of the SSE vary with the applied magnetic field.

Thermal spin currents in magnetic heterostructures

G. Reiss[1], A. Böhnke[1], M. Glas[1], D. Meier[1], T. Kuschel[1,2], Ch. Klewe[1,3], H.W.Schumacher[4], S. Serrano-Guisan[5], M. Walter[6], M. Münzenberg[6]

[1] Department of Physics, Universität Bielefeld, 33615 Bielefeld, Germany
[2]Physics of Nanodevices, Zernike Institute for Advanced Materials, University of Groningen, 9747AG Groningen, The Netherlands
[3]Advanced Light Source, 6 Cyclotron Rd, Berkeley, CA 94720, USA
[4]Physikalisch-Technische Bundesanstalt, 38159 Braunschweig, Germany
[5]International Iberian Nanotechnology Laboratory, 4715-330 Braga, Portugal
[6]I. Physikalisches Institut, Georg-August-Universität Göttingen, 37077 Göttingen, Germany and Institut für Physik, Ernst-Moritz-Arndt-Universität Greifswald, 17489 Greifswald, Germany

Author email: reiss@physik.uni-bielefeld.de
Keywords: Spinelectronics, Spincaloritronics, Magnetoresistance.

Abstract. Spin-electronics and -caloritronics are rapidly developing and many new effects have been observed such as the Spin-Seebeck effect, SSE [1], the Tunneling Magneto Seebeck Effect (TMS) [2] or spin transfer torque switching (STT) at ultralow current density [3].

The first part will discuss the tunneling magnetoresistance (TMR) and tunneling magneto Seebeck effect (TMS) in magnetic tunnel junctions. We present results on the TMS obtained for CoFeB and Heusler compounds, discuss time-resolved experiments [4] and aspects of a possible intrinsic TMS. For TMR devices with ultrathin MgO barrier, we demonstrate arbitrarily low "critical current" for magnetization switching down to a few 10 A/cm².

This effect (shown in figure 1) will be discussed in terms of temperature- and voltage-driven anisotropy changes. In relation with the thermally driven spin currents, the possibility to achieve sizeable thermally driven spin transfer torque will be evaluated [3].

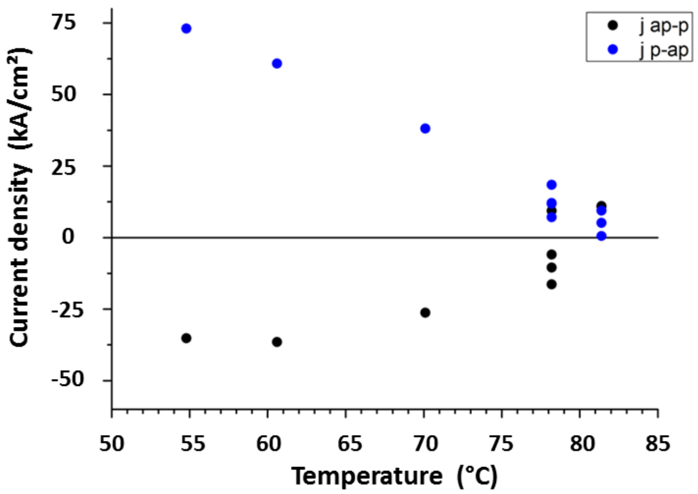

Figure 1: The critical current density for switching the magnetization in $CoFeB_{1nm}/MgO_{0.9nm}/CoFeB_{1.2nm}$ MTJs as a function of temperature. Puls time was ≈ 1msec. Close to the vanishing $H_c^{\perp}$ above 75°C, thermally activated magnetization switching occurs.

The second part will discuss the SSE in transverse and longitudinal geometry. We demonstrate the LSSE and its dependence on the base temperature in insulating and semiconducting ferromagnets [5] and use X-ray resonant magnetic reflectivity to exclude proximity induced magnetization in Pt [6]. Finally, we show that the voltage detected at a Pt stripe on $NiFe_2O_4$ or YIG that was attributed to a "TSSE" is most probably due to unintended out-of-plane temperature gradients [7].

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Eiji Saitoh (Tohoku)

Title: *Spin current generators*

Abstract: Generation and utilization of a flow of spin angular momentum of electrons in condensed matter, called spin current, are the key challenge of today's nano-scale magnetism and spintronics. The discovery of the inverse spin Hall effect (ISHE) [1-3], the conversion of spin current into electric voltage via spin-orbit interaction, has allowed researchers to detect and utilize spin current directly, and, since then, many spin-current driven effects have been discovered by exploiting the ISHE. Here, such newly discovered spin-current effects will be outlined, including light-spin conversion [1,4], plasmon-spin conversion, sound-spin conversion, and heat-spin conversion [5-6], and their common mechanism and future possible application will be discussed. Among them, a typical conversion effect is the spin Seebeck effect (SSE) [5], spin current generation from a temperature gradient. SSE has attracted a great deal of interest since it may realize new type thermo-electric convertors which make full use of the characteristic feature of spins: the non-reciprocal dynamics. This non-reciprocity allows a spin to rectify thermal fluctuation into unidirectional spin current via the spin pumping mechanism, which can be converted into electric power via the ISHE. Spins, working as a natural rectifier in magnets, may thus provide a versatile mechanism of energy conversion in condensed matter. I will show also that the rectification mechanism underlies various spin related phenomena which were found recently. At the end of my talk, spin current generation from mechanical motion of condensed matter will be discussed.

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Spin current in antiferromagnets and multiferroics

Shinichiro Seki[1]

[1] RIKEN Center for Emergent Matter Science (CEMS)
shinichiro.seki@riken.jp

Recently, spin waves in insulating materials have attracted attention as the efficient carrier of spin current characterized by the longer propagation length as compared to the conduction electrons in metallic or semiconducting systems[1, 2]. Previously, the study of such spin wave spin current has mostly been performed for a limited number of simple room temperature ferromagnetic insulators, such as garnet, spinel and hexaferrites. However, the majority of insulating materials are rather antiferromagnetic, and it is crucial issue whether the spin waves in antiferromagnets can carry spin current or not.

In this talk, I introduce our recent experimental detection of thermally-induced spin current (i.e. longitudinal spin Seebeck effect) in antiferromagnet Cr_2O_3[3] and helimagnet $Ba_{0.5}Sr_{1.5}Zn_2Fe_{12}O_{22}$[4]. This finding proves that the spin waves in antiferromagnets can be an effective carrier of spin current. Here, both compounds are also known to host spin-driven ferroelectricity, which enables the alignment of antiferromagnetic or helimagnetic domain by applying external electric field. Such an alignment of antiferromagnetic domain doesn't affect the magnitude of thermally-induced spin current, suggesting that spin-wave spin current is rather robust against the antiferromagnetic domain wall unlike the case with the conventional ferromagnetic domain wall.

If time allows, I will also discuss the diode effect of spin wave propagation in multiferroic materials with noncentrosymmetric crystal lattice, where the spin wave propagating parallel and antiparallel to external magnetic field can show different propagating character due to the contribution of Dzyaloshinskii-Moriya interaction[5].

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Jing Shi (UC Riverside)

Title: *Spin Seebeck effect in magnetic insulator/topological insulator heterostructures*

Abstract: Spin-momentum locked surface states in topological insulators plays a unique role in the magnon-electron relaxation process which results in efficient spin-charge voltage conversion. We demonstrate this effect in heterostructures of topological insulator, (BixSb1-x)2Te3, and magnetic insulator yttrium iron garnet under a temperature gradient. An unusually large spin Seebeck response is found as the Fermi level of the topological insulator is tuned into the band gap where the topological surface states dominate the transport. We attribute this effect to the spin-momentum locking property of the surface states. I will present our recent spin Seebeck experimental results with gating.

Oleg Tchernyshyov (Johns Hopkins University)

Title: *Propulsion of a domain wall by magnons in an antiferromagnet*

Abstract: Domain walls in magnetic nanowires can be used to store information and perform logical operations. Whereas the mechanism of domain wall propulsion in ferromagnet (by an applied field, spin-polarized current, or a flux of magnons) are well understood, much less is known about the antiferromagnetic domain walls.
We analyze the dynamics of a domain wall in an easy-axis antiferromagnet driven by a current of circularly polarized magnons. Magnons pass through a stationary domain wall without reflection and thus exert no force on it. However, they reverse their spin upon transmission, thereby transferring two quanta of angular momentum to the domain wall and causing it to precess. A precessing domain wall partially reflects magnons back to the source. The reflection of spin waves creates a previously identified reactive force. We point out a second mechanism of propulsion, which we term redshift: magnons passing through a precessing domain wall lower their frequency by twice the angular velocity of the domain wall; the concomitant reduction of magnons' linear momentum indicates momentum transfer to the domain wall. We solve the equations of motion for spin waves in the background of a uniformly precessing domain wall with the aid of supersymmetric quantum mechanics and compute the net force and torque applied by magnons to the domain wall. Redshift is the dominant mechanism of propulsion at low spin-wave intensities; reflection dominates at higher intensities. We derive a set of coupled algebraic equations to determine the linear velocity and angular frequency of the domain wall in a steady state.

Yaroslav Tserkovnyak (UCLA)

Title: *Transport and condensation of thermally-pumped magnons*

Abstract: Spin and heat transport mediated my magnons will be discussed in layered heterostructures based on magnetic insulators. While the physics at interfaces is governed by the isotropic exchange coupling (as captured by the spin-mixing conductance), spin transport and torques away from the interfaces are crucially modified by the relativistic spin-orbit interactions. In this talk, I will review the following set of topics in a unified theoretical framework: (1) Interfacial spin and heat transfer between metals and magnetic insulators, including the longitudinal spin Seebeck/Peltier effects as well as the transverse torque/pumping, (2) Thermally-driven spin torques in layered magnetic insulators, with a focus on magnonic torques exerted by an out-of-equilibrium magnon ensemble, and (3) Bose-Einstein condensation of magnons pumped by the bulk spin Seebeck effect. The key emphasis will be on the interplay between the incoherent (e.g., thermal) and coherent (e.g., superfluid) magnetic dynamics.

Bart van Wees (Groningen)

Title: *Non-local magnon spin transport in ferromagnetic insulators*

Abstract: I will give an overview of our recent results on the transport of magnon spins in the ferrimagnetic insulator yttrium iron garnet (YIG). Magnons can be injected electrically as a response to the spin accumulation generated in a Pt strip due to the spin Hall effect. Joule heating in the injector strip results in thermal generation of magnons, due to the bulk spin Seebeck effect. It is shown that both mechanisms result in the creation of a non-equilibrium magnon accumulation which can propagate over a magnon spin relaxation length which is typically 10 micrometer at room temperature [1]. Non-local detection is employed where the magnon spin accumulation is converted back into a charge signal using the inverse spin Hall effect.
Recent results have shown that this length is reduced as a function of applied magnetic field [2]. The temperature dependence of the magnon spin relaxation length shows a weak dependence in the temperature interval 2K-200K. The magnon spin conductivity is reduced considerably when reducing the temperature, which results from the interplay of the reduction of the number of magnons, together with an increase in the magnon mean free path [3].
Measurements of the non-local signal as a function of the YIG thickness in the range 0.2 micrometer-50 micrometer show a counterintuitive result, where the non-local signal decreases with increasing YIG thickness. These results cannot be explained with a isotropic magnon diffusion/relaxation model [4], and indicate that the magnon injection/detection process is not fully understood [5]. Implications for further research will be discussed.

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Vatalij Vasyuchka (Kaiserslautern)

Title: *Influence of a thermal gradient on parametric excitation of magnons*

Abstract: The influence of a possible spin transfer torque induced by the longitudinal spin Seebeck effect on the parametric generation of magnons is studied. The excitation of magnons by the parametric pumping is characterized by a power threshold at which the inflow of energy into the magnetic system overcomes the spin-wave damping. Therefore, as soon as the threshold is overcome for a distinct magnon mode with minimal damping, magnons in this mode are generated. An influence by the longitudinal spin Seebeck effect on the damping parameter would thus lead to a shift in the threshold power, which can be precisely measured. Moreover, such influence can be probed for a wide range of magnon wavelengths since they can be easily controlled by changing the applied external magnetic field.
Investigations were performed on a 6.7 µm thick yttrium iron garnet sample covered by a 5 nm thick platinum film that is clamped between two separately controlled Peltier elements. The threshold power for the generation of magnons using a pumping frequency of 14 GHz was measured with respect to the applied external magnetic field, firstly changing the temperature of the sample homogeneously and in a second step with an applied temperature gradient perpendicular to the sample plane where the pronounced longitudinal spin Seebeck effect is present. Precise measurements of the threshold power behavior reveal that there is no measurable influence of the longitudinal spin Seebeck effect on the parametric excitation threshold in a wide range of magnon wavelengths down to 100 nm, whereas a homogeneous temperature change largely influences this threshold power in the whole range.
Financial support by Deutsche Forschungsgemeinschaft within SPP 1538 “Spin Caloric Transport” is gratefully acknowledged.

Ke Xia (BNU)

Title: *Spin transfer torques and spin-orbit interaction at interfaces between metals and magnetic insulators*

Abstract: $CoFe_2O_4$ (CFO), a ferrite with spinel crystal structure, is a ferrimagnetic insulator. By first principles calculations we predict eff ective spin mixing conductances for gold and platinum contacts to CFO that are anisotropic in the presence of spin-orbit coupling. For the CoO-terminated interface in the (001) direction, the spin orbit coupling strongly enhances the spin mixing conductance. And it indicated that the local density of state of the normal metal enhanced by the spin-orbit coupling around the interface plays a very important role in the spin mixing conductance.

Barry Zink (Denver)

Title: *Extreme thermal engineering in non local spin valves*

Abstract: The thermal generation of pure spin currents in metallic systems remains a central goal in spincaloritronics, with the promise of producing pure spin current sources that could easily be integrated in nanoelectronic circuits. Recent efforts understandably focus on devices where the thermal gradients and resulting spin current phenomena are generated on length scales comparable to the spin diffusion length in metallic ferromagnets. These several-nanometer lengths can be probed using nanolithographically patterned non-local spin valves (NLSV), which have been used to demonstrate thermal spin injection or the spin-dependent Seebeck effect (SDSE). In this talk we describe our recent work on the SDSE in similar structures. We discuss two main areas of study: our work to understand interfacial effects in thermal spin injection in the NLSV, and fabrication and testing of ``extreme" thermal engineering of the NLSV. The first topic overviews our observation of insensitivity of the SDSE to contamination of the FM/NM surface and our first efforts to manipulate and understand this interface. The second describes our fabrication of the thermal spin injection device on a suspended silicon-nitride membrane, dramatically altering heat flow in this nanoscale system and leading to several revealing results including a significant modification of Nernst effects that can contribute to thermal signals in the NLSV. This talk includes the work of Ph.D. students A. Hojem and D. Wesenberg, and the research is supported by the US National Science Foundation (DMR and ENG).