DFG priority programme 1538
Spin Caloric Transport

Program for the

2^{nd} SpinCaT PhD workshop

08.-09.10.2012
in
Göttingen

Contents

Monday, 08.10.2012

1 Invited Talks

1.1 09:15-10:00

Thermal spin effects in tunnel junctions: Ab initio calculations

Ch. Heiliger[1]

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The first part of the talk will briefly discuss different approaches for the calculation of transport properties in nanostructured materials. Thereby, I will talk about different length scales from atomistic to macroscopic models.

In the second part of my talk I focus on the novel field of spincaloritronics which combines thermal and spin-dependent effects. In particular, some basic effects like magneto-Seebeck and thermal spin-transfer torque will be explained. In addition, I present first ab initio results of these quantities in MgO based tunnel junctions.

1.2 10:00-10:45

Spin-dependent thermo-galvanic effects

Sebastian T. B. Gönnenwein[1]

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A pure spin current – i.e., the directed flow of spin angular momentum – is a fascinating manifestation of spin physics in the solid state. In ferromagnet/normal metal hybrid bilayers, pure spin currents can be generated, e.g., by means of spin pumping [1], or via the application of thermal gradients in the so-called spin Seebeck effect [2]. Interestingly, both of these approaches hinge on non-equilibrium, "hot" magnetization states in the ferromagnet, and thus are at the heart of the emerging field of spin caloritronics.

In the talk, I will introduce and compare our recent experimental investigations of pure spin currents in ferromagnet/normal metal hybrid devices. We took advantage of the spin pumping process driven by either coherent microwave photons or phonons [3, 4], as well as by local thermal gradients [5] to induce pure spin currents in these hybrid structures, and exploited the inverse spin Hall effect to detect the spin current in the normal metal layer. Our results show that spin current generation is possible from both electrically conductive as well as electrically insulating ferromagnets (so-called magnetic insulators), with comparable efficiency. Moreover, local spin currents with magnetically controllable polarization are obtained upon locally exciting the ferromagnetic layer. This opens interesting perspectives for the study and the exploitation of pure spin currents in particular in electrically insulating magnetic materials. Last but not least, I will critically compare the spin-dependent thermo-galvanic voltages induced by spin currents in combination with the inverse spin Hall effect in spin Seebeck-type experiments to the conventional magneto-thermo-galvanic potentials induced by charge transport in conductive ferromagnets.

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[2] K. Uchida et al. "Spin Seebeck insulator." In: *Nat. Mater.* 9 (2010), pp. 894–897.

[3] F. D. Czeschka et al. "Scaling Behavior of the Spin Pumping Effect in Ferromagnet-Platinum Bilayers." In: *Phys. Rev. Lett.* 107 (2011), p. 046601.

[4] M. Weiler et al. "Spin Pumping with Coherent Elastic Waves." In: *Phys. Rev. Lett.* 108 (2012), p. 176601.

[5] M. Weiler et al. "Local Charge and Spin Currents in Magnetothermal Landscapes." In: *Phys. Rev. Lett.* 108 (2012), p. 106602.

2 Contributed Talks

2.1 11:30-11:50

Thermally Induced Magnonic Spin Currents and Domain Wall Motion

U. Ritzmann[1], Denise Hinzke[1] and U. Nowak[1]

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Recently, it has been demonstrated that in ferromagnetic insulators spatial temperature gradients can lead to magnon accumulation [1]. This underpins the fact that in addition to spin polarized charge currents due to electron motion also chargeless angular momentum currents driven by spin waves can exist. The latter current leads to pure magnonic effects without any charge currents involved.

We investigate domain wall dynamics driven by magnonic spin currents due to temperature gradients. To get some insight into this new effect two different approaches for the simulation of coupled thermo-magnetic properties are introduced: the stochastic Landau-Lifshitz-Gilbert equation, applied to atomistic spin models, and the Landau-Lifshitz-Bloch equation describing the dynamics of the thermally averaged spin polarization on micromagnetic length scales.

We find a new type of domain wall dynamics, where pure spin currents resulting from a temperature gradient drag a domain wall into the hotter region. In the limit of low damping constants and large temperature gradients this domain wall motion is accompanied by precession and a Walker breakdown occurs [2].

Continuing our investigation we focus on a better understanding of the relevant length scales of magnonic spin currents. We explore the propagation of thermally induced magnons, the magnon accumulation, and calculate the magnon temperature for a given phonon temperature profile. Furthermore, we determine the frequencies generated and the propagation range of these thermal spin waves. An analysis of the spin accumulation for given phonon temperature gradients dependent on the thickness of the system shows finite-size effects for thicknesses smaller than the magnon propagation length.

We acknowledge financial support by the DFG through SFB 767 and through SPP "Spin Caloric Transport".

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[1] K. Uchida et al. “Spin Seebeck insulator.” In: *Nat. Mater.* 9 (2010), pp. 894–897.

[2] D. Hinzke and U. Nowak. “Domain Wall Motion by the Magnonic Spin Seebeck Effect.” In: *Phys. Rev. Lett.* 107 (2011), p. 027205.

2.2 — 11:50-12:10

Thermally excited magnonic spin currents probed by the longitudinal spin-Seebeck effect in YIG

Andreas Kehlberger[1], René Röser[1], Gerhard Jakob[1], Ulrike Ritzmann[2], Denise Hinzke[2], Dong Hun Kim[3], Caroline Ross[3], Ulrich Nowak[2] and Mathias Kläui[1]

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[2] *Department of Physics, University of Konstanz, Germany*
[3] *Department of Materials Science and Engineering, Massachusetts Institute of Technology, Cambridge MA, USA*

The spin-Seebeck effect has drawn much attention to the research of thermally induced spin currents in magnetic systems. In contrast to its conventional equivalent (charge Seebeck effect), the spin Seebeck effect (SSE) was also measured in ferromagnetic insulators [1], which points to an underlying effect that is related to magnonic spin currents in the ferromagnetic system. While most thin film studies focus on lateral geometries by applying an in-plane thermal gradient, recently it has been shown, that in this geometry the heat conductance between the substrate and the ferromagnetic film plays an important role and unwanted thermoelectric effects, such as the anomalous Nernst effect can occur [2]. Furthermore the anisotropic magneto resistance effect in the non-magnetic spin current detector (platinum) needs to be subtracted, to obtain the genuine signal of the SSE.

Our work focuses on the longitudinal spin Seebeck effect in different thickness Yttrium Iron Garnet (YIG) films epitaxial grown on GGG by pulsed laser ablation. Compared to lateral setups, our out-of-plane setup is not sensitive to a heat conductance difference between substrate and ferromagnetic film and allows us to purely probe the spin seebeck effect by also subtracting the AMR in the Pt.

Figure a) shows the size of the inverse Spin Hall signal as a function of the angle (0° corresponds to magnetization parallel to the voltage contacts that sense the spin current). In b) the SSE signal is shown for 0° and as expected in the saturated state the difference is zero. In the low field regime, there is a clear signal that corresponds to the switching of the magnetic domains with transverse magnetization so that we can use this to sense the reversal mode of the YIG.

We have measured different thickness YIG films, and we find a systematic thickness dependence of the spin-Seebeck effect. Corresponding simulations on atomistic length scales support this behavior and deduce it from a propagation length of the thermally excited magnons that carry the spin current. This work is supported by the DFG priority program SPP 1538 Spin Caloric Transport.

References

[1] K. Uchida et al. "Spin Seebeck insulator." In: *Nat. Mater.* 9 (2010), pp. 894–897.

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2.3 12:10-12:30

Magnon Temperature Measurement in Magnetic Insulators

M. Agrawal[1], V. I. Vasyuchka[1], A. A. Serga[1], B. Hillebrands[1] and G. A. Melkov[2]

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[2] *Department of Radiophysics, National Taras Schevchenko University of Kiev, Ukraine*

The study of the magnon-phonon interaction is a baseline for the emerging field of spin caloritronics [1]. The magnon and phonon temperature distributions in ferromagnets can explain the thermal spin transport phenomena like the spin Seebeck effect [2]. These phenomena have been recently studied electrically by measuring the induced inverse spin Hall voltage in Platinum (Pt) stripes placed over the ferromagnets, however, the underlying physics is yet not fully understood. Different experiments and theories have demonstrated the role of phonons, magnons and magnon-phonon interaction behind these phenomena in magnetic metals, semiconductors, and insulators. Here, we develop a new route for measuring the spatial distribution of phonon and magnon temperatures in a magnetic insulator subject to a lateral thermal gradient by studying the variation of the local magnetization of the system. The local magnetization variation is detected by measuring the frequency shift of exchange-dominated thermal spin waves using the Brillouin light scattering technique. Our results demonstrate the close similarity in the spatial profiles of the phonon and the magnon temperature distributions and reveal that the contribution of exchange magnons to the spin Seebeck effect is negligible at room temperature. Furthermore, the experimental data is interpreted with the existing theoretical models [3, 4] and the length scale of magnon-phonon interaction is determined.

References

[1] G. E W Bauer, E. Saitoh, and B. J. van Wees. "Spin caloritronics." In: *Nat Mater* 11 (2012), pp. 391–399.

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2.4 13:30-13:50

Heat-induced spin-transfer torque in YIG/Pt bilayer structures

M. B. Jungfleisch[1], T. An[2], K. Ando[2], Y. Kajiwara[2], K. Uchida[2], V. I. Vasyuchka[1], A. V. Chumak[1], A. A. Serga[1], B. Hillebrands[1] and E. Saitoh[2]

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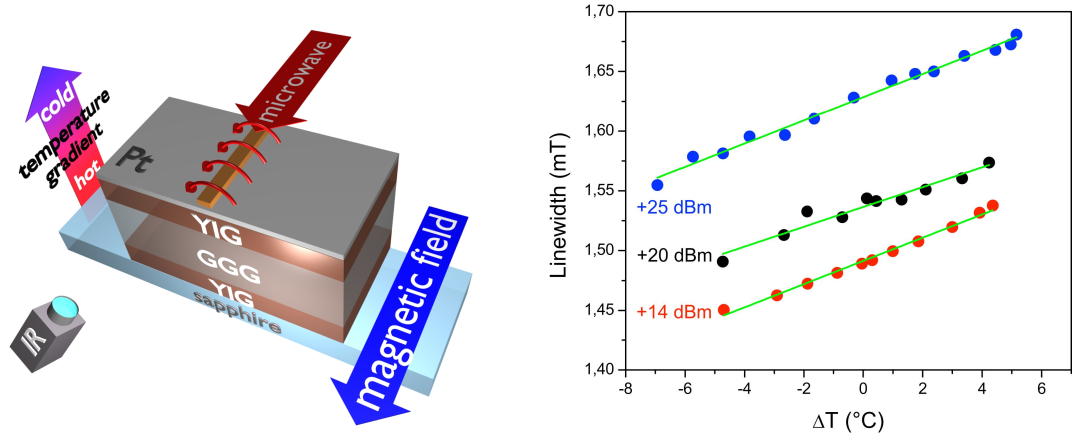
[2] *Institute for Materials Research, Tohoku University, Sendai, Japan*

In this presentation, we report on the heat-induced spin-transfer torque in a magnetic insulator/non-magnetic metal structure. Using a temperature gradient along the thickness of an yttrium iron garnet/platinum (YIG/Pt) bi-layer, we demonstrate the manipulation of magnetization relaxation. This manipulation is detected by spin pumping into an adjacent Pt layer and the subsequent conversion into a charge current by the inverse spin Hall effect [1, 2].

The applied temperature gradient leads to the spin Seebeck effect: an imbalance between the magnon and the electron temperature, which results in the generation of a spin current across the YIG/Pt interface [3]. This spin current accompanies transfer of angular momentum and exerts a torque on the magnetization in the YIG layer. As a result, the magnetization dynamics can be controlled: either the damping is increased or decreased. This change of damping is equivalent to a change of the ferromagnetic resonance linewidth, which can be measured by spin pumping. The investigated sample is a 2.1 μm thick YIG waveguide grown on a 500 μm thick gadolinium gallium garnet substrate (GGG) by liquid phase epitaxy. A 10 nm thick Pt layer is deposited on top by molecular beam epitaxy (Fig. 2.1a). Magnetization precession is excited by a 50 Ohm loaded copper microstrip antenna and the temperature gradient is established by a Peltier element, which is mounted on the Pt capped sample surface. The opposite side is covered by a sapphire substrate connected to a heat bath. Using an infrared camera we monitor



(a) **(b)**

Figure 2.1: Experimental setup (a), linewidth as a function of the applied temperature gradient for different microwave powers (b).

the sample temperature (sapphire is transparent for infrared radiation). Magnetization precession is excited by microwave signals of 4 GHz and different powers (+14 dBm, +20 dBm, +25 dBm). In the presence of a temperature gradient, the magnetic field is swept and the inverse spin Hall voltage across the Pt layer is detected. The change of the linewidth as a function of the applied temperature gradient is shown in Fig. 2.1b. For all microwave powers the same behavior is visible: if the Pt is hotter than the YIG, the linewidth is decreased, while it is increased for the opposite case. For higher microwave powers the linewidth increases due to non-linear effects.[4]

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2.5 13:50-14:10

Cooling nano-devices by spin-polarized currents

J. Brüggemann[1] and M. Thorwart[1]

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We theoretically analyze a cooling scheme for nano-devices based on spin-polarized currents using a Master equation approach. In analogy to the macroscopic demagnetization cooling a quantum dot is magnetized using a spin-polarized current. Free evolution of the magnetized system leads to demagnetization and should - due to coupling between mechanical and electronic degrees of freedom - lead to a decrease in the phonon temperature. Using real-time diagramatic pertubation theory we aim to determine the full dynamics of the system.

2.6 14:10-14:30

The temperature dependence of the longitudinal and transversal conductivity in 3d transition-metals and their alloys

K. Chadova[1], D. Ködderitzsch[1] and H. Ebert[1]

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The temperature dependence of the longitudinal and transversal conductivity in 3d transition-metals and their alloys is studied from first-principles. The calculations were performed using the fully relativistic Korringa-Kohn-Rostoker (KKR) Green's function method in combination with the Coherent Potential Approximation (CPA) alloy theory [1] on the basis of the Kubo-Středa equation [2]. Employing an alloy analogy model the thermal lattice vibrations are taken into account to describe the temperature dependence.

The calculations are performed for the pure systems Fe, Ni, and Co. The influence of the impurities in Ni on the temperature dependence of the transport properties is studied. The pronounced dependence on temperature of the transversal conductivity is observed in Ni. This is in agreement with recent experimental data [3].

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2.7 **14:30-14:50**

Thermodynamics of continuous media with spontaneous electric polarisation and magnetisation

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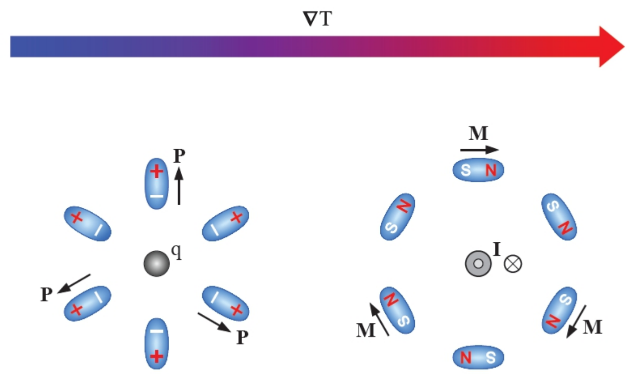
In order to understand the interplay between charge, spin and heat current, we decided to establish the thermodynamics of continuous media with spontaneous polarisation and magnetisation in the presence of electromagnetic fields.



At local thermal equilibrium between the matter and the electromagnetic fields, we derived explicit expressions for the temperature and chemical potentials in terms of the electromagnetic fields, the spontaneous electric polarisation and the spontaneous magnetisation, i.e.

$$T\left(s,n,\vec{P},\vec{M},\vec{D},\vec{B}\right) = T^{\text{mat}}(s,n) + \frac{1}{2}\frac{\partial \overleftrightarrow{\varepsilon}^{-1}}{\partial s}\cdot\left(\vec{D}-\vec{P}\right)\otimes\left(\vec{D}-\vec{P}\right) + \frac{1}{2}\frac{\partial \overleftrightarrow{\mu}^{-1}}{\partial s}\cdot\left(\vec{B}-\mu_0\vec{M}\right)\otimes\left(\vec{B}-\mu_0\vec{M}\right),$$

$$\mu\left(s,n,\vec{P},\vec{M},\vec{D},\vec{B}\right) = \mu^{\text{mat}}(s,n) + \frac{1}{2}\frac{\partial \overleftrightarrow{\varepsilon}^{-1}}{\partial n}\cdot\left(\vec{D}-\vec{P}\right)\otimes\left(\vec{D}-\vec{P}\right) + \frac{1}{2}\frac{\partial \overleftrightarrow{\mu}^{-1}}{\partial n}\cdot\left(\vec{B}-\mu_0\vec{M}\right)\otimes\left(\vec{B}-\mu_0\vec{M}\right).$$

Our thermodynamical approach leads to more general coupling terms in the linear phenomenological relations than those obtained earlier for the thermodynamics of continuous media with electromagnetic fields by de Groot and Mazur (S. R. de Groot and P. Mazur, *Non-equilibrium thermodynamics*, Dover : New York, (1984)). As an example, our general formalism describes properties of electrorheological fluids : a non-uniform electric field generates a dissipative shear stress, i.e.

$$\overset{\leftrightarrow}{\sigma}^{\text{mat}} = \overset{\leftrightarrow}{\beta}_P \left(s, n, \vec{P}, \vec{M}, \vec{D}, \vec{B}\right) \cdot \left(\vec{\nabla} \otimes \vec{E}\right).$$

Similarly, it describes properties of magnetorheological fluids : a non-uniform magnetic field generates a dissipative angular stress, i.e.

$$\overset{\leftrightarrow}{\Theta} = \overset{\leftrightarrow}{\beta}_M \left(s, n, \vec{P}, \vec{M}, \vec{D}, \vec{B}\right) \cdot \left(\vec{\nabla} \otimes \mu_0 \vec{H}\right).$$

2.8 15:10-15:30

Existence of spin Seebeck effect in GaMnAs structures

I. Soldatov[1], N. Panarina[1], R. Schäfer[1], Ch. Hess[1], S. Meyer[2], W. Limmer[3] and L. Schultz[1]

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[2] *Walther-Meissner Institut,Bayerische Akademie der Wissenschaften, Garching, Germany* [3]

If magnetic semiconductor is subjected to the temperature gradient and external magnetic field, it may show a number of thermoelectric effects: anomalous Nernst effect (ANE, $\vec{E} = -\alpha \cdot [\vec{m} \times \vec{\nabla}T]$), or anisotropic magneto-thermopower ($\vec{E}$, $\vec{m}$, $\vec{\nabla}T$ are in-plane), which is widely known as planar Nernst effect (PNE). If Pt stripes are deposited on the surface of the structure, one new effect appears. Namely the spin Seebeck effect (SSE), which reveals itself in a pure spin current, injected into the platinum in direction, perpendicular to the surface, where it could be detected via inverse spin Hall effect (ISHE). The important issue is to distinguish the later from the mentioned earlier effects.

In this work we investigate SSE in semiconducting GaMnAs structure. The observed signal could be attributed to the sum of SSE and PNE. To evaluate the contribution from PNE we analyzed the field dependence of the measured transversal voltage on the external magnetic field, swiped at different angles with respect to applied charge current in absence of temperature gradient. This procedure is valid as PNE has the same origin as planar Hall effect. Another important issue is temperature gradient, thus the role of out-of-plane temperature gradients is discussed.

3 Poster session

3.1 Poster 1

Optical techniques for spin caloric applications

Y. Manzke[1], R. Farshchi[1], J. Herfort[1], M. Ramsteiner[1]

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We show how optical spectroscopy can serve as an analysis tool for studying spin caloric transport phenomena. In particular, methods such as photoluminescence or Raman spectroscopy can be used to map lateral temperature distributions. Within this approach, Raman spectroscopy potentially allows us to investigate simultaneously the phonon as well as the magnon subsystem of a ferro- or ferrimagnetic insulator.

3.2 Poster 2

Ferromagnetic Resonance in the presence of a heat current

E. Papa[1] and J-Ph. Ansermet[1]

[1] *École Polytechnique Fédérale de Lausanne, Switzerland*

We explore the magnetization dynamics of a ferromagnetic system subjected to an in-plane temperature gradient. For this purpose, local ferromagnetic resonance studies at 4GHz are performed on single crystal Yttrium Iron Garnet (YIG) - $Y_3Fe_2(FeO_4)_3$ in presence of a heat current.

The YIG sample studied has dimensions of 10mm x 2mm x 0.025mm and the temperature gradient, applied as in the well-known Spin Seebeck geometry [1], is of the order of 20K/cm. This experiment offers a direct observation of the dynamic response of an insulating ferromagnet to an applied temperature bias through an investigation which is independent of any transport measurement and is free of electrical contacts.

By monitoring the magnetostatic modes excited and detected at a local level using a loop probe, we observe that the YIG magnetization is responsive to a temperature gradient. An evident effect is in fact seen on specific magnetostatic modes of the ferromagnetic spectrum. From the measurements taken for different orientations and positions of the coil with respect to the YIG specimen, it is possible to recognize the excited magnetostatic modes and assess which modes couple to the heat current.

References

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3.3 Poster 3

Effects of heat current in magnetic nanostructures

F. Antonio Vetrò[1], He Li[1] and J-Ph. Ansermet[1]

[1] *École Polytechnique Fédérale de Lausanne, Switzerland*

This work is aimed at investigating the interplay between spin dynamics and heat current in magnetic systems. We looked e.g. at Co/Cu granular films and conducted local ferromagnetic resonance (FMR) measurements at 4.4 GHz. The samples were in the famous Spin Seebeck geometry [1] and subjected to a temperature gradient of the order of 20K/cm. We studied also electrically detected FMR of electrodeposited Co/Cu/Co asymmetric spin valves positioned at the middle of Cu nanowires, when subjected to a strong heat current in order to extend the quasi-static study of switching field versus heat current. [2] This work is supported by the Polish-Swiss Research Program NANOSPIN under the grant number PSRP-05/2010.

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3.4 Poster 4

Modifying the thermal Boltzmann distribution in a nanoscale paramagnet using spin-polarized currents

T. Marzi[1], R. Meckenstock[1], A. Ney[2] and M. Farle[1]

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[2] *Abteilung für Festkörperphysik, Johannes Kepler Universität Linz, Austria*

In future spintronics devices information will be transported by the spin instead of charge like nowadays. Also the ability to switch spins by means of spin currents opens up an interesting field of possibilities to design these devices. For those reasons the development of spintronics devices requires to understand the interaction between isolated magnetic moments and spin currents.

Because conducting experiments with a single spin proves to be difficult to perform, we investigate the possibility to control and characterize a system of non-interacting isolated magnetic moments.

These isolated magnetic moments can be stabilized by dispersing Cr^{3+} ions in MgO. In an external magnetic field the paramagnetic energy levels split up according to the Zeeman effect. At a resonant microwave frequency electrons are excited to the upper

Zeeman level and an equal population of energy levels can be achieved depending on the magnetic relaxation rate and the microwave power. In parallel the dilute paramagnet can be exposed to a spin-polarized current which should change the population of one spin direction predominantly. This reduction of the occupation number for example of the excited level corresponds to a "magnetic" cooling of the system which in turn is measured by electron spin resonance (ESR).

This work is funded by the DFG SPP 1538. Helpful discussions with Jürgen Lindner and Kilian Lenz are acknowledged.

3.5 Poster 5

Thermoelectric Hall effects in Co_2FeAl

I.-M. Imort[1], D. Meier[1], J. Schmalhorst[1], G. Reiss[1], and A. Thomas[1]

[1] *Thin Films and Physics of Nanostructures, Bielefeld University, Germany*

Thermoelectric Hall effects are one of the most fundamental but controversially discussed aspects of spin caloritronic transport phenomena reflecting the interplay between heat and charge as well as spin currents. In normal metals the thermal Hall effect also known as Nernst effect reproduces a Hall voltage induced by heat currents in the presence of external magnetic fields. Due to the spin degree of freedom in ferromagnetic materials, thermoelectric Hall effects are also observable in the absence of external magnetic fields. In dependence on the orientation between the magnetization and both currents (heat and charge), there is a distinction between anomalous and planar thermoelectric Hall effects. In the presented work we investigated both thermoelectric Hall effects in thin films of the ferromagnetic Heusler compound Co_2FeAl.

3.6 Poster 6

Magneto-thermoelectric effects in Py/Pt systems

M. Schmid[1], S. Srichandan[1], M. Vogel[1], Ch. Back[1], Ch. Strunk[1]

[1] *Universität Regensburg, Germany*

We present the magneto thermoelectric effects in Py/Pt systems on MgO and GaAs substrates. We apply a temperature gradient of values up to 50 K with an in-plane magnetic field applied at several angles. It turns out that the results exhibit a combination of various contributions which can be addressed to the planar Nernst effect and the anomalous Nernst effect. The contribution from Spin Seebeck effect can't be altogether excluded but its value is an order smaller than presented in the literature [1, 2]. Futher COMSOL simulations supplementing the above bulk substrate system were carried out. Finally in another section the above effects have been presented on the same FM/NM system but on SiN substrate.

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3.7 Poster 7

Side-jump scattering contribution to anomalous Nernst effect from ab inito

J. Weischenberg[1], Y. Mokrousov[1]

[1] *Institute for Advanced Simulation, FZ Jülich, Germany*

We present a calculation of the off-diagonal part of the thermoelectric conductivity tensor from ab initio. Similar to the anomalous Hall effect, we have taken all the scattering independent contributions into account and investigate their relevance to thermoelectric transport phenomena. In particular, the role of the side-jump contribution to the anomalous Nernst effect for the ferromagnetic materials Fe, Co, Ni, FePd and FePt is discussed. In these materials, the validity of the Mott formula in the zero temperature limit could be numerically established as well.

3.8 Poster 8

Boltzmann approach to the spin Seebeck effect

F. Wilken[1] and T. Nunner[1]

[1] *Dahlem Center for Complex Quantum Systems, Freie Universität Berlin, Germany*

Applying a thermal gradient on an insulating ferromagnet results in a sloped phonon temperature profile. The effect of phonon-magnon-coupling on the magnon and phonon temperature profile ist studied. This effect was also studied by Xiao et. al (Phys. Rev. B 81, 214418 (2010)), and here we used the more detailed ansatz of Boltzmann equation. As a result, new drag terms appear, which in terms increase the temperature difference between magnons and phonons, especially at the end sections of the ferromagnet, and decrease the characteristic length scale. Additionally, we calculate the spin current injection from a ferromagnet into a normal metal caused by a different magnon temperature by using the same method.

3.9 Poster 9

Propagating spin waves in an out of plane thermal gradient

T. Langner[1], V. I. Vasyuchka[1], M. Agrawal[1], A. A. Serga[1], B. Hillebrands[1]

[1] *Fachbereich Physik and Landesforschungszentrum OPTIMAS, Technische Universität Kaiserslautern, Germany*

Spin waves, the collective excitation of magnetic moments in a magnetic material, have the potential to transport information without moving charge carriers. The investigation of the interaction of spin waves and thermal gradients is a highly interesting field in the frame of spincaloric transport research. It is well known that the Spin-Seebeck effect in insulating materials is induced by a transport of angular momentum by spin waves in a thermal gradient [1].

Beside the transversal Spin-Seebeck effect that creates an in-plane spin current there is also the longitudinal Spin-Seebeck effect causing an out of plane spin current [2]. This provides the question on the behavior of coherently excited spin waves propagating perpendicular to a heat gradient that induces a spin current by the Spin-Seebeck effect. According to Rezende et al. such a system could lead to an amplification of spin waves [3].

Here we present results of measurements on propagating spin waves excited by a microstrip antenna with applied microwave currents in an out of plane thermal gradient. The spin waves propagate in Yttrium iron garnet (YIG), an insulating material with low damping coefficients for spin waves. The YIG-sample has the sizes 8mm x 2mm x 4.1 μm and is grown on a gallium gadolinium (GGG) substrate. On top of the YIG sample a 10 nm thick platinum layer is deposited that is used to create the temperature gradient by one side Joule heating due to an applied DC current. It is shown that the properties of the spin waves depend on the temperature gradient and the applied excitation frequency.

Financial support by Deutsche Forschungsgemeinschaft (DFG) within Priority program SPP 1538 “Spincaloric Transport” is gratefully acknowledged.

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3.10 Poster 10

Spin wave propagation and transformation in a thermal gradient

B. Obry[1], V. I. Vasyuchka[1], A. V. Chumak[1], A. A. Serga[1], and B. Hillebrands[1]

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Thermal gradients have a significant influence on the spin system of magnetic materials giving rise to the flow of spin currents. This also applies for magnetic insulators, where spin waves play an important role in the mediation of spin currents. Considered in another way, a thermal gradient can act as a new method of creating, amplifying and manipulating spin waves. Hence, it is instructive to study the spin-wave behavior in a region with inhomogeneous temperature.

We investigate the propagation behavior of spin waves in an yttrium iron garnet (YIG) waveguide under the influence of a thermal gradient. Therefore, in a first experiment, spin waves propagating towards a colder region have been investigated utilizing phase-resolved Brillouin light scattering (BLS) spectroscopy. By mapping the spatial distribution of the interference between the spin-wave signal and a reference signal with constant phase it is possible to observe with space resolution a decrease of the spin-wave wavelength to about half of its original value. The wavelength reduction is caused by a change in saturation magnetization which continuously changes with local temperature.

Furthermore, a reflection of spin waves is achieved when propagating towards a hotter region. Measurements of the spin-wave intensity reveal the existence of two waveguide modes. For each mode a reflection point can be determined, behind which the spin-wave amplitude becomes evanescent. Due to the temperature increase the change in saturation magnetization is large enough to shift the dispersion relation out of range of the spin-wave frequency. For a given temperature increase, i.e. beyond a critical point of the waveguide, no spin waves can exist and propagation in this region is prevented.

In conclusion the experimental findings show that manipulation of propagating spin waves by thermal gradients is possible, revealing the potential of thermal gradients for application in spintronic and magnon logic devices.

Financial support by the Deutsche Forschungsgemeinschaft (DFG, VA 735/1-1) within Priority Program 1538 “Spin Caloric Transport” is gratefully acknowledged.

3.11 Poster 11

Magnonic domain wall heat conductance in ferromagnetic wires

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It is known that the continuum approximation for magnetic domain walls (DW) will break down in materials with high anisotropies, in which the DW width can be as small as a few lattice constants. The atomic-scale DWs can display very different properties from predictions in a continuum model [1]. In this work, we present a theoretical investigation of the magnon-mediated heat transport in electrically insulating ferromagnetic wires containing a DW [2]. The DW heat conductance is formulated through Landauer-Büttiker formula. In the regime of validity of continuum micromagnetism a DW is found to have no effect on the heat conductance (the spin wave transmission probability through the DW is unity, see Fig. 3.1a), which serves a confirmation of previous results [3]. However, SWs are found to be reflected by DWs with widths approaching

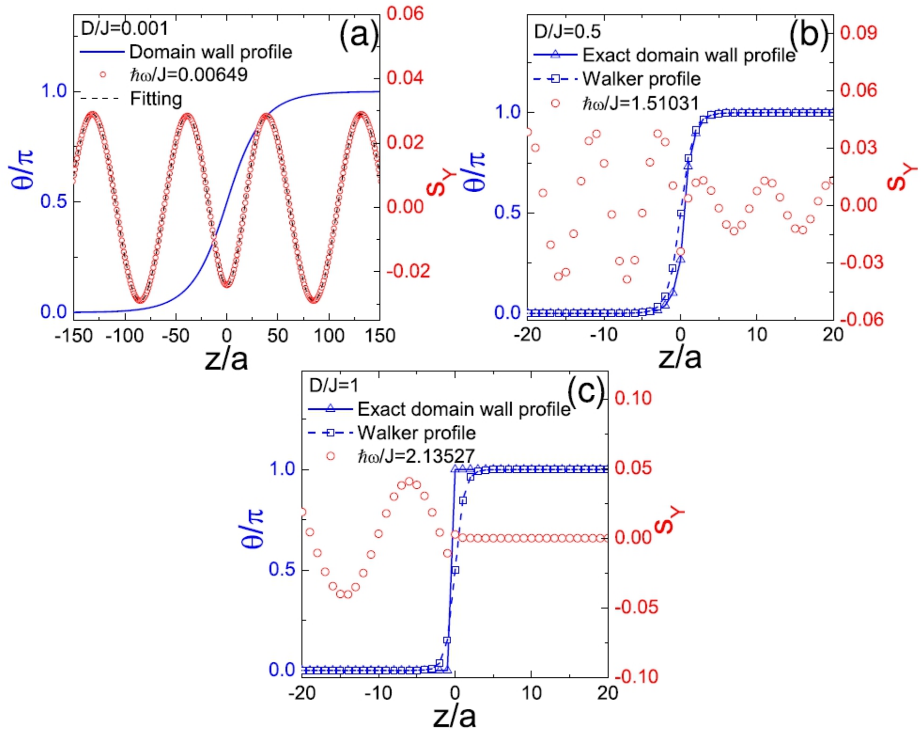

Figure 3.1: Calculated DW profiles and SW profiles under different parameters. D is the magnetic anisotropy, J is the exchange interaction, ω is the eigenfrequency of SW, and a is the lattice constant.

the lattice constants (see Fig. 3.1b), associated with emergence of an additional SW bound state which in absent in the continuum limit (see Fig. 3.2a). The transmission probability monotonically decreases with increasing wave vector (see Fig. 3.2b), which is different from the results obtained with a local spin-spiral approximation [4], which leads to perfect transmission for SWs with large wave vector, but hindered propagation at long wave lengths [4]. Moreover, SWs get total reflection if the magnetic anisotropy exceeds a critical value, above which the DW becomes abruptly sharp (see Fig. 3.1c and Fig. 3.2b). We also discuss the role of dipolar interaction on the magnon-mediated heat transport. The calculated DW heat conductance is shown to be significant for thin films of yttrium iron garnet with sharply defined magnetic domains [2]. Our result should help to detect and manipulate DWs in insulating ferromagnetic wires.

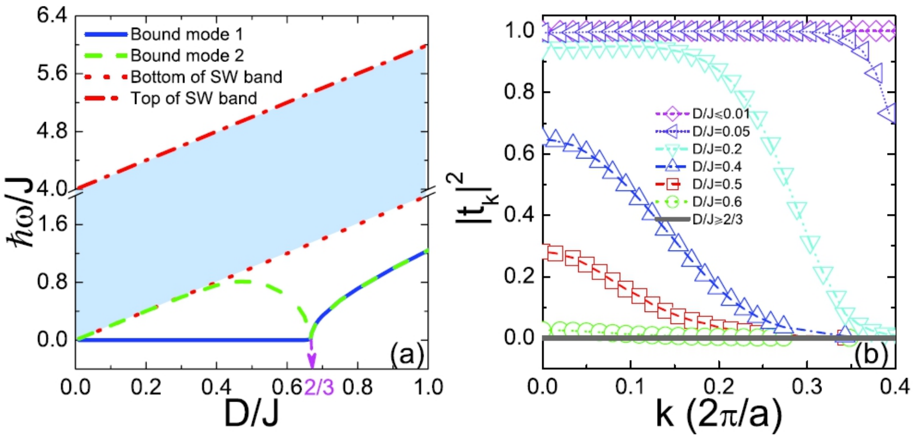

Figure 3.2: Calculated SW spectrum and SW transmission probabilities as a function of wave vectors with different materials parameters.

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3.12 Poster 12

Switching Behavior of Single Magnetic Nanowires under the Influence of Temperature Gradients

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The addition of thermal/thermoelectric effects to magnetic properties of nanostructures, such as thermal driven spin transfer torque [1], has become a field of huge interest. Also the generation of a spin current in a ferromagnet due to a temperature gradient, called spin Seebeck effect [2], has been receiving much attention. Both of these effects can be used to manipulate and control the switching behavior of magnetic nanostructures, which reveals potential for new domain-wall driven devices. We report on significant changes of the switching behavior of single magnetic nanowires (NWs) due to an externally applied temperature gradient ΔT along the NW. MOKE magnetometry is used to image square-like hysteresis curves that exhibit one sharp Barkhausen jump.

An increase in the switching field of 15 % at $\Delta T \approx 80\,\mathrm{K}$, a dc heating current I_{Heater} of 10 mA, for single $Co_{39}Ni_{61}$ alloy NWs can be observed. Electrochemically synthesized CoNi and NiFe alloy NWs [3] with a 10 nm SiO_2 protective shell and typical diameter of 150 nm have been magnetically characterized individually under tunable temperature gradients. Therefore, resistive thermometers have been positioned at each NW's extremity using optical lithography. Through the effect of Joule heating the thermometers are also used as heaters to create a temperature gradient along the NW. Temperature gradients of up to 80 K can be applied from each end of the NW independently. For CoNi NWs an increase of the switching field with ΔT has been observed. The estimated maximum Oerstedt fields, which are originated by the joule heaters, are in the order of 0.1 Oe and therefore can be neglected. The ΔT effect on the magnetization dynamics of NWs unveils a possible correlation between switching field and Seebeck coefficient.

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3.13 Poster 13

Phenomenological Model of Temperature Dependent Tunneling Anisotropic Magnetoresistance

C. López-Monís[1], A. Matos-Abiague[1] and J. Fabian[1]

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Tunneling anisotropic magnetoresistance (TAMR) has recently been observed in the epitaxial semiconductor heterostructure Fe/GaAs/Au [1]. For low temperatures (4.2 K), the observed TAMR has been successfully described theoretically [1, 2]. The dependence of the magnetoresistance on the magnetization orientation in the ferromagnet was shown to be originated by the interference between Bychkov-Rashba and Dresselhaus spin-orbit couplings that appear at the junction interfaces and in the tunneling region. For high temperatures (∼100 K), experiments show that the TAMR effect in the Fe/GaAs/Au system is slightly reduced (∼0.3% [3]) compared with other tunnel junctions [4]. As temperature increases additional spin scattering processes responsible for the reduction of the TAMR effect become relevant (e.g., phonon induced spin-orbit interactions [4]). In this work, we investigate theoretically the temperature dependence of the TAMR effect in Fe/GaAs/Au tunnel junctions. For this purpose, an effective magnetic field is added to the symmetry based phenomenological model developed in Ref. [2]. This effective magnetic field accounts for the temperature dependent spin scattering processes. We find that this model gives a good description of the observed TAMR reduction.

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3.14 Poster 14

Laser Induced Magneto-Seebeck Effect: Substrate Side Effects

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The discovery of the Magneto-Seebeck Effect (TMS) induced by laser heating has initialised a discussion concerning the origin of the Seebeck voltage and possible side effects. [1, 2, 3]

We investigated magnetic tunnel junctions heated by laser irradiation. To evaluate possible side effects, the junctions have been deposited on two different substrates: Insulating MgO and semiconducting Si covered by 50 nm of SiO_2. The results showed striking differences between the time resolved traces of the laser-heating induced voltage across the tunnel junctions. The analysis of the different substrate materials with comparable magnetic tunnel junctions (MTJ) can give a first glance on side effects occurring in the layer stacks and the substrates due to laser heating and capacitive coupling.

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3.15 Poster 15

Magneto-Seebeck Effect in Magnetic Tunnel Junctions with different barrier thicknesses

M. Walter[1], N. Roschewsky[1], J. Walowski[1], V. Zbarsky[1], J. C. Leutenantsmeyer[1], M. Marahrens[1], M. Münzenberg[1], V. Drewello[2], A. Böhnke[2], K. Rott[2], G. Reiss[2], A. Thomas[2], P. Peretzki[3], M. Seibt[3], M. Czerner[4], M. Bachmann[4], Ch. Heiliger[4]

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[4] *I. Physikalisches Institut, Universität Giessen, Germany*

CoFeB/MgO/CoFeB devices showing a giant TMR effect are possible candidates for the generation of spin-currents by thermal heating. A magneto-Seebeck effect was already observed experimentally in these devices [1, 2]. It is theoretically predicted that the MgO barrier has drastic influence on the thermal spin-dependent electron transport : The Seebeck coefficients can even change the sign at a certain temperature for 6 monolayers MgO which leads to a divergence of the magneto-Seebeck effect [3]. For a barrier as thin as 3 monolayers, the torkance of the spin-polarized tunneling electrons might be sufficient to observe thermal spin transfer torque [4].

In this regard, we present investigations of the influence of the MgO barrier thickness on the magneto-Seebeck effect in CoFeB/MgO/CoFeB magnetic tunnel junctions (MTJ), especially with respect to the sign change of the magneto-Seebeck effect observed in earlier experiments.

The samples presented in this work consist of a minimal pseudo-spin-valve stack with sputtered Ta and CoFeB layers and an e-beam evaporated MgO barrier. The MTJs are heated by either a diode laser which achieves powers of up to 150 mW or a Ti:Sa femtosecond laser for higher powers. The laser is focused onto the sample in a standard confocal microscope setup. An increasing laser fluence raises the base temperature of the MTJ as well as the temperature gradient across the MgO barrier. A sign change of the magneto-Seebeck effect is attributed to the higher base temperature at high laser fluences. The heating is simulated by finite element methods and the experimental results are compared with ab initio calculations of the Seebeck coefficients for parallel and antiparallel magnetization configuration. The experimental data and the temperature simulations are in good agreement with the ab-initio calculations.

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3.16 Poster 16

Perpendicular anisotropy and out-of-plane tunnel magnetoresistance of CoFeB/MgO–based magnetic tunnel junctions

V. Zbarsky[1], M. Walter[1], J. Walowski[1], J. C. Leutenantsmeyer[1], G. Eilers[1], P. Peretzki[2], H. Schumann[2], M. Seibt[2], R. Gareev[3] and M. Münzenberg[1]

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[3] *Physikalisches Institut, Universität Regensburg, Germany*

The optimization of magnetic tunnel junctions (MTJs) is necessary to increase the tunnel magnetoresistance (TMR) and therefore is important for the production of magnetic random-access memory (MRAM) devices. Additionally, spin-transfer torque MRAM based on CoFeB/MgO MTJs promises lower power consumption and higher storage density compared to conventional RAM. Reduction of the switching current density leads to improvement of the energy efficiency of STT-RAM. For that reason, the investigations on the MTJs are of great interest in the present research.

The quality of the tunnel barrier in CoFeB/MgO/CoFeB MTJs is essential for getting a high TMR ratio. For that reason we minimized the roughness of the MgO layer in the MTJ. Another important parameter is the choice and preparation of the buffer layer. Thus we compare two sorts of Ta buffer layers: prepared via magnetron sputtering and via e-beam evaporation. An increase of the TMR from 80% to above 270% is achieved.

The next step is the fabrication of samples with a perpendicular magnetic anisotropy. These enable a decrease of the switching current density in spin-transfer torque-MRAM. The first experiments show that the thicknesses of CoFeB and MgO layers are crucial for the out-of-plane magnetic behavior [1]. In this context, samples with a CoFeB thickness gradient were fabricated. For CoFeB layers below 1.3 nm a perpendicular anisotropy is observed. This enables the preparation of MTJs with out-of-plane TMR which is of great importance for the development of spin-transfer torque devices.

Research is supported by DFG through SFB 602 and SPP 1538 SpinCaT.

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Tuesday, 09.10.2012

4 Invited Talks

4.1 09:00-09:45

Description of galvanomagnetic transport using Kubo linear response formalism

Hubert Ebert[1], Diemo Ködderitzsch[1] and Sebastian Wimmer[1]

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Starting from the Kubo-equation we derive a general scheme for the first-principles determination of various transport properties of solids and layered systems.

We introduce the Kubo-Greenwood expression as well as the Kubo-Streda equation to deal with both longitudinal and transverse electronic transport. We illustrate its application in a multiple scattering KKR-Green function method. The extension of the former formalism to describe galvanomagnetic phenomena will be shown. We give various examples of the application of the developed framework, e.g. the calculation of the resistivity, the anomalous magneto resistance, the spin-dependent Seebeck effect, the Spin-hall and anomalous Hall conductivity as well as the anomalous Nernst effect. The extension to layered systems is discussed as well and will be illustrated by corresponding examples.

4.2 10:30-11:15

Tunneling Magneto Seebeck effect

A. Thomas[1]

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We prepared Co-Fe-B/MgO/Co-Fe-B magnetic tunnel junctions (MTJ) by magnetron sputtering and observed the tunnel magnetoresistance (TMR) effect. The TMR effect designates the difference in the tunnel resistance of the parallel and anti-parallel alignment of the two ferromagnetic electrodes. The difference in resistances is called TMR ratio and the maximum TMR ratio was 330% and 530% at room temperature and 13K, respectively.

Recently, a new research direction was established by creating temperature gradients in magnetic nanostructures: Spincalorics combines magneto- and thermoelectric effects. If we heat our junctions with short laser pulses of a laser diode or a Ti:sapphire laser to induce a temperature gradient between the two electrodes, we observe a spincaloric effect called tunneling magneto Seebeck (TMS) effect. The TMS effect is similar to the TMR effect, but in this case the Seebeck coefficient of the junction changes if the magnetic configuration is altered, e.g. from anti-parallel to parallel alignment.

The Seebeck coefficients in parallel and antiparallel configurations are similar to the voltages known from the charge Seebeck effect. The tunneling magneto Seebeck effect was investigated in dependence of the laser intensity and, therefore, the base temperature and temperature gradient across the tunnel barrier. We find a characteristic sign change of this effect and explain the observed behavior with ab-initio calculation of the Seebeck effect in magnetic tunnel junctions. The size and sign of the effect can be controlled by the composition of the electrodes' atomic layers adjacent to the barrier and the temperature. We show the temperature dependent investigations of this effect, supported by TEM studies of the microstructure, numeric simulations of the temperature profile in the junction and possible devices utilizing the tunneling magneto Seebeck effect.

5 Contributed Talks

5.1 11:15-11:35

Anisotropy of the Seebeck effect and anomalous Nernst effect from Kubo linear response formalism

S. Wimmer[1], D. Ködderitzsch[1] and H. Ebert[1]

[1] *Department Chemie, Ludwig-Maximilians-Universität München, Germany*

Employing the linear response Kubo formalism [1, 2, 3] implemented using the relativistic multiple scattering Korringa-Kohn-Rostoker technique we study the anisotropy of the Seebeck effect (ASE) and the anomalous Nernst effect (ANE) in ferromagnetic cubic transition-metal alloys. The diagonal and off-diagonal elements of the thermomagnetoelectric tensor, Seebeck and Nernst coefficients, respectively, are derived from Kubo-Středa transport calculations by use of Mott's formula for the thermopower [4]. Results for the ASE are discussed in comparison to the corresponding electric field-driven effect, the anisotropic magneto-resistance (AMR). The ANE is analogously compared to calculations of its galvanomagnetic counterpart, the anomalous Hall effect (AHE). Applying Fermi-Dirac statistics can be used as a first step to simulate elevated temperatures, as will be shown for the thermoelectric power in Ag_xPd_{1-x} alloys. The chemical disorder of the investigated alloys is treated on the level of the coherent potential approximation (CPA). As will be shown, a corresponding description of the spin-dependent counterparts, spin Seebeck and anomalous spin Nernst effect, can be achieved by making use of a relativistic spin projection scheme [5].

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5.2 11:35-11:55

Recent results of longitudinal spin Seebeck effect measurements on $NiFe_2O_4$/Pt films

D. Meier[1],T. Kuschel[1], J. Schmalhorst[1], G. Reiss[1], L. Shen[2], A. Gupta[2], T. Kikkawa[3], K. Uchida[3] and E. Saitoh[3]

[1] *Thin Films and Physics of Nanostructures, Bielefeld University, Germany*
[2] *Center for Materials for Information Technology, University of Alabama, Tuscaloosa AL, USA*
[3] *Institute for Materials Research, Tohoku University, Sendai, Japan*

The longitudinal spin Seebeck effect (LSSE) was first studied in a ferrimagnetic insulator slab of $Y_3Fe_5O_{12}$ (YIG), which was covered by a thin Pt film [1]. When a temperature gradient is applied along the YIG/Pt system a spin current parallel to the temperature gradient is generated, which can be converted into an electromotive force via the inverse spin Hall effect. As a consequence one can measure a voltage between the ends of the Pt film in a range of a few μV. In the ferrimagnetic insulator / paramagnetic metal system are no regions expected which are conductive and spin-polarized simultaneously. That is the reason why thermomagnetic effects like the anomalous Nernst effect (ANE) can be neglected in most cases. In this work we present recent results for $NiFe_2O_4$/Pt obtained in a setup for longitudinal spin Seebeck effect measurements. A detailed temperature dependence is studied as well as the influence of the external magnetic field direction. An additional effect could be observed, which can be correlated to the anisotropy of the magnetic film. The origin of the measured effects is discussed on the base of conductivity measurements in order to correlate the effects to the LSSE and ANE.

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5.3 11:55-12:15

In search of spin caloric effects in thin permalloy films using different setups for transverse spin Seebeck effect measurements

T. Kuschel[1], D. Meier[1], J.-M. Schmalhorst[1], G. Reiss[1],T. Kikkawa[2], K. Uchida[2], E. Saitoh[2]

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[2] *Institute for Materials Research, Tohoku University, Sendai, Japan*

In the very active research field of spin caloritronics new spin- and temperature-dependent effects have been reported in the last years [1]. One of these effects in magnetic thin films describes the generation of a spin current by a temperature gradient and is called the spin Seebeck effect (SSE) [2]. A thin Pt wire is attached to the film in order to detect a voltage signal by means of the inverse spin Hall effect [3, 4]. The SSE has originally been observed in thin permalloy films on sapphire substrates using the transverse geometry, which indicates a spin current perpendicular to the in-plane temperature gradient.

Henceforward, a lot of scientific groups tried to measure the so called transverse spin Seebeck effect (TSSE). The effect was reported for films of the ferromagnetic insulator $LaY_2Fe_5O_{12}$ [5], semiconductor GaMnAs [6] and half-metallic Heusler compound Co_2MnSi [7]. Often an additional out-of-plane temperature gradient generates an anomalous Nernst effect (ANE) [7, 8] which contributes to the measured signal. Therefore, the homogeneity of the in-plane temperature gradient is very important to avoid additional parasitic thermoelectric effects.

We built up a setup for TSSE measurements and investigated thin permalloy films on sapphire and MgO substrates. Our measurements reveal a planar Nernst effect [9] which originates from the magnetic anisotropy in the film and is symmetric concerning the external magnetic field direction. An additional asymmetric contribution due to the TSSE or ANE is not observed in most cases. For comparison of the studied effects we performed measurements in the original setup in Japan, where the first TSSE was observed in 2008 [1]. For the same samples we obtained different results. An asymmetric contribution due to the TSSE or ANE is now contributing for nearly every sample. This inconsistency is discussed in the context of setup differences and probable out-of-plane temperature gradients.

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Participants & Timetable

Nachname, Vorname	Affiliation	Session
Agrawal, Milan	Uni Kaiserslautern	Mo, 12:10
Böhnke, Alexander	Uni Bielefeld	Mo, 15:45, P14
Bréchet, Sylvain	EPF Lausanne	Mo, 14:30
Brüggemann, Jochen	Uni Hamburg	Mo, 13:50
Chadova, Kristina	LMU München	Mo, 14:10
Gönnenwein, Sebastian	WMI München	Di, 09:00
Heiliger, Christian	Uni Giessen	Mo, 09:15
Imort, Inga-Mareen	Uni Bielefeld	Mo, 15:45, P05
Jungfleisch, Benjamin	Uni Kaiserslautern	Mo, 13:30
Kehlberger, Andreas	Uni Mainz	Mo, 11:50
Klewe, Christoph	Uni Bielefeld	–
Ködderitzsch, Diemo	LMU München	Di, 09:00
Krzysteczko, Patryk	PTB Braunschweig	–
Kuschel, Timo	Uni Bielefeld	Di, 11:55
Langner, Thomas	Uni Kaiserslautern	Mo, 15:45, P09
Liebing, Niklas	PTB Braunschweig	–
López-Monís, Carlos	Uni Regensburg	Mo, 15:45, P13
Manzke, Yori	Paul Drude Institut	Mo, 15:45, P01
Marzi, Thomas	Uni Duisburg-Essen	Mo, 15:45, P04
Meier, Daniel	Uni Bielefeld	Di, 11:35
Michel, Ann-Kathrin	Uni Hamburg	Mo, 15:45, P12
Münzenberg, Markus	Uni Göttingen	–
Obry, Björn	Uni Kaiserslautern	Mo, 15:45, P10
Papa, Elisa	EPF Lausanne	Mo, 15:45, P02
Ritzmann, Ulrike	Uni Konstanz	Mo, 11:30
Röser, René	Uni Mainz	–
Schmalhorst, Jan	Uni Bielefeld	–
Schmid, Maximilian	Uni Regensburg	Mo, 15:45, P06
Soldatov, Ivan	IFW Dresden	Mo, 15:10
Srichandan, Sasmita	Uni Regensburg	–
Thomas, Andy	Uni Bielefeld	Mo, 10:30
Vetrò, F. Antonio	EPF Lausanne	Mo, 15:45, P03
Vogel, Michael	Uni Regensburg	–
Walter, Marvin	Uni Göttingen	Mo, 15:45, P15
Weischenberg, Jürgen	FZ Jülich	Mo, 15:45, P07
Wilken, Francis	FU Berlin	Mo, 15:45, P08
Wimmer, Sebastian	LMU München	Di, 11:15
Yan, Peng	Delft University	Mo, 15:45, P11
Zbarsky, Vladyslav	Uni Göttingen	Mo, 15:45, P16
Zhang, Jia	Uni Giessen	–

Monday

- 09:00 – 09:15 Welcome — SR05
- 09:15 – 10:10 Ch. Heiliger — SR05
- 10:15 – 10:30 Coffee break — Meeting room
- 10:30 – 11:25 S. Gönnenwein — SR05
- 11:30 – 11:50 U. Ritzmann — SR05
- 11:50 – 12:10 A. Kehlberger — SR05
- 12:10 – 12:30 M. Agrawal — SR05
- 12:30 – 13:30 Lunch break — Nordmensa
- 13:30 – 13:50 B. Jungfleisch — SR05
- 13:50 – 14:10 J. Brüggemann — SR05
- 14:10 – 14:30 K. Chadova — SR05
- 14:30 – 14:50 S. Bréchet — SR05
- 14:50 – 15:10 Coffee break — Meeting room
- 15:10 – 15:30 I. Soldatov — SR05
- 15:30 – 15:45 Organizational Issues — SR05
- 15:45 – 17:30 Poster Session — in front of SR05

Tuesday

- 09:00 – 09:55 D. Ködderitzsch — SR05
- 10:00 – 10:55 A. Thomas — SR05
- 11:00 – 11:15 Coffee break — Meeting room
- 11:15 – 11:35 S. Wimmer — SR05
- 11:35 – 11:55 D. Meier — SR05
- 11:55 – 12:15 T. Kuschel — SR05