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Magnon spintronics in non-collinear magnetic insulator/metal heterostructures

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Summary

Controlling the generation, propagation and detection of pure spin currents carried by magnons is the essence of the field of magnon spintronics. In this thesis, I investigate pure spin currents generated in a normal metal and the spin currents carried by thermally generated magnons in magnetic insulators. I investigate these spintronic phenomena in the prototype yttrium iron garnet (YIG)|platinum (Pt) bilayer system (chapter 3) and in different non-collinear magnetic insulator|Pt bilayer systems (chapters 4, 5). The spin currents are driven by both charge currents and temperature gradients. I also study the growth of non-collinear magnetic insulators (chapter 7). Moreover, I investigate the role of ever-present background contributions in these spintronic experiments by a magnetic probe based on a muon spectroscopy technique (chapter 6).

The electron can be considered as a particle, with charge and magnetic character “spin”. It behaves as a tiny magnet with an intrinsic magnetic moment. The motion of an electron (charge current) is thus automatically accompanied with the flow of angular momentum, i.e., a spin current. In paramagnetic metals, the number of electrons with spin pointing in one direction, “spin-up” electrons, is equal to the number of electrons with spins pointing in the opposite direction, “spin-down” electrons. Hence, these charge currents do not carry a net spin current. However, in ferromagnetic (ferrimagnetic) materials, the majority of electron spins point in one direction making the material magnetic. Therefore, a charge current in a magnetic material effectively transports a spin current. This spin current can be injected into an adjacent non-magnetic metal in close proximity. The main complexity of working with spin currents is that these injected spin currents can decay over short distances of the order of hundreds of nanometers due to interactions with their environment. The relation between charge and spin current transport has led to spin-based electronics - known as spintronics. The recent developments in the field of spintronics

have shown that pure spin currents can be generated transverse to a charge current. This effect is known as the spin-Hall effect (SHE). In the SHE, a moving electron in a paramagnetic metal is deflected from its initial trajectory (along the charge current flow direction) due to the spin-orbit interaction (an interaction of a particle's spin momentum with its orbital momentum). The deflection direction is opposite for spin-up electrons and spin-down electrons. Therefore, when a charge current flows in materials with strong spin-orbit coupling (heavy metals like Pt) the electrons with opposite spins deflect in different directions, resulting in a spin current transverse to the charge current direction. The inverse of this effect (ISHE) also exists in which a spin current converts to a transverse charge current.

Spin currents can also flow in magnetic insulators carried by magnetic excitations known as magnons. The relation between spin currents in metals and spin currents carried by magnons in insulators has led to a new research field - known as "magnon spintronics". In this thesis, the transfer of spin currents across the metal|magnetic interfaces is investigated by two effects: spin-Hall magnetoresistance (SMR) and spin-Seebeck effect (SSE). In the SSE, a temperature gradient is applied over a non-magnetic NM|ferromagnetic FM stack which generates thermal magnons (magnetic excitations) in the FM layer. These magnons carry a spin current with spin polarization along the average magnetization direction of the FM layer. This spin current carried by thermal magnons transfers into the adjacent NM layer and converts into a charge current by the ISHE - known as the SSE signal. As the spin current goes from the FM to NM layer through the interface, the quality of the interface plays an important role.

The first experiment (chapter 3) investigates the role of the interface quality in the SSE. In this experiment, a collinear magnetic insulator yttrium iron garnet (YIG) is investigated. In this system all magnetic moments can be easily aligned along the applied magnetic field direction (with magnetic field strength of few millitesla). Before sputtering the Pt layers on top of YIG films, different YIG surfaces are prepared by polishing with coarse or soft polishing particles of different sizes. The creation of a temperature gradient over these Pt|YIG stacks is achieved by using external heaters. Interestingly, the SSE signal observed in the NM layer depends on the surface roughness of the YIG layer and the type of polishing (i.e, coarse or soft polishing particles). A second experiment is the simultaneous detection of the SMR and SSE in the NM|FM stacks. In the SMR, the resistance of the NM layer changes depending on the magnetization direction of the FM layer underneath. In this effect, the SHE and ISHE both play a concerted role. This effect is measured by rotating the NM|FM stack in a magnetic field and measuring the resistance of the NM layer along (or transverse to) the applied current direction. Importantly, this effect is sensitive to the surface magnetization of the magnetic layer and provides the possibility to electrically detect the magnetization direction of this insulating layer. The charge current sent through the NM layer creates a thermal gradient across the NM|FM stack due to Joule heating. This thermal gradient will create the SSE which can be separated from the SMR signal by a technique called lock-in detection. The principle is that the SMR scales linearly with the applied current while the SSE scales quadratically. By simultaneously, but separately, measuring the SMR and SSE in a single measurement, detailed information about the surface and bulk magnetization of the magnetic layer can be determined. This experiment is performed on the Pt|YIG stack (chapter 4) by measuring the SMR and SSE simultaneously. In the literature, mostly the prototype YIG collinear magnet has been investigated. However, magnetic insulators exhibit a large variety of magnetic orders, varying from collinear magnetic states in which all magnetic moments align along one axis to non-collinear states with magnetic moments aligned in complex spin arrangements. In non-collinear magnetic insulators, usually a large magnetic field of several Tesla is needed to align all magnetic moments along the applied field. In such magnetic systems, the competing magnetic interactions (spin frustration) do not favor a parallel arrangement of magnetic moments, resulting a complex arrangement, such as triangles or spirals. An example of such a system is $CoCr_2O_4$ (CCO) (discussed in chapter 4) in which at low temperatures the spin frustration leads to a conical spiral arrangement of magnetic moments. Even a magnetic field of 30 T is not sufficient to fully align all magnetic moments along the applied field direction. To study the sensitivity of the SMR and SSE towards the surface and bulk magnetization of a magnetic insulator, I performed experiments on the Pt|CCO bilayer system (chapter 4). I observe that the SMR and SSE both show large anomalies at the magnetic transitions where the collinear magnetization of the CCO films transforms to the conical spiral state. The large changes in the SMR and SSE signals are related to the non-collinear magnetization of the insulating CCO magnetic layer. This experiment establishes that both the SMR and SSE are powerful tools that complement ferromagnetic resonance and neutron scattering techniques to analyze the magnetization dynamics of complex oxides like CCO.

The third investigation in my thesis is similar to the second one in which the SMR and SSE are simultaneously detected. In this study a chiral non-collinear magnetic insulator is used. In chiral magnets the Dzyaloshinskii-Moriya (DM) interaction can lead to a non-collinear magnetic order. In these magnetic systems, the DM interactions twist an initially collinear arrangement of magnetic moments to a certain handedness. This leads to the formation of chiral spin arrangements. The advantage of using such magnetic systems is their rich phase diagrams in which different magnetic states like helical, conical, skyrmions and collinear magnetic states (co-)exist at different temperatures and applied magnetic fields. For this purpose, we investigate the chiral magnetic insulator Cu_2OSeO_3 (CSO)|Pt bilayer system (chapter 5). I observe that the SMR can be used as an all-electric detection tool for different magnetic transitions of CSO, such as the helical and conical spiral magnetic states. The results show the SMR to be sensitive to the orientation of the spiral wave vector and to the magnitude of the cone angle between the applied magnetic field direction and the magnetic moments in the spiral. Large discontinuities and anomalies in the SMR are observed when the magnetic order of the CSO changes from a single magnetic domain state to a multidomain state. The SSE generated due to Joule heating also shows strong sensitivity to changes in magnetic ordering of CSO. In the future perspective, it would be interesting to apply these techniques (SMR and SSE) to the detection of even more complex spin textures, such as the skyrmion crystal in these chiral magnets.

The fourth investigation described in this thesis (chapter 6) deals with the determination of the ever-present background contributions in these spintronic experiments. I used a muon spectroscopy technique (LEμSR) for this purpose. The LEμSR is a magnetic probe and is sensitive to small magnetic fields of the order of 0.1 mT. This technique can be used to detect the current-induced fields, e.g., due to the spins created by the SHE, Oersted fields or due to proximity effects at buried interfaces. In this experiment, a Au|YIG bilayer system is used to study the depth resolved magnetic fields in this system. I observe that the LEμSR can be used to resolve the small magnetic fields of the order of 0.04 mT associated with background signals present due to the interface roughness and Oersted fields.

In the last chapter of this thesis (chapter 7) a new method for growth of large single crystals of the chiral magnetic insulator CSO is demonstrated. I find that with this method both left- and right-handed crystals of CSO can be grown. The crystals have excellent quality gauged by single crystal x-ray diffraction and verified by observing the presence of higher harmonic modes in ferromagnetic resonance data. The same crystals have been used in this thesis for the spintronic experiments described in chapter 5.

Considerable experimental efforts have been made already on magnon spintronic effects in collinear magnetic insulators. The experiments in this thesis provide understanding of spintronic phenomena related to the generation and detection of spin currents in non-collinear magnetic insulators with complex magnetic spin structures, like helices and skyrmions. Additionally, a new route to grow high quality single crystals of non-collinear magnets is described along with the spin transport experiments on these crystals. These investigations lead to new insights regarding the sensitivity of the SMR towards the surface magnetization and the cone angle of the spiral spin structures. The combination of these results and the improved understanding of the physics involved in spin transport in non-collinear spin structures leads to new possibilities to electrically detect and manipulate nanomagnetic structures, such as domain walls and skyrmions. A technique like SMR, with which one can observe nanosized objects by measuring electric currents, would be indispensable for utilizing skyrmions and other topological defects as information carriers in the next generation spintronics devices.