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Magnon spintronics in non-collinear magnetic insulator/metal heterostructures

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1.1 Spintronics

Today's technology-oriented world with billions of daily-use electronic devices including computers and mobile phones could never have been realized without the availability of small and cheap information storage devices. Interestingly, these devices including the modern hard drives, utilize not the charge of the electron but its intrinsic angular momentum called the electron spin. The famous demonstration of the potential of spintronics to be used in electronic devices was done by A. Fert [1] and P. Grünberg [2] in 1988 by the discovery of the Giant Magneto Resistance (GMR) effect and they were rewarded with the Nobel Prize in Physics in 2007 for their discovery. The GMR effect, the working principle for read-out in today's hard drives, makes it possible to read out the magnetic state of a tiny magnetic domain, as a change in the electrical resistance depending on the relative magnetic alignment of magnetic domains. Every tiny magnetic domain therefore will act as a distinct binary (1/0) magnetic state. Together with the successful downscaling of the size of a stable bit, hard disks can be packed with areal densities reaching up to 128 GBit/cm² dramatically lowering the cost down to \$0.032 per gigabyte till now.

Over the last two decades in the field of spintronics, different methods have been investigated to use the electron's spin degree of freedom for storage, transport and manipulation of information. For example, in the spin-valves, a typical spintronics device with two magnetic layers for information storage, the GMR effect is used to read the magnetic states. Spin transfer torque (STT) [3, 4] is used to manipulate the spin information. Spintronic devices, including spin-valves, are mostly based on the flow of spin-polarized charge currents. Undoubtedly, spintronics has uncovered many fundamental questions in pursuit of its goal to control electronic spin currents and their interaction with magnetic order in metals. Several spin-related phenomena including spin transfer torque in magnetic layers [3, 4], spin pumping driven by magnetization precession [5, 6] and thermally induced spin currents [7–9] are being currently used to manipulate spin currents in metallic systems. However, spin currents in magnetic metals carried by moving electrons are limited by spin relaxation and Joule heating.

1.2 Magnon Spintronics: A new approach towards dissipationless spin electronics

Magnon spintronics is the field of spintronics in which the spin currents are carried by magnons instead of moving charge carriers. Magnons are the quanta of collective spin-wave excitations in magnetic materials. Magnons are *charge current free* and, therefore, less subject to dissipation caused by scattering with impurities on the atomic level. This renders magnons a promising information carrier alternative compared to electric (spin) currents. Spintronics in magnetic insulators is fundamentally different from that in metals and gives rise to quantum many-body phenomena that lie beyond the paradigm of single-electron spintronics [10]. Magnon spintronics promises to find ways to exploit magnonic spin currents for novel energy-harvesting and power-conserving spintronics technologies that are urgently needed for tomorrow's information society [11].

Magnon spintronics came into focus by two recent discoveries that demonstrate the conversion between charge currents carried by itinerant electrons and magnonic spin currents at an interface between a normal metal and a magnetic insulator. This conversion can be driven thermally [12] or electrically [13], and opens the possibility for integrating electron and magnon spintronics. In the long term, these breakthroughs may lead to novel device concepts that exploit magnons for spin transport with minimal dissipation over much longer distances than the spin relaxation lengths.

1.3 Motivation and Outline

The research presented in this thesis focusses on the growth of complex magnetic materials with unique magnetic properties and experimental investigation of fundamental spintronic phenomena in these magnetic insulators with magnetic orders varying from collinear to non-collinear chiral spin structures. The usage of non-collinear magnetic insulators for spintronic devices opens up not only the possibility to study and control pure spin currents but also their interaction with non-collinear nano-magnetic spin structures like helices and skyrmions. We study different spintronic effects including spin Hall magnetoresistance (SMR) and spin-caloritronics effects like spin Seebeck effect (SSE) by using a metal|insulator bilayer nanoscale device configuration. In these bilayer devices a Pt metal electrode, with large spin-orbit coupling, is used to electrically inject or detect spin currents. The magnetic insulators including prototype yttrium iron garnet - $\text{Y}_3\text{Fe}_5\text{O}_{12}$ (a room-temperature collinear magnetic insulator), cobalt chromate - CoCr_2O_4 (a non-collinear magnet) and copper oxoselenite - Cu_2OSeO_3 (a chiral magnet) are investigated in these bilayer devices. Moreover, some investigations have been carried out by replacing Pt metal by Au on top of a magnetic insulator.

This thesis consists of the following chapters, of which a brief overview is given below:

- *Chapter 2* introduces the fundamental concepts needed to understand the work presented in the following chapters. Firstly, a general introduction into spin transport is given including the (inverse) spin Hall effect, which is the most important feature for the interconversion of charge currents and pure spin-currents by using Pt as metallic

electrode. Further, two main spintronic effects presented in this thesis are introduced: SSE and SMR. Thereafter, important material properties of different magnetic insulators are discussed, followed by the Dzyaloshinskii-Moriya interaction, which can be used to describe the magnetization behavior in chiral magnetic insulators. Moreover, we briefly introduce the low-dimensional antiferromagnets with the ongoing discussion about the possibility of their use in spintronic devices. The final part of this chapter is based on the device fabrication and measurement methods which are used for the experiments presented in this thesis.

- *Chapter 3* shows the investigation of the SSE in a single crystal Yttrium iron garnet (YIG)|Pt bilayer system. By using the inverse spin Hall effect, the spin currents carried by magnons in a magnetic insulator can be electrically detected. Here, the magnons are excited by creating a thermal gradient with an external heater on top of Pt. Magnetic field dependence of the SSE is measured at room temperature for several devices prepared with different mechanical treatment conditions for YIG surface, showing a strong dependence of the signal on the interface condition of the Pt|YIG bilayer system.
- *Chapter 4* manifests the SMR and SSE in a non-collinear magnetic insulator CoCr_2O_4 |Pt device and shows their behavior in different magnetic states of CoCr_2O_4 (CCO). We were the first group to experimentally demonstrate these effects in a non-collinear spiral magnetic insulator. Both effects were simultaneously detected at different temperatures (5 K - 300 K), in different applied magnetic fields (0 T - 7 T). Finally, also a comparison has been made between CCO|Pt and YIG |Pt systems, showing a large influence on the measured SMR and SSE signals, depending on the magnetic order of the magnetic insulator.
- *Chapter 5* continues on the investigation of the SMR and SSE in a non-collinear magnetic insulator, focusing on a magnetic system without inversion center Cu_2OSeO_3 (CSO). Angular dependence of these effects has been measured in a single crystal CSO|Pt bilayer device, in different magnetic fields ($B \leq 8$ T) and temperatures ($T \leq 70$ K). By this work it has been shown for the first time that the SMR and SSE are not only sensitive to the magnetization direction but also locally sensitive to the angles of magnetic moment constructing nanomagnetic spin structures; depending on the angle of these helical spirals, the SMR signal changes from positive to negative values. Furthermore, theoretical simulations have been shown indicating a good qualitative agreement with the experimental observations.
- *Chapter 6* presents a study of the depth dependence of the current-induced magnetic fields including the Oersted and dipolar fields in a thin-film YIG|Au device, by using low energy muon spectroscopy ($\text{LE}\mu\text{SR}$). The measurements are done at different muon implantation energies, allowing us to probe muons at different depths from the YIG|Au interface. Furthermore, a model to quantify the dipolar field close to the interface is presented. Finally, the limits on the spatial resolution and the sensitivity of $\text{LE}\mu\text{SR}$ are discussed to provide guidance for a future experiment designed to probe spin Hall effects with muons.

- *Chapter 7* describes the method used to grow single crystals of CSO used for the SMR and SSE study presented in Chapter 5. Furthermore, the single crystal x-ray diffraction analysis is provided including the analysis of the absolute structures for both enantiomers of CSO. Finally, the ferromagnetic resonance data with presence of higher harmonic modes is shown, confirming the excellent quality of grown single crystals.

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