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Controlled magnon spin transport in insulating magnets

Liu, Jing

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Chapter 1

Introduction

1.1 Magnetism

Magnetism is a discovery of the ancient times since people found that lodestones, naturally magnetized stones, attract iron. This magic force without touching has puzzled many philosophers and scientists, transcending location and culture: Since the time of classical Greece, people have been using the term of a *magnet*. In ancient Indian medical texts, it is suggested to use magnets to remove arrows from people's bodies. In ancient China, a lodestone was made into a spoon shape, where the handle of the spoon was found to always point to the direction of the south, thereby discovered the compass. This curiosity ended up having profound consequences for human discoveries. Magnetism was employed to navigate, to explore new lands, and to figure out the stars and the relationship between humans and the universe.

In modern times, after the discovery of matter's microscopic structure people started to wonder: *What makes a magnet magnetic?* This ancient topic became magnificent again. After hundreds of years of exploration, we now know that the building blocks of magnetic materials are atoms or molecules with nonzero magnetic moments due almost entirely to the orbital motion and spin of electrons. When the magnetic atoms get together and form a solid, the force which calls the magnetic moments to order is the *exchange interaction*[†]. The alignment of the magnetic moments is disrupted by thermal fluctuations so that above a certain temperature, called the *Curie temperature* Θ_c, the net magnetic moment is zero. However, below Θ_c, the magnetic moments are aligned in the absence of an applied field so that the material is spontaneously magnetized. This emergent phenomenon is caused by spontaneous symmetry breaking: The chaotic sea of magnetic moments containing all the rotational symmetries is suddenly left with only one rotational symmetry axis by freezing all the moments in one single direction just like other *phase transitions* such as from water to ice.

Based on their magnetic characteristics, materials can be roughly classified into

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[†] The importance of exchange interaction was first pointed out by Ya. I. Frenkel, Ya. G Dorfman and W. Heisenberg in 1928 [1]

five categories depending on the properties of the building blocks and binding forces [2]: When the constituent atoms or molecules do not possess permanent magnetic moments, i.e. unpaired electrons, the material is *diamagnetic*. By contrast, the materials composed of magnetic atoms but without long-range ordering as a result of the exchange interaction show *paramagnetism*. If however, the exchange energy is able to align the neighboring magnetic moments parallel to each other, this gives rise to *ferromagnetic* long-range ordering. Alternatively, the neighbouring moments can be aligned antiparallel to each other due to a different type of exchange interaction. Depending on the numbers of the parallel and antiparallel moments, the materials are *antiferromagnetic* or *ferrimagnetic* when the numbers are equal or unequal, respectively. Among different types of exchange interaction, direct exchange interaction makes most ferromagnets conducting and superexchange interaction makes most of the ferri- or anti-ferromagnets insulating.

In reality, there are more complicated magnetic order arrangements. Also, for a given magnetic specimen, the energy is minimized by dividing it into many *domains*, within which magnetic moments are aligned. However, the neighbouring domains have magnetic moments that are not aligned. Nevertheless, people have figured out quite a bit about the arrangement of the magnetic moments in different materials, which is not the end of the story. For a full understanding, one needs to know how the magnetic moments move, i.e. the dynamics of magnetism.

1.2 Magnetic excitation: Magnons or spin waves

"Magnon" is a concept to describe the thermodynamics of magnetism, proposed by Bloch [3] in 1930 when he was in Utrecht, the Netherlands. They are bosons, whose statistical properties suggest that their number is proportional to $T^{3/2}$ [4, 5]. This temperature dependence matches the $T^{3/2}$-dependent reduction of spontaneous magnetization at low temperatures and that of the specific heat, which shows that magnons carry both spin and heat. Deviations from that are attributed to the phonon contribution. For more than half a century, the study of magnons has always been focused on the long wavelength GHz magnons, which have dominating wave (rather than particle) properties [6]. Thanks to the rise of nanotechnology and crystal fabrication techniques, it has become possible to study magnons at a different scale: namely those found in ultra-thin films and nanodevices [7–12]. Fundamentally, this provides a better chance to explore the quasiparticle properties of magnons. Practically, this makes it possible to scale down the magnon-based device.

1.3 Magnon spintronics

Unlike the spin transport in metals which is mainly contributed by the mobile electrons [13], in insulators the spins are mainly carried by magnons. Therefore, the magnon emerges as another player on the playground of spintronics, leading to *magnon spintronics* [6], which is appealing for information technology for several reasons: First, the motion of the information carrier magnons is not accompanied by any Joule heating like in the field of electronics or conventional electron spintronics. Therefore, magnon-based data processing can be an antidote to the thermodynamic bottleneck of Moore's law [14–16] due to overheating from Ohmic dissipation produced by electron motion in conducting circuits. Secondly, magnons possess different statistics than fermions, i.e. Bose-Einstein statistics. One of the most profound results is that the whole band of magnons contribute to the transport. This provides a possibility to operate the device at different frequencies. Thirdly, when the number of magnons is large enough, the Bose-Einstein condensation can be realized even at room temperature [17]. The resulting state may lead to the holy grail of dissipationless information transport for next-generation logic devices. More attention has been drawn to the spin transport in insulating materials since the experimental demonstration of the spin Seebeck effect [18] in 2008. This opened up a field called *spin caloritronics* [19, 20], where the spin degree of freedom is connected with heat. In the case of magnon spins, abundant physics are explored and even efficient use of waste heat can be applied to manipulate magnon transport. To facilitate this transport in magnon spintronics, the desired materials are those with low damping, which generally means long magnon life time.

1.4 A gem: Yttrium iron garnet (YIG)

Yttrium iron garnet (YIG) is a ferrimagnetic oxide, which was first synthesized in 1956[†] by Bertaut and Forrat [21]. Synthesizing garnets was a trendy thing at that time, because their high refractive index makes them good candidates for economical jewelry. Surprisingly, this synthetic gemstone shows magnetic properties, especially its lowest magnetic damping properties, a record which still holds after more than half a century. Because of this, YIG has become a real gem in the field of magnetism. Kittel made the analogy between YIG in magnetism and fruit flies in biology in the 1960s. In 1993, one of the most comprehensive reviews dedicated to YIG [22, 23] compared the role of YIG to that of germanium in semiconductor physics, water in hydrodynamics and quartz in crystal acoustics. With the development of material synthesis [24] and nanotechnology, people still keep being surprised by the

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[†] Coincidentally, YIG shares the year of its birth with my parents.

knowledge and applications we can obtain from this gem.

1.5 Motivation and thesis outline

The aim of this thesis is to study the transport of magnons. For this purpose, YIG is used as the platform or the transport channel. All the experiments have been conducted in atmosphere at room temperature. The effects observed in this thesis provide ways to steer the flow of information carried by the magnon spins in magnonic devices. This thesis is made up of the following chapters, of which a brief overview is given below:

- *Chapter 2* gives an overview of the theoretical background, which is necessary for understanding the effects studied in this thesis.
- *Chapter 3* systematically explains the fabrication process and measurement methods used for the experiments presented in this thesis.
- *Chapter 4* provides experimental evidence for the magnon planar Hall effect and anisotropic magnetoresistance. The relative difference between magnon current conductivities parallel ($\sigma_{\parallel}^{\mathrm{m}}$) and perpendicular ($\sigma_{\perp}^{\mathrm{m}}$) to the magnetization is found to be approximately 5%.
- *Chapter 5* uses different heavy-metal paramagnetic electrodes to study the magnon spin transport in a nonlocal experiment: Pt and Ta on YIG. For both electrodes, a similar magnon relaxation length of $\sim 10\,\mu$m is extracted. However, since Pt and Ta have opposite sign of the spin Hall angle and different properties at the YIG interface, changes in nonlocal transport are observed.
- *Chapter 6* demonstrates that an rf microwave field strongly influences the transport of incoherent thermal magnons. Transport can be suppressed by 95% or experience an enhancement as large as 800%. This study shows the interplay between coherent and incoherent spin dynamics.
- *Chapter 7* documents the properties of 3-terminal magnon transistors on ultrathin YIG.

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