University of Groningen

Controlled magnon spin transport in insulating magnets

Liu, Jing

DOI:
10.33612/diss.97448775

IMPORTANT NOTE: You are advised to consult the publisher's version (publisher's PDF) if you wish to cite from it. Please check the document version below.

Document Version
Publisher's PDF, also known as Version of record

Publication date:
2019

Link to publication in University of Groningen/UMCG research database

Citation for published version (APA):
Liu, J. (2019). *Controlled magnon spin transport in insulating magnets: from linear to nonlinear regimes*. [Thesis fully internal (DIV), University of Groningen]. University of Groningen. https://doi.org/10.33612/diss.97448775

Copyright
Other than for strictly personal use, it is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license (like Creative Commons).

The publication may also be distributed here under the terms of Article 25fa of the Dutch Copyright Act, indicated by the “Taverne” license. More information can be found on the University of Groningen website: https://www.rug.nl/library/open-access/self-archiving-pure/taverne-amendment.

Take-down policy
If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Downloaded from the University of Groningen/UMCG research database (Pure): http://www.rug.nl/research/portal. For technical reasons the number of authors shown on this cover page is limited to 10 maximum.

Download date: 12-04-2024

Summary

Magnons are quasiparticle representations of spin waves, which describe the collective excitations of a magnetic system. They can propagate and carry spin information in electrically insulating and magnetically ordered materials, i.e. magnetic insulators. One of the most famous examples is yttrium iron garnet (YIG) due to its uniquely small magnetic damping and long magnon lifetime. Magnons carry integer spin, so they are boson particles and their distribution obeys Bose-Einstein statistics. As a result, transport of magnons is affected by the whole spectrum, from the magnon band minimum up to the energy level corresponding to the thermal energy ~ $k_\mathrm{B}T$.

Depending on the wavelength, the magnon spectrum is dominated by two types of energies: In the long-wavelength regime, dipolar energy is dominant, where dipolar magnons, typically with GHz frequencies, can be excited by microwave fields. In comparison, in the short wavelength regime, exchange energy dominates: Exchange magnons typically have THz frequencies. Throughout the whole thesis, in order to study the transport properties of magnons, an electrical method is used to generate magnons with energies up to $k_\mathrm{B}T$. All the experiments were carried out at room temperature, which corresponds to frequencies of ~ 6 THz.

The magnon transport set-up is composed of two heavy metal (HM) strips such as platinum (Pt) or tantalum (Ta) on top of a single crystal YIG film, which is grown on a gadolinium gallium garnet (GGG) by liquid phase epitaxy (LPE). A small ac current is sent through the first HM strip (the magnon injector), where the spin Hall effect (SHE) transfers the electrical current into a transverse spin current. This leads to an electrical spin accumulation at the HM interface which is in contact with the YIG. At the HM|YIG interface, the incoming mobile s-orbital electrons of the HM scatter with the localized d-orbital electrons of the YIG. Due to the conductivity mismatch at the interface, the mobile electrons themselves cannot go deeply into the insulator. However, the spins can be transferred, which gives rise to magnon generation

in YIG. The resulting magnons propagate inside the YIG and they can be picked up by the second HM strip (the magnon detector), where the detected spin currents are transferred back to a charge current via the inverse spin Hall effect (ISHE), which is the reciprocal process of the SHE. Under an open circuit condition, an ISHE voltage is measured. Since current supply and voltage measurement are conducted at two different HM strips, this experiment is referred to as nonlocal measurement, which is in contrast to a ”local” experiment where the sourcing and detecting of electrical signals occur at the same place. This nonlocal geometry is also used in the spin transport experiment for conducting system. In one word, these electrical magnon injection and detection processes are the most important methods to characterize the magnon spin transport properties in thin YIG film in this thesis.

Beyond the exchange-coupled electrical magnon injection at the HM|YIG interface, the Joule heating by electrical current through the magnon injector sets up a temperature gradient, which drives magnon currents inside the YIG due to the spin Seebeck effect (SSE). The temperature gradient stretches beyond the YIG film into GGG, whereas the resulting magnons cannot enter the GGG paramagnet but instead accumulate at the YIG|GGG interface. This gives rise to a magnon depletion regime near the magnon injector and a magnon accumulation region at the bottom of the YIG film near the injector, which both contribute to the ISHE voltages measured by the detector but with opposite signs. Depending on the thickness of the YIG film and distance between the injector and detector, depletion/accumulation magnon spin currents are dominant for the small/large distance cases. These processes are referred to as magnon thermal injection and electrical detection. In comparison with the electrical injection and detection, the propagation distance of the thermally generated magnons is less well-defined.

With a lock-in technique, the electrically and thermally generated magnons can be detected simultaneously. They are measured as the first and second harmonic signals, which scale linearly and quadratically with the ac current through the injector, respectively. In a typical experiment, the sample is situated in between a pair of static magnetic dipoles. A static field is applied to orient the magnetization of the YIG in the plane of the film. Since the electrical injection and detection depend on the angle of the YIG magnetization with respect to the HM strip, the sample is rotated so that the YIG magnetization rotates with respect to the HM strip. Specifically, the electrical magnon generation/annihilation has the highest efficiency when the YIG net magnetization is parallel/antiparallel to the SHE-generated electron spin polarization at the HM|YIG interface, which is oriented along the interface and perpendicular to the HM strip. In other words, when the in-plane YIG magnetization is perpendicular to the HM strip, the highest electrical magnon injection efficiency is achieved. This is also the case for the magnon electrical detection: Only the magnon spins perpendicular to the HM strip can contribute to the ISHE voltage measured along the HM strip. The angle between the static field and the direction perpendicular to the HM strip is defined as α. Based on the relations described above, magnon electrical injection and detection both have an angle dependence of $\cos\alpha$. Therefore, the first harmonic signal has an angle dependence of $\cos^2\alpha$ due to the electrical injection and detection, while the second harmonic signal shows a $\cos\alpha$ angle dependence since the thermal injection due to Joule heating is not sensitive to the direction of the YIG magnetization. These nonlocal voltages are normalized by the rms amplitudes of the ac current and ac current squared as first and second harmonic nonlocal resistances, respectively. Their amplitudes are extracted from the field angle-dependent modulations of $\cos^2\alpha$ and $\cos\alpha$, respectively. Moreover, instead of angle-dependent measurement, the field is swept at a fixed angle in measurements combined with rf set-up for the stability of the microwave power.

The transport properties are studied by the distance-dependent behavior of the nonlocal signals: Series of HM|YIG|HM nonlocal devices are fabricated with different distances between the injector and detector, from tens of nanometers to tens of micrometers. For Pt devices, with increasing distances, the nonlocal signals first decay geometrically, i.e. as a function of one over distance, then exponentially. This distance-dependent behavior can be described by a spin diffusion-relaxation model, which has also been used to explain the spin transport in metals. In the short-distance regime, the diffusion process dominates whereas in the long-distance regime the relaxation process takes over. From the slope of the exponential decay, a length scale can be extracted, which characterizes the distance of magnon spin diffusion before relaxation starts to dominate, which is referred to as magnon diffusion length λ_m. At room temperature, this magnon diffusion length is around $10\,\mu$m for 210 nm thick LPE single crystal YIG.

The distance-dependent behavior depends not only on the magnon spin conductivity and magnon spin relaxation properties but also on the interface spin resistances, which for metals has been shown by applying the spin diffusion-relaxation model. For magnon spin transport, the influence of the interface resistances at the HM|YIG interfaces, or spin mixing conductance, is studied by using different HMs in *Chapter* 5: Pt and Ta. Ta|YIG interface has been reported to have poorer spin mixing conductance, higher interface spin resistance, than Pt|YIG interface. As a result, the distance-dependent behavior of Ta|YIG|Ta devices shows only exponential decay instead of both geometric and exponential decay, which is qualitatively consistent with the prediction of the spin diffusion-relaxation model. Besides, a comparable magnon diffusion length of ~ 10μm has been extracted from the results of Ta|YIG|Ta devices. Moreover, Pt and Ta have spin Hall angles of opposite signs. This gives rise to the same and opposite signs of the first and second harmonic signals, respectively. The reason is that both electrical injection and detection processes involve the spin Hall angle for the first harmonic signals whereas only the electrical detection does for the second harmonic signals.

After establishing the basis of magnon spin transport, the nonlocal method is applied to study the anisotropic character of magnon spin transport in *Chapter* 4. In analogy to the magnetoresistance of the electron transport in magnetic metals where electrons show different conductivities parallel and perpendicular to the direction of the magnetization, magnons show a similar magnetotransport behavior. This character can be measured in both longitudinal geometry where the detector is parallel to the injector, and transverse geometry where the injector is at one end of the detector and perpendicular to the detector. They are referred to as magnon anisotropy magnetoresistance (MAMR) and magnon planar Hall effect (MPHE), respectively. From both MAMR and MPHE measurement, the anisotropic properties of the electrically generated magnons have been measured: The difference between the magnon conductivities parallel ($\sigma_{\parallel}^{\mathrm{m}}$) and perpendicular ($\sigma_{\perp}^{\mathrm{m}}$) to the magnetization is approximately 5%, which is comparable with the magnetoresistance of the electron transport in metal (around 2% for Ni).

So far magnon transport shows many analogous properties to electron transport; however, as bosonic particles, magnons of all energies can contribute to the transport but not equally. The electrical nonlocal method generates thermal magnons with energy up to 6 THz at room temperature, which have been shown to be significantly affected by the population of magnons with GHz frequencies excited by a microwave field in *Chapter* 6. This is achieved by exposing the nonlocal device to an rf power provided by an on-chip stripline connected to an rf power source. At the ferromagnetic resonance (FMR) condition, the transport of thermal magnons is suppressed by more than 95%, whereas at a non-FMR condition the nonlocal signals are enhanced more than 800%, namely when the four-magnon scattering gives rise to a population of band-minimum magnons. Besides, when the rf frequency coincides with the magnon band minimum, a small enhancement of the nonlocal signals is observed. All these phenomena indicate that thermal magnons play a role as a bath for the coherent GHz magnons so that the coherent magnons can be damped into this bath and increase the population of the thermal magnons. On the other hand, the distribution of the GHz magnons strongly influences the transport properties of the thermal magnons, especially the occupation of the band-minimum magnons, which do not themselves contribute directly to the transport because they have zero group velocity. Here, the rf power is already so big so that it drives the magnet into a highly nonlinear regime, where magnon-magnon interaction plays a role.

Apart from using rf power to enhance the magnon population at the GHz regime, a dc current can be applied to a third electrode (modulator) in between the magnon injector and detector, so that the thermal magnon population is altered by the electrical magnon generation or annihilation. As a result, the magnon conductivity is tuned. Therefore, this three-terminal device is referred to as a magnon transistor, where the third HM strip modulator functions as a gate: The magnon transport properties are controlled by changing the magnon densities. This proof-of-principle experiment has been realized on a 210 nm thick YIG film, where the nonlocal magnon transport from the injector to detector has been modified by the SHE-injected magnons and the Joule heating of the modulator. *Chapter* 7 documents the characteristics of magnon transistors on 10 nm thick YIG films: In the low dc current regime, comparable results have been observed but with much higher modulation efficiencies than the prediction based on the results of 210 nm thick YIG films. In the high dc current regime, the modulation does not scale linearly with the dc current through the modulator anymore. However, there are still open questions about the origin of this nonlinearity and the cause of the transition from linear to nonlinear regimes.