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Towards two-dimensional magnon spin transport in ultrathin magnetic insulator films

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Summary

Magnon spin current flowing through magnetic insulators can be applied for low-dissipation data processing, which benefits the development of low-energy consuming spintronics devices. With state-of-art thin film growth techniques, we explore room-temperature magnon transport in thin yttrium iron garnet (YIG) films with a thickness below 10 nm in this thesis. We observe a giant magnon spin conductivity in 3.7 nm thickness YIG by an all-electrical method (Chapter 4), and we evidence a strong perpendicular magnetic anisotropy in unit-cell thin YIG films (Chapter 6). We also find that the ultrathin-YIG-film-based magnon transistor can sufficiently modulate magnon transport by (magnon) spin current with a record modulation efficiency (Chapter 5). Furthermore, we drive magnon transport to a non-linear regime by high current density in the heterostructure of Pt|YIG with both non-local geometry and local cross devices (Chapter 5 and Chapter 7).

The development of the microchip has boosted the Third Industrial Revolution, also known as the Digital Revolution. The number of transistors on the microchip has been doubling every two years for decades. Nowadays the electronics promotes further technological innovation, but it also faces challenges. ChatGPT, an artificial intelligence (AI) chatbot recently released by OpenAI, shows high performance in natural language assigned tasks, such as generating codes according to users' descriptions, and aiding in the preservation of the Icelandic language. Such an outstanding AI model requires tens of thousands of expensive microchips, and it consumes an enormous amount of energy during training and application. The bottlenecks from the energy efficiency and the physics limits of the transistor size lead to a technical invention competition for next-generation electronics. The spintronics is one of the candidates to overcome bottlenecks, which utilizes spin current instead of charge current for the information transport, processing, and storage.

In this thesis, we study the spintronics in magnetic insulators, magnon spintronics, where the spin current is carried by magnons. Magnons are quasi-particles in magnets. The spin angular momentum of each magnon is $\hbar$, consequently, the population of magnon states obeys Bose-Einstein statistics. The yttrium iron garnets, $Y_3Fe_5O_{12}$ (YIG), have a complex crystal structure with 80 atoms per unit cell, and the iron atoms unequally located in two different coordination sites maintain opposite spins, resulting in ferrimagnet. The magnon gap in YIG is quite high, so it can be simplified as a ferromagnet unless the temperature in experiments is much higher than room temperature. The ultralow Gilbert damping of YIG makes it the best platform for magnon spintronics. A fully electrical method is applied to study the magnon transport. The device consists of two Pt strips on the top of the YIG film as the injector and the detector respectively, which is also called the non-local geometry. The charge current sent through the Pt injector forms a spin current towards the Pt surface by the spin Hall effect (SHE), and the consequent spin accumulation at the Pt|YIG interface creates a magnon current in the YIG film. The Joule heating effect simultaneously causes a thermal gradient in the YIG films, which also generates magnon current due to the spin Seebeck effect. Both two effects generate incoherent magnons. The frequency of incoherent magnons, also known as thermal magnons, is up to several terahertz at room temperature while the coherent magnons stay in the gigahertz range. When the magnon current reaches the Pt detector, it is absorbed, and it forms a measurable voltage at the Pt detector by the inverse spin Hall effect. The magnon current with different origins can be separated by the lock-in technique. The SHE-generated magnon current contributes to the first harmonic signal while the SSE-generated magnon current is in the second harmonic signal.

The magnon spin current is driven by the gradient of the magnon chemical potential, and the magnon spin conductivity can be defined as the magnon spin current density divided by the gradient of the magnon chemical potential. For a uniform thermal/electronic conductor in the classical regime (without quantum effects), the conductance decreases with decreasing thickness while the conductivity remains a size-independent constant. Counter-intuitively, we observe that the non-local signal at the same distance in ultrathin YIG films increases as decreasing thickness in Chapter 4. The magnon relaxation in the direction perpendicular to the film plane can explain the decreasing non-local signal observed in thicker YIG films where the thickness is greater than the magnon relaxation length. However, this explanation is not suitable for ultrathin YIG films. We extract the magnon spin conductivity from a two-dimensional diffusive model which includes the magnon relaxation in the direction perpendicular to the film plane. Surprisingly, we find a giant magnon spin conductivity up to 10^8 S/m in the ultrathin YIG film with a thickness down to 3.7 nm at room temperature while the magnon spin conductivity remains a constant around 3×10^4 S/m in the bulk regime. It is corresponding to a transition from three-dimensional to two-dimensional magnon transport. The number of magnon subbands, which the excited thermal magnon can occupy at room temperature, decreases in thinner films. There are only the lowest three subbands notably occupied in 3.7 nm thickness YIG film, and the magnon transport approaches to the two-dimensional limits, where magnon experience lower magnon-phonon scattering, resulting in longer magnon scattering time than in three-dimensional transport. The corresponding two-dimensional magnon spin conductivity we find in ultrathin YIG films is around 1 S, even comparable to the electronic conductivity of the high-mobility two-dimensional electron gas in GaAs quantum wells at millikelvin temperatures.

The two-dimensional magnon transport at room temperature is expected to be observed in unit-cell thin YIG films, where only the lowest magnon subband is occupied. It motivates us to study a unit-cell thin YIG system grown by the pulsed laser deposition in Chapter 6. However, we could not observe the signal from SHE-generated magnons in this unit-cell thin YIG system. It is a discontinuous layer instead of a continuous film. Although it remains a challenge to grow a uniform unit-cell thin YIG film, the spin Hall magnetoresistance (SMR) measurements reveal that there is a strongly perpendicular magnetic anisotropy (PMA) in this unit-cell thin YIG system, which is also supported by the field-dependent signals from the spin Nernst magnetoresistance (SNMR) and the SSE. Even if the external field is up to 6 T, the magnetization of this unit-cell thin YIG system still maintains partial out-of-plane component, and the lower coordination numbers in unit-cell size YIG may be responsible for the strong PMA we observed. The origin of this strong PMA still needs further investigation. The most inspiring observation in the unit-cell thin YIG system is the signal from the SSE. The SSE coexists with the SNMR in the second harmonic signals, and the signal from the SSE has an angle dependence of $\cos\alpha$ in in-plane field rotating measurements while the SNMR has an angle dependence of $\cos^2\alpha$. In previous research, the magnitude of the signal from the spin Nernst magnetoresistance is relatively small compared with the SSE-driven non-local magnons in Pt|YIG heterostructures. Here, the inhomogeneity of the unit-cell thin YIG system traps the generated magnons, which strongly weakens the SSE. Thus, the SNMR dominates the second harmonic signal at room temperature. As the spin Nernst angle decreases at a lower temperature, the contribution from the SSE becomes more significant. The detection of the SSE indicates the YIG with a size down to unit-cell remains quite good quality for magnon transport. The improvement of the unit-cell thin film growth technique will offer the opportunity for room-temperature two-dimensional magnon spintronics research.

In a linear regime of magnon transport, the magnon gas is assumed to be dilute, and the magnon spin conductivity linearly scales with the number of magnons. In contrast, the magnon gas can not be treated as non-interacting in the non-linear regime of magnon transport, and non-linear magnon transport is still an uncharted field. With the high magnon spin conductivity in ultrathin YIG films, it is possible to dramatically raise the magnon current density and consequently drive the magnon transport to a non-linear regime. Analogous to the structure of the field effect transistor (FET), a three-terminal magnon transistor consists of three Pt strips on the top of ultrathin YIG film as magnon *source*, *gate* and *drain* respectively in Chapter 5. An AC current with a small amplitude is sent through the magnon source, and the SHE-generated magnon current is detected at the magnon drain. The magnon spin conductivity of YIG is tuned by the magnon gate when a DC current passes through it, and the non-local magnon current from the source to the drain probes the change of magnon spin conductivity. The modulation efficiency in 10 nm thickness is larger than 40%/mA, which is far beyond the modulation efficiency of 1.6%/mA in 210 nm thickness YIG. Note that although the magnon spin conductivity quadratically scales with the DC current at a low current range, the magnon transport is still in a linear regime since the magnon spin conductivity linearly scales with the number of magnons (The Joule heating effect creates magnons quadratically with the DC current.). A non-linearity is also observed at high DC current density. However, the non-linear behavior in magnon transport varies with the width of the gate, which indicates that the non-linearity at high DC current density may be not only related to the magnon interaction but also affected by the electronic spin accumulation at the Pt|YIG interface, such as spin-orbit torque.

To further explore the non-linearities in magnon transport, we deposited small Pt cross structures on the top of ultrathin YIG films, which allows us to send even higher charge current density passing through the device to generate higher magnon current density underneath the Pt cross (Chapter 7). With the second harmonic technique, we confirmed that the spin-orbit torque is large at a high current density, which should be taken into account in the analysis of the current-induced non-linear magnon transport. Meanwhile, we also observed a component with five-fold symmetry in in-plane field rotating measurements at high current density. Although the origin of this five-fold symmetry component still needs further investigation and analysis, we are getting closer to revealing the non-linearity in magnon transport step by step.