Spin transport in antiferromagnetic insulators: progress and challenges

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Abstract
Spin transport is a key process in the operation of spin-based devices that has been the focus of spintronics research for the last two decades. Conductive materials, such as semiconductors and metals, in which the spin transport relies on electron diffusion, have been employed as the channels for spin transport in most studies. Due to the absence of conduction electrons, the potential to be a spin channel has long been neglected for insulators. However, since the demonstration of spin transmission through a ferromagnetic insulator, it was realized that insulators with magnetic ordering can also serve as channels for spin transport. Here, the recent progress of spin transport in antiferromagnetic insulators is briefly described with an introduction to the experimental techniques. The observations regarding the temperature dependence of spin transmission, spin current switching and the negative spin Hall magnetoresistance are discussed. We also include the challenges for developing the functionality of antiferromagnetic insulators as well as the unresolved problems from the experimental observations.

A core mission for spintronics is to develop spin-based devices in which information is processed by spin rather than charge1. Efficient spin transport is a prerequisite for the operation of spin-based devices. If spin transport can be further controlled by some external parameters, e.g., gate voltage, a spin transistor can be realized2. Following these visions from the pioneers, spin transport has been studied extensively in various materials, and different approaches have been developed for its manipulation3.

It is likely that the mainstream materials for spin transport have been semiconductors and metals in which the spin current is essentially electron diffusion with a difference between the up-spin and down-spin electron chemical potentials because the spin current was initially introduced and demonstrated with conduction electrons4,5. However, since a spin current can generally be considered as a flow of angular momentum, electrons should not be the only choice for the carrier of spin. In principle, systems comprising any particle or quasiparticle with an angular momentum degree of freedom can host spin current. For instance, the spin transport mediated by magnons in Y3Fe5O12 (YIG), a ferrimagnetic insulator, was demonstrated by Kajiwara et al.6. From then on, the study of spin transport in ferromagnetic insulators has been a topic of interest in the spintronics field.

Since the spin current in ferromagnetic insulators is believed to be mediated by magnons, antiferromagnetic insulators (AFMI), which also host magnons, hold potential for spin transport as well. Indeed, the demonstration of spin transport through antiferromagnetic insulators was first achieved by Wang et al.7, which was followed by similar results from other groups8,9. This breakthrough included a new class of materials for spin transport, which opened up new possibilities for future device development.

Here, the experimental configurations for the study of spin transport in AFMI are briefly introduced with a discussion of the observation results. Figure 1 illustrates...
the essential processes for the observation of spin transport in AFMI from left to right: spin current generation, spin transmission, and spin current detection. The spin pumping process, spin Seebeck effect or spin Hall effect can be used to generate and inject a spin current into an AFMI, in which the driving forces are microwave, temperature gradient and charge current, respectively. The spin current transmitted through an AFMI can be detected with a voltage signal via the inverse spin Hall effect.

The sample structure used in the ref. 7, a Pt/NiO/YIG trilayer, is taken as an example and illustrated in Fig. 2a. A spin current is injected into NiO, which is an antiferromagnetic insulator (AFMI), from Y3Fe5O12 by spin pumping and detected by the inverse spin Hall effect (ISHE) in Pt. Surprisingly, the ISHE voltage in the Pt/NiO/YIG device is even larger than that in the Pt/YIG device when the NiO is approximately 1 nm, which means that the spin current is somehow enhanced by the presence of the NiO interlayer. Such a counterintuitive result was also found in the spin Seebeck measurement for Pt/NiO/YIG device. A spin current can be detected with a voltage signal via the inverse spin Hall effect when the NiO is approximately 1 nm, which means that the spin current is somehow enhanced by the presence of the NiO interlayer. Such a counterintuitive result was also found in the spin Seebeck measurement for Pt/NiO/YIG device.

So far, the studies mentioned above were more about the characterization of the spin transport property in AFMIs, while the control of the spin transport in the AFMIs, e.g., the switching of a spin current, which is indispensable for next-step applications, has not been achieved yet. Recently, isothermal switching of a spin current was demonstrated in Cr2O3, in which the spin transmission modulation is greater than 500% under a magnetic field. Figure 3a shows the illustrations for the experimental configuration, and Fig. 3b is the cross-section TEM image of the device. Here, the YIG/Cr2O3/Pt structure is employed, in which a spin current is driven by a temperature gradient, V7, from the YIG into the Cr2O3 by the spin Seebeck effect. In contrast to the samples used in a previous study, the Cr2O3 layer has a well-aligned out-of-plane Néel vector due to its single-pumping enhancement temperature may be close to the Néel temperature.

Although the IrMn alloy is metallic rather than insulating, the result undoubtedly highlights the intriguing behavior of spin transport in the phase transition regime of antiferromagnets.
crystalline structure and uniaxial magnetic anisotropy. Figure 3c plots the temperature dependence of the spin Seebeck voltage in a YIG/Cr$_2$O$_3$/Pt device measured with an in-plane magnetic field, which shows a sudden transition from the spin conductor state to the spin non-conductor state within 14 K of the Néel temperature. Such behavior is in sharp contrast to the gradual decay of spin transmission below the Néel temperature in CoO and NiO$^{13,15}$. The suppression of spin transmission in the antiferromagnetic phase can be understood by the symmetry requirement of the magnon spin current: the spin polarization of magnons must be parallel to the Néel vector, which is different from the arbitrary spin polarization direction in electron systems. This property can be inferred from the spin transmission in the YIG, in which the spin current is blocked when the magnetization of YIG is perpendicular to the direction of the injected spin from Pt. Thus, the configuration in Fig. 3a corresponds to an “OFF” state for spin transmission due to the orthogonal relative orientation between the magnetization of YIG and the Néel vector of Cr$_2$O$_3$.

Then, it is highly desirable to reach an “ON” state for spin transmission in the same device. Since the inverse spin Hall effect in Pt can only detect the spin with an in-plane orientation, a nonzero component of the Néel vector in Cr$_2$O$_3$ in the sample plane is essential for measurable spin transmission for the present device. From the calculation of the Néel vector orientation in a uniaxial antiferromagnet under an external magnetic field, we found that the Néel vector can be tilted slightly when the external field is neither parallel nor perpendicular to it$^{23}$. Guided by this understanding, we measured the temperature dependence of the spin Seebeck effect in the Pt/Cr$_2$O$_3$/YIG device under different magnetic fields with a 20-degree tilting angle relative to the sample normal, the results of which are plotted in Fig. 3d. With an increase in the field magnitude from 0.5 T to 2.5 T, the enhancement of the spin Seebeck voltage is observed due to the rotation of the Néel vector. The change ratio due to the magnetic field, Ratio ($T_{S}$) = ($V_{SSE}@H - V_{SSE}@0.5T$)/$V_{SSE}@0.5T$, is plotted in Fig. 3e, which exceeds 500% for the temperature regime just below the Néel point and demonstrates an “ON” state for spin transmission. A systematic field angle dependence of the $V_{SSE}$ results can be found in the original paper, which supports the Néel vector rotation scenario$^{20}$. The Néel vector direction-dependent spin transport in AFMI has also been reported in a Pt/hematite/Pt lateral structure$^{24}$.
In addition to the recently studied spin transport, antiferromagnetic insulators also show a nontrivial effect on the magnetoresistance in neighboring heavy metals, such as Pt. In 2016, Shang et al. reported the temperature dependence of the magnetoresistance measurement in a Pt/NiO/YIG structure. It was found that Pt shows a typical spin Hall magnetoresistance (SMR) behavior at room temperature, which was described for a Pt/YIG bilayer structure. However, it is surprising that the SMR in Pt has a sign change for $T < 70$ K, which is hard to understand with the standard SMR model. Since the effect of NiO has been shown to quantitatively modulate the spin transmission between YIG and Pt, it is unexpected that the SMR shows a negative sign at low temperatures. We reproduced a sign change in a Pt/NiO/YIG device, and similar results were reported by another group. The measurement configurations are illustrated in Fig. 4a–c, and the SMR results at 260 K and 20 K are plotted in Fig. 4d, e, respectively, which show the same SMR symmetry with opposite signs. Thus, the task is to explain the sign change. To achieve this, the magnetoresistance is measured for the Pt/NiO/YIG samples in a wide range of NiO thicknesses from 1.6 nm to 30 nm. We noticed that the negative SMR is still finite even when the spin transmission between Pt and YIG is completely blocked for low temperature limits and thick NiO, indicating that the negative SMR is not caused by the spin current reflected from the YIG. Based on this observation, we develop the following interpretation, as illustrated in Fig. 3f. We attribute the negative SMR at low temperature to the NiO, which is assumed to have a 90° coupling with the YIG, which is a so-called spin-flip coupling. In other words, the Pt/NiO interface contributes a negative SMR because the Néel vector of NiO is always perpendicular to the magnetic field. It is worth noting that NiO shows parallel coupling with a ferromagnet in some cases and winds up in a domain under manipulation. With increasing temperature, the spin transmission between the Pt and YIG through the NiO, which contributes the conventional positive SMR, is enhanced. Therefore, a sign change of the SMR occurs when these two contributions compensate for each other. Recently, the spin-flip coupling between the NiO and YIG was confirmed by Luan et al. by polarized neutron reflectometry. The negative SMR in the Pt/NiO bilayer was also reported by several other groups. These works open the possibility of using AFM insulators as memory materials since orthogonal orientations of the Néel vector can be electrically determined. The prototype memory devices based on Pt/NiO bilayer structures were recently demonstrated independently by two groups, the results of which are shown in Fig. 4g, h.
Although spin transport has been demonstrated in several AFMIs, the mechanisms of spin transfer through an AFMI, which is indispensable for further device design and development, have not been clarified. The scaling law of magnon spin current is another important issue to be addressed, which is closely related to the mechanism of spin transport. It might be approached by either a good theory capable of fitting the experimental data or a nicely designed experiment yielding the scaling law. Some unique features have been systematically captured by experiments but are still hard to understand, e.g., the pronounced microwave frequency dependence of spin pumping efficiency near the Néel point\textsuperscript{15}. Meanwhile, the proposed spin transport mechanisms need to be carefully verified by some intelligent and well-controlled experiments\textsuperscript{16,38}. Another challenge lies in excitation of the THz dynamics of an AFMI by a spin current, which is quite interesting but still challenging due to the large anisotropy of antiferromagnets\textsuperscript{39–41}.

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Conflict of interest

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