Controlling spins in nanodevices via spin-orbit interaction, magnons and heat
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Chapter 7

Spin injection and detection via the anomalous spin Hall effect of a ferromagnetic metal

Abstract

We report a novel spin injection and detection mechanism via the anomalous Hall effect in a ferromagnetic metal. The anomalous spin Hall effect (ASHE) refers to the transverse spin current generated within the ferromagnet. We utilize the ASHE and its reciprocal effect to electrically inject and detect magnons in a magnetic insulator (yttrium iron garnet) in a non-local geometry. Our experiments reveal that permalloy has a comparable spin injection and detection efficiency to that of platinum, owing to the ASHE. We also demonstrate the tunability of the ASHE via the orientation of the permalloy magnetization, thus creating new possibilities for spintronic applications.

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7. Spin injection and detection via the anomalous spin Hall effect of a ferromagnetic metal

7.1 Introduction

In non-magnetic metals with high spin-orbit coupling, a charge current generates a transverse spin current via the spin Hall effect (SHE) [1, 2]. This type of spin current generation perpendicular to a charge current has a significant technological relevance for spin transfer torque devices [3, 4] and also for the electrical injection of magnons (quantized spin waves) in magnetic insulators [5, 7]. The electrical injection and detection of magnons offer a distinct technological advantage for the integration of magnon spintronics into solid state devices, over other magnon generation mechanisms such as spin pumping by radiofrequency fields [8] or the spin Seebeck effect due to a temperature gradient [9]. In this regard Platinum (Pt), a normal metal with a large spin-orbit coupling, is the most commonly used material for the electrical generation (and detection) of magnons via SHE. Recent studies showed that ferromagnets can also be utilized for electrical detection of magnons via the inverse spin Hall effect (ISHE) [10–13]. In particular, Tian et al. [13] reported that ISHE in a ferromagnetic cobalt was independent of its magnetization direction.

In a ferromagnetic metal the presence of the magnetization order parameter leads to the anomalous Hall effect (AHE) [14]. Here, we report a novel mechanism of spin current generation in a ferromagnet related to the AHE as described in theory [15]. The AHE generates a transverse electric potential, mutually orthogonal to the applied charge current (I) in a FM and its magnetization (M) direction. Due to a finite spin polarization in a FM, we expect that AHE can also result in a transverse spin accumulation. We call this effect the anomalous spin Hall effect (ASHE) in a ferromagnet. In addition to this new ASHE, the regular SHE due to the spin-orbit coupling in the ferromagnetic material will also be present and contribute to a spin accumulation perpendicular to I. The spin accumulation due to SHE in the FM will be independent of M, since the inverse process (ISHE) in a FM was shown to be independent of its magnetization by Tian et al. [13]. To demonstrate this mechanism we realize for the first time non-local magnon transport in a ferrimagnetic insulator, yttrium iron garnet(Y$_3$Fe$_5$O$_{12}$, YIG), with all-electrical injection and detection using a ferromagnetic metal, permalloy (Ni$_{80}$Fe$_{20}$, Py). The insulating spin transport channel (YIG) facilitates our observation of ASHE due to the lack of any parallel conducting path. Our experimental geometry is depicted in Fig. 7.1(a). A charge current (I) sourced through a Py strip will result in a transverse spin accumulation. Given the presence of both a large spin-orbit coupling and a magnetization order parameter, we consider two contributions to the spin accumulation at the Py/YIG interface: i) SHE, which is independent of the Py magnetization ($M_{Py}$) [13] and ii) ASHE, which is maximized when $M_{Py}$ is perpendicular to the direction of I. This spin accumulation at the Py/YIG interface will generate magnons in the YIG by the transfer of angular momentum across the interface. Following the non-local magnon transport and its
conversion into a pure spin current at the Py detector, there are reciprocal processes (ISHE and a magnetization-dependent inverse ASHE) that will generate an electrical voltage (V). Using a reference Pt detector, we directly compare the detection efficiencies of Py and Pt. Our experiments reveal that the detection efficiency of Py is comparable (10% higher) to that of Pt when the contribution due to ASHE in the Py is tuned to its maximum value.

7.2 Experimental details

The 210 nm thick YIG film used in this study was grown on GGG (Gd$_3$Ga$_5$O$_{12}$) substrate by liquid-phase epitaxy. Electron beam lithography was used to pattern the devices, which consist of two Py strips and one reference Pt strip, as shown in the optical image in Fig. 7.1(b). The Py and Pt strips were deposited by d.c. sputtering in Ar$^+$ plasma. The Ti/Au leads and bonding pads were deposited by e-beam evaporation. The thicknesses of the Py and the Pt strips are 13 nm and 7 nm respectively, with widths of 200 nm. The electrical conductivities of the Py and Pt strips were measured to be $1.64 \times 10^6$ S/m and $4.71 \times 10^6$ S/m, respectively. The middle Py strip is used as the injector and the left Py strip and right Pt strip act as detectors. Both the Py and Pt detectors have the same geometry and are located 500 nm (centre-to-centre) away.
from the middle Py injector. The electrical connections for the non-local magnon transport experiment are shown schematically in Fig. 7.1(b). An alternating current, with an amplitude of 350 \( \mu \)A and frequency of 11 Hz, is applied to the middle Py strip (injector). The non-local voltage across the left Py detector \( V_{Py} \) and across the reference Pt detector \( V_{Pt} \) are simultaneously recorded by a phase-sensitive lock-in detection technique. The linear signal corresponding to the electrical injection and detection is measured as the first harmonic \( (1f) \) response of the non-local voltage \[6\], while the thermally generated magnons due to Joule heating at the injector are detected as a Spin Seebeck signal, measured as the second harmonic \( (2f) \) response.

For all our experiments, we normalize the detected non-local voltage \( V_{1(2)f} \) by the injection current \( I \) for the first harmonic response \( R_{1fNL} = V_{1f}/I \) and by \( I^2 \) for the second harmonic response \( R_{2fNL} = V_{2f}/I^2 \). All measurements have been conducted under a low vacuum atmosphere at room temperature.

### 7.3 Results and discussion

An external in-plane magnetic field \( (B) \) is applied at an angle \( \theta \) with respect to the direction of the strips (and \( I \)), as shown in Fig. 7.1(c). The coercive field of our YIG film is approximately 1 mT \[16\] and any \( B \) greater than this value will cause the YIG magnetization \( (M_{YIG}) \) to align parallel to \( B \). On the other hand, the Py strips have a shape anisotropy, which leads to a higher saturation field and to the Py magnetization \( (M_{Py}) \) fully aligning along \( B \) only above 50 mT. In general, for \( B < 50 \) mT, \( M_{Py} \) makes an angle \( \phi (\neq \theta) \) with respect to \( I \). The experimental data is presented in Figs. 7.2(a-d). The non-local resistance, corresponding to the electrical generation and detection of the magnons, is measured as a function of the angle \( \theta \) by the Py detector \( R_{1fNL}(Py) \) and the Pt detector \( R_{1fNL}(Pt) \), as shown in Figs. 7.2(a) and 7.2(b), respectively. \( R_{1fNL}(Py) \) and \( R_{1fNL}(Pt) \) exhibit lineshapes resembling that of \( \sin^2 \theta \) \[6\].

The angular dependence measurements are performed for different magnitudes of \( B \). The amplitudes of both \( R_{1fNL}(Py) \) and \( R_{1fNL}(Pt) \) increase with \( B \) and saturate above \( B \approx 50 \) mT. This behaviour is confirmed in the \( B \)-sweep measurements at \( \theta = 90^\circ \), shown in Figs. 7.2(c) and 7.2(d) for the Py and the Pt detectors, respectively.

The \( B \)-dependence of \( R_{1fNL}(Py) \) and \( R_{1fNL}(Pt) \) follows from the rotation of \( M_{Py} \). At low \( B \), \( M_{Py} \) is aligned along the easy axis of the Py strips (y-axis, see definition of axes in Fig. 7.1(c)), such that \( \phi = 0^\circ \) independently of \( \theta \). In this regime, when \( M_{Py} \parallel I \), there is no contribution from the ASHE. However, we still measure a finite amplitude of \( R_{1fNL}(Py) \) and \( R_{1fNL}(Pt) \), which we attribute to the magnons generated due to the SHE in Py, which is independent of \( M_{Py} \) \[13\]. This contribution due to SHE, denoted as \( R_{SHE} \) in Figs. 7.2(a) and 7.2(b), remains approximately constant for
7.3. Results and discussion

Figure 7.2: Non-local resistance ($R_{NL}^{1f}$) as a function of angle $\theta$ for different magnetic fields ($B$), measured by the Py detector (a) and by the reference Pt detector. (b). Dependence of $R_{NL}^{1f}$ on $B$ at a fixed angle, $\theta = 90^\circ$, measured by the Py detector (c) and the Pt detector (d). The black and the red curves represent trace and retrace of $B$ in the magnetic field sweep measurements, respectively.

As $B$ is further increased above 10 mT, $M_{Py}$ begins to tilt from the easy axis ($\phi \neq 0^\circ$), leading to a finite contribution towards magnon generation due to the ASHE. This contribution will be maximum when $M_{Py} \perp I$, i.e. $\phi = \pm 90^\circ$, which corresponds to $M_{Py}$ aligned along the hard axis of the Py strips (x-axis). The hard axis orientation of $M_{Py}$ is achieved for $B \approx 50$ mT, above which $R_{NL}^{1f}(Py)$ and $R_{NL}^{1f}(Pt)$ are saturated. Thus in this regime, both ASHE and SHE contribute, quantified as $R_{ASHE+SHE}$ in Figs. 7.2(a) and 7.2(b).

We also measure the second harmonic response $R_{NL}^{2f}$ for both the Py and Pt detectors, as well as the anisotropic resistance (AMR) of the Py strips, as shown in Figs. 7.3(a) and 7.3(b), respectively. The thermally generated magnons due to Joule heating at the Py injector produce the $R_{NL}^{2f}$ signal at the detector, via the spin See-
7. Spin injection and detection via the anomalous spin Hall effect of a ferromagnetic metal

Figure 7.3: (a) The second harmonic response of the non-local resistance ($R_{NL}^{2f}$) as a function of $B$, for $\theta = 90^\circ$. $R_{NL}^{2f}$ measured by both the Pt and the Py detectors shows a sharp switch around $B = 0$, corresponding to the switching of $M_{YIG}$. The additional feature, only for the case of the Py detector, is due to the hard axis alignment of $M_{Py}$. (b) AMR measurement of the Py injector, exhibiting the saturation of $M_{Py}$ along the hard axis at $B \approx 50$ mT. (c) Schematic representation of $M_{Py}$ with respect to $I$ for two different magnetic fields (5 mT and 200 mT). (d) The relative detection efficiency of Py over Pt ($\eta(Py/Pt)$), as a function of $B$, for $\theta = 90^\circ$.

beck effect [6]. Thus $R_{NL}^{2f}$ is independent of the magnetization of the injector. In Fig. 7.3(a), $R_{NL}^{2f}$ measured by the Pt detector exhibits a sharp switch around 0 mT, corresponding to the switching of $M_{YIG}$. A similar sharp switch is observed in the $R_{NL}^{2f}$ measured by the Py detector, only now it is followed by a gradual hard axis saturation of $M_{Py}$, up to $B \approx 50$ mT. Thus from $R_{NL}^{2f}(Py)$, we can clearly identify the separate behaviour of $M_{YIG}$ and $M_{Py}$, suggesting the lack of any strong coupling between the two. Additional experiments also ruled out the effect of interfacial exchange interaction between the YIG and the Py (see supporting information). The hard axis saturation of $M_{Py}$ is unambiguously confirmed from the AMR measure-
7.3. Results and discussion

The local resistance (2-probe) of the Py injector is measured as a function of $B$ for $\theta = 90^\circ$. It clearly shows that $B \approx 50 \text{ mT}$ is required to align $M_{\text{Py}} \perp I$, which corresponds accurately with the non-local data in Figs. 7.2 and 7.3(a). The orientations of $M_{\text{Py}}$ and $M_{\text{YIG}}$ with respect to $I$ in the Py injector, for two different magnetic field strengths, are illustrated in Fig. 7.3(c). These observations strongly support our hypothesis of two different contributions: ASHE and SHE.

We now directly compare the magnon detection efficiencies of Py and Pt in the same device. Since the spin resistance of the medium (YIG) is much larger than the spin resistances of the injector and detectors [17], the measured non-local resistance can be expressed as a product of the injection efficiency ($\eta_I$) of the injector and detection efficiency ($\eta_D$) of the detector. $\eta_I$ is the ratio of the spin accumulation created at the injector/YIG interface to the charge current sourced through the injector, whereas $\eta_D$ is the ratio of the measured non-local voltage in the detector to the spin current flowing across the YIG/detector interface. Thus, $R_{\text{NL}}^{\text{ff}}(\text{Py}) \propto \eta_I(\text{Py})\eta_D(\text{Py})$ and $R_{\text{NL}}^{\text{ff}}(\text{Pt}) \propto \eta_I(\text{Py})\eta_D(\text{Pt})$, since we use the same Py injector in both cases. The relative detection efficiency of Py to Pt can then be expressed as $\eta(\text{Py}/\text{Pt}) = R_{\text{NL}}^{\text{ff}}(\text{Py})/R_{\text{NL}}^{\text{ff}}(\text{Pt}) = \eta_D(\text{Py})/\eta_D(\text{Pt})$. In the lack of any theoretical study on ASHE, we phenomenologically express the dependence of the non-local resistance by updating Eq. 3 of Ref. [10]:

$$\eta_D(\text{Py}) \propto (\theta_{\text{SH}}^{\text{Py}} + \theta_{\text{ASH}}^{\text{Py}}) \frac{\lambda_{\text{Py}}}{t_{\text{Py}} \sigma_{\text{Py}}} \tanh\left(\frac{t_{\text{Py}}}{2\lambda_{\text{Py}}}\right),$$

(7.1)

where, $\theta_{\text{SH}}^{\text{Py}}$ is the spin Hall angle in Py, $\theta_{\text{ASH}}^{\text{Py}}$ is the anomalous spin Hall angle, accounting for the spin-charge conversion in Py via the ASHE, $\lambda_{\text{Py}}$, $\sigma_{\text{Py}}$ and $t_{\text{Py}}$ being the spin relaxation length, electrical conductivity and the thickness of the Py strip, respectively. Considering $\lambda_{\text{Py}} = 2.5 \text{ nm}$ [10] and $t_{\text{Py}} = 13 \text{ nm}$, $\tanh\left(\frac{t_{\text{Py}}}{2\lambda_{\text{Py}}}\right) \approx 1$. $\eta_D(\text{Pt})$ can be expressed similarly as relation 7.1 with the absence of the anomalous spin Hall angle in Pt. Considering $\lambda_{\text{Pt}} = 1.5 \text{ nm}$ [17] and $t_{\text{Pt}} = 7 \text{ nm}$, $\tanh\left(\frac{t_{\text{Pt}}}{2\lambda_{\text{Pt}}}\right) \approx 1$. For accurately comparing the detection efficiencies of Py and Pt (considering that $\theta_{\text{ASH}}$, $\lambda$ and $\sigma$ are material specific properties), we account for the difference in their thicknesses and redefine $\eta(\text{Py}/\text{Pt}) = |R_{\text{NL}}^{\text{ff}}(\text{Py}) \cdot t_{\text{Py}}|/|R_{\text{NL}}^{\text{ff}}(\text{Pt}) \cdot t_{\text{Pt}}|$. The ratio $\eta(\text{Py}/\text{Pt})$ is thus directly derived from the experimental data and normalized only by the thicknesses of the Py and Pt strips. In Fig. 7.3(d), $\eta(\text{Py}/\text{Pt})$ is plotted against $B$. The detection efficiency of Py exceeds that of Pt [(\eta(\text{Py}/\text{Pt}) \geq 1)] in the SHE+ASHE regime, where the ASHE in Py is maximized. In the SHE only regime, the detection efficiency of Py is about 55% that of Pt. These observations show that the SHE and ASHE contributions in Py have the same polarity as the SHE in Pt. Note that since the electrical injection and detection are linear processes, the injection efficiency is equivalent to the detection efficiency. We therefore demonstrate an efficient and tunable magnon
injection and detection process in Py by manipulating $M_{Py}$, switching on and off the contribution from the ASHE.

Figure 7.4: The modelled $R_{NL}^{1f}(Py)$ and $R_{NL}^{1f}(Pt)$ from Eqs. 7.2 and 7.3 are plotted against $\theta$ in (a) and (b), respectively. The magnetic field dependence of $R_{NL}^{1f}(Py)$ and $R_{NL}^{1f}(Pt)$ is modelled in (c) and (d), respectively. The simulated results exhibit an excellent agreement with the experimental data in Fig. 7.2.

The SHE will generate a spin accumulation in Py perpendicular to $I$, along the x-axis. The component of this spin accumulation parallel to $M_{YIG}$ will result in the generation of magnons in YIG. Thus the magnon generation due to the SHE will follow a $\sin \theta$ dependence [6] and will be independent of $M_{Py}$ [13]. On the other hand, the contribution due to the AHE is two-fold and proportional to $\sin \phi \cdot \cos(\theta - \phi)$. The first term $\sin \phi$ corresponds to the magnitude of the spin accumulation due to ASHE, controlled by the orthogonality between $I$ and $M_{Py}$, whereas the second term $\cos(\theta - \phi)$ corresponds to the projection of the spin accumulation due to ASHE (along $M_{Py}$) on $M_{YIG}$. The corresponding reciprocal processes will occur in the Py detector.
7.4. Conclusions

In this study, we have demonstrated a new spin injection and detection mechanism via the ASHE in Py, which can be tuned by an external magnetic field via manipulation of \( M_{Py} \). We also found a finite contribution to the spin accumulation generated to generate \( R_{NL}^{1f}(Py) \). In the Pt detector, the spin to charge conversion will occur only via the ISHE and follow a \( \sin \theta \) dependence. \( R_{NL}^{1f}(Py) \) and \( R_{NL}^{1f}(Pt) \) can therefore be expressed as:

\[
R_{NL}^{1f}(Py) = [a \sin \theta + b \sin \phi \cos(\theta - \phi)]^2, \quad (7.2)
\]
\[
R_{NL}^{1f}(Pt) = c \sin \theta \sin \phi \cos(\theta - \phi), \quad (7.3)
\]

where the coefficients \( a, b \) and \( c \) can be expressed as \( a \propto \frac{G_{Py} \theta_{Py} \lambda_{Py}}{t_{Py} \sigma_{Py}} \), \( b \propto \frac{G_{Py} \theta_{ASH} \lambda_{Py}}{t_{Py} \sigma_{Py}} \) and \( c \propto \frac{G_{Pt} \theta_{Py} \lambda_{Pt}}{t_{Pt} \sigma_{Pt}} \), where \( G_{Py(Pt)} \) represent the effective spin mixing conductance for the Py(Pt)/YIG interface. Considering the case of \( \phi = 0^\circ \) and \( \theta = 90^\circ \) (low \( B \)) and equating Eq. 7.2 to \( R_{NL}^{1f}(Py) \) obtained from Fig. 7.2(a), we calculate \( a = 0 \) m\( \Omega \) \( 1/2 \). For \( \phi = 90^\circ \) and \( \theta = 90^\circ \) (high \( B \)), and substituting the value of \( a \) in Eq. 7.2, we calculate \( b = 0 \) m\( \Omega \) \( 1/2 \). Using these values of \( a \) and \( b \) and Eq. 7.3, we find \( c = 2.58 \) m\( \Omega \) \( 1/2 \).

Next, for simulating the angular dependence measurements, we first consider the two extreme cases: i) the high \( B \) regime \( (B \approx \infty) \), where \( M_{Py} \) is always aligned parallel to \( M_{YIG} \), such that \( \phi = \theta \) and ii) the low \( B \) regime \( (B \approx 0) \), where \( M_{Py} \) is always aligned parallel to \( I \), such that \( \phi = 0^\circ \). Substituting the values of the coefficients calculated above in Eqs. 7.2 and 7.3, we model the angular dependence of \( R_{NL}^{1f}(Py) \) and \( R_{NL}^{1f}(Pt) \), as shown in Figs. 7.4(a) and (b), respectively. For the intermediate regime of \( B \) \( (0 < B < \infty) \), we use the Stoner-Wohlfart model \[18\] to calculate the dependence of \( \phi \) on \( \theta \) for different values of \( B \), assuming a simple uniaxial shape anisotropy for \( M_{Py} \), in order to simulate the angular dependence for different magnitudes of \( B \). For modelling the \( B \)-sweep measurements, we extract the dependence of \( \phi \) on \( B \) from the AMR measurement in Fig. 7.3(b), following the expression \[19, 20\]

\[
R_{Py}(B) = R_{Py}(\phi = 90^\circ) + [R_{Py}(\phi = 0^\circ) - R_{Py}(\phi = 90^\circ)] \cos^2 \phi(B). \]

The modelled results for the \( B \)-sweep measurements, using the same coefficients, are shown in Fig. 7.4(c) and (d) for the Py and the Pt detectors, respectively. All the modelled results exhibit an excellent agreement with the experimental data both in terms of line-shapes and magnitudes of the non-local resistances. Finally, we can approximately calculate the ratio \( \left[ G_{Py} \cdot \theta_{SH}^{Py} \right] / \left[ G_{Pt} \cdot \theta_{SH}^{Pt} \right] \approx (a \frac{t_{Py} \sigma_{Py}}{\lambda_{Py}})/(c \frac{t_{Pt} \sigma_{Pt}}{\lambda_{Pt}}) = 0.09 \). Additionally, we can estimate the ratio of the magnetization-dependent anomalous spin Hall angle to the magnetization-independent spin Hall angle in Py, \( \frac{\theta_{ASH}^{Py}}{\theta_{SH}^{Py}} \approx b/a = 1.28 \).

7.4 Conclusions

In this study, we have demonstrated a new spin injection and detection mechanism via the ASHE in Py, which can be tuned by an external magnetic field via manipulation of \( M_{Py} \). We also found a finite contribution to the spin accumulation generated...
at the Py/YIG interface due to the SHE, independent of $M_{Py}$. This spin accumulation along the x-axis is non-trivial, since one would expect the spins to dephase under the influence of the exchange field of $M_{Py}$ which is oriented along the y-axis at low magnitudes of $B$. Following a previous report of ISHE in Co being unaffected by its magnetization [13], we conjecture that in Py (with lower magnetization) such dephasing is similarly negligible. Future efforts could look at the possible role of the spin mixing conductance and its nature when the concept is applied to the interface between two magnetic materials [21] [22]. Our work opens up the usage of ferromagnets as efficient and tunable sources of perpendicular spin current injection by electrical means.
7.5 Supporting information

7.5.1 Ruling out the effect of interfacial exchange interaction between YIG and Permalloy

The role of any relevant interfacial exchange interaction between the YIG film and the Py strips has been carefully investigated. With the support of the following experiments and observations, we confirm the absence of strong coupling between the Py and the YIG magnetizations and that their magnetizations ($M_{Py}$ and $M_{YIG}$) can move freely at the interface.

1. The most striking feature of our experimental data that rules out the presence of textures due to strong interfacial coupling between $M_{Py}$ and $M_{YIG}$, is the angular dependence measurements presented in Fig. 2(a-b) of the main text. We observe smooth curves even at low magnetic fields, which would otherwise be distorted in the presence of interfacial exchange interaction. To further investigate the effect of any interfacial exchange interaction, we carried out additional experiments by aligning the YIG and the Py magnetizations parallel (P) and anti-parallel (AP) with respect to each other before proceeding with the angular dependence measurements. The presence of strong exchange interaction would lead in the P-alignment case to an initial state where there is no texture to a state with a $180^\circ$ rotation of the magnetic order from the YIG to the Py (like a domain wall). Whereas the AP-alignment case would lead to an opposite scenario, with a $180^\circ$ texture getting unwinded as one proceeds with the angular dependence measurements. This would lead to a different angular dependence and magnitude of the signal for the P and the AP cases. Moreover, the trace and retrace of these curves should also exhibit significant differences in the presence of magnetic textures. However, we do not observe any significant difference between the two states and the traces and retraces within our experimental accuracy. In Fig. 7.5, the first harmonic signals measured by the Py and the Pt detectors at a field of 10 mT, less than the coercive field of our Py wires (evident from the AMR data in Fig. 7.7), are presented. The smooth shape of these curves can therefore result only due to the free rotation of the YIG magnetization.

2. A strong interfacial exchange interaction, should affect the magnetization orientation of both the Py and the YIG. On the YIG side, a magnetic texture would result in distortion of the spin Seebeck curve (second harmonic data shown in Fig. 7.6) measured by the Pt detector as well. However, we see a sharp switch
7. Spin injection and detection via the anomalous spin Hall effect of a ferromagnetic metal

Figure 7.5: Non-local resistance ($R_{\text{NL}}^{1f}$) as a function of angle $\theta$, along which a magnetic field $B = 10$ mT is applied with respect to the current ($I$) through the Py injector, measured by the Py detector (a) and by the reference Pt detector (b). Before the measurements were started, $M_{\text{Py}}$ and $M_{\text{YIG}}$ were either aligned parallel (P) or anti-parallel (AP) with respect to each other. Both the trace and retrace curves are shown for each of the configurations.

Figure 7.6: The second harmonic response (spin Seebeck signal) of the non-local resistance ($R_{\text{NL}}^{2f}$) as a function of $B$, for $\theta = 90^\circ$. $R_{\text{NL}}^{2f}$ measured by both the Pt and the Py detectors show a sharp switch around $B = 0$, corresponding to the switching of $M_{\text{YIG}}$.

in the spin Seebeck signal at low magnetic field, corresponding to the switching of the YIG magnetization. The second harmonic response measured by the Py detector also exhibits this sharp switching at the same magnetic field, followed by a slow hard axis saturation, which would not be the case in the
presence of inhomogeneous textures of the magnetization. Note that the hysteresis in the magnetic field sweep curves is mostly due to the hysteresis in the superconducting magnet used for these experiments.

3. On the Py side, any effect of an interfacial exchange interaction on its magnetization should decay within a length scale of about 5 nm, given by the magnetic exchange length in Py. This is about 40% of the thickness of the Py film. Therefore, any magnetic texture present in the Py should also affect the anisotropic magnetoresistance (AMR) measurement of the Py wire. However, in Fig. 7.7 we see a smooth AMR curve of the Py wire without any signature of magnetic texture. Note that the hysteresis is again due to the hysteresis in the superconducting magnet.

![Figure 7.7: Anisotropic magnetoresistance (AMR) measurement of the Py injector, exhibiting the saturation of $M_{py}$ along the hard axis at $B \approx 50$ mT.](image)

4. Furthermore, just by taking into account the shape anisotropy of the Py wire and the corresponding AMR data, we are able to model the experimental data accurately in Fig. 4 of the main text. Thus all the features of the experimental data can be modelled just by the shape anisotropy of the Py wire, which would be highly unlikely in the presence of a relevant interfacial exchange interaction.

5. In addition to the in-plane measurements, we have carried out out-of-plane magnetic field sweeps and measured the second harmonic response of the non-local resistance ($R_{2f, NL}^f$) across the Py detector and the Pt detector. For these out-of-plane measurements, $R_{2f, NL}^f$ measured by the Py detector is dominated by the anomalous Nernst effect (ANE), resulting from an in-plane heat flow in combination with the out-of-plane orientation of $M_{py}$. In contrast, the Pt de-
Spin injection and detection via the anomalous spin Hall effect of a ferromagnetic metal

Figure 7.8: The second harmonic response of the non-local resistance ($R_{2f}^{NL}$), measured by the Py detector (a) and by the reference Pt detector (b), as a function of an out-of-plane magnetic field applied at different angles (indicated in the legend) along the $xz$-plane with respect to the $x$-axis. $R_{2f}^{NL}$ measured by the Py detector is dominated by the anomalous Nernst effect (ANE) and increases as $M_{Py}$ goes out-of-plane. In contrast, $R_{2f}^{NL}$ measured by the Pt detector is sensitive only to the spin Seebeck effect (SSE) and decreases as $M_{YIG}$ goes out-of-plane.

The Py detector is only sensitive to the spin Seebeck effect and dependent on $M_{YIG}$. With these measurements, we can separately study the magnetization behaviour of the YIG film and the Py strips, which saturate at different magnetic fields ($\approx 200$ mT for the YIG film and $\approx 550$ mT for the Py strips). This clearly demonstrates the lack of any strong interfacial exchange interaction between the two. These out-of-plane magnetic field sweep experiments are shown in Fig. 7.8 for different angles along the $xz$-plane with respect to the $x$-axis. For the Py detector, as $M_{Py}$ goes out-of-plane, ANE starts to dominate and an overall increase in the signal is observed till $M_{Py}$ gets completely saturated in the out-of-plane direction (along the $z$-axis). For the Pt detector, in the absence of the ANE, we can clearly observe the decrease in the spin Seebeck effect (SSE) as $M_{YIG}$ goes out-of-plane. From these out-of-plane experiments, we can clearly identify the separate magnetization behaviour of YIG and Py.

Therefore, via five different methods we conclude that $M_{Py}$ and $M_{YIG}$ behave in an uncoupled manner. We do not observe any signature of interfacial exchange interaction that is strong enough to couple the magnetizations of YIG and Py at the interface, leading to inhomogeneous textures in the two magnetic materials. Note that such an interfacial exchange interaction would require a coherent coupling between $M_{Py}$ and $M_{YIG}$. The absence of such a strong interfacial exchange interaction is not in contradiction with our observation of
transport-driven spin transfer between the magnons in the YIG and electrons in the Py since the latter requires conservation of spin angular momenta via an exchange between the electron spins in the Py and the magnon spins in the YIG and does not necessarily require an exchange interaction between the magnetizations of the two materials.

References


Spin injection and detection via the anomalous spin Hall effect of a ferromagnetic metal


