Distinguishing spin pumping from spin rectification in a Pt/Py bilayer through angle dependent line shape analysis

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Distinguishing spin pumping from spin rectification in a Pt/Py bilayer through angle dependent line shape analysis

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A pure spin current driven by spin pumping is converted to a DC voltage and detected electrically in a Py/Pt bilayer sample. This DC voltage mixes with a DC voltage produced through spin rectification. The ferromagnetic resonance line shape strongly depends on the microwave magnetic field distribution. We have systematically studied the line shapes by changing the external magnetic field orientation in plane of a Pt/Py bilayer. A method is demonstrated which allows us to calculate the microwave field vector distribution, and distinguish spin pumping from spin rectification. © 2013 AIP Publishing LLC.

Spin pumping is a recently developed method for generating spin currents (others include DC injection and optical excitation) and has recently attracted much attention. The process of spin pumping drives a pure spin current from a ferromagnetic metal (FM) into a normal metal (NM) via ferromagnetic resonance (FMR); this current is then converted to a DC voltage in the Pt through the inverse spin Hall effect (ISHE) and detected electrically. In similar samples, the spin rectification effect will also generate a DC voltage through anisotropic magnetoresistance (AMR) in the FM material. The two DC voltages generated by spin rectification and spin rectification will mix together during measurement and cannot be easily separated. One method for distinguishing the voltages generated by these two effects involves examining the symmetry properties of the FMR line shape. Previous works have assumed that a Lorentz line shape originates solely from spin pumping and that a dispersive line shape originates solely from spin rectification; this assumption demands that, when the external magnetic field is applied in plane to the bilayer, the microwave magnetic field vector distribution and determined the relative phase respect to the microwave current. Therefore, we established a method for separating spin pumping and spin rectification in general spintronics devices.

The sample was prepared using photolithography, magnetron sputtering deposition, and lift-off on semi-insulating GaAs substrates. To simplify the h field distribution, a Pt (18 nm)/Py (20 nm) bilayer sample was patterned between the signal (S) and ground (G) lines of a CPW to set the microwave magnetic h field along the normal direction of the strip, as shown in Fig. 1(a). The bilayer has lateral dimensions of 20 μm × 2.5 mm. The sample resistance was 1070 Ω and its saturation magnetization μ0M0 was 1030 mT. FMR was excited by sending a microwave signal through the CPW and was electrically detected by lock-in via probes at both ends of the strip along the x axis by sweeping the external magnetic field H. The microwave signal was modulated at a frequency of 8.33 kHz. The external magnetic field H was applied in the x-y plane at an angle θ with respect to the x axis, as shown in Fig. 1(b). The dependence of the DC voltage on θ was determined.

Figure 2(a) displays a DC voltage as a function of the external magnetic H field at 8 GHz. Such a curve can be fitted to the following equation of consisting a linear combination of dispersive and Lorentz line shape components

\[ V = \frac{L \Delta H^2}{(H - H_0)^2 + \Delta H^2} + D \frac{\Delta H (H - H_0)}{(H - H_0)^2 + \Delta H^2}, \]

where H0 is the resonant magnetic field and ΔH is the half width at half maximum. D and L are the amplitudes of both line shape components. The dispersive and Lorentz curves are plotted separately in Fig. 2(a). Figure 2(b) plots the DC voltage as a function of the external magnetic field H for several θ angles. It clearly shows that the line shape of the DC voltage changes with θ.

Spin rectification leads to different dispersive and Lorentz line shape amplitudes depending on the microwave magnetic h field distribution and its relative phase respect to the microwave current \( j_r \), which can be deduced from

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The Landau-Lifshitz Gilbert equation as seen in the following equations:

\[
\frac{DSR}{\sin(2\theta)} = (A_L h_x^2 \cos(\theta) - A_T h_x^2 \sin(\theta)) - A_L h_y^2 \sin(\theta) - A_T h_y^2.
\] (2a)

\[
\frac{LSR}{\sin(2\theta)} = (A_L h_x^2 \cos(\theta) + A_L h_y^2 \sin(\theta)) - A_T h_x^2.
\] (2b)

Here, the coefficients \(A_L\) and \(A_T\) are the longitudinal and transverse elements in the Polder tensor with the demagnetization field taken into account, and the superscripts \(r\) and \(i\) indicate the real and imaginary parts of the \(h\) component which are in phase and 90°-out-of-phase with the microwave current \(j_x\) in the Py, respectively.

The dispersive amplitude \(D\) shown in Fig. 3(a) originates entirely from spin rectification and thus follows Eq. (2a). The \(\sin(2\theta)\) symmetry means that the dispersive amplitude crosses zero at the angles 0°, 90°, 180°, and 270°. Due to the spin pumping component present in the Lorentz amplitude \(L\), it does not have the same symmetry properties of the dispersive amplitude, notably not crossing zero at 90° and 270°.

The \(\theta\) dependence of the spin pumping DC voltage is dominated by a \(\sin(\theta)\) term which is the component of spin pumping voltage along \(x\) axis, as shown in the following equation:

\[
L_{SP} \propto \langle m^2 \rangle \sin(\theta).
\] (3)

It is clear that spin pumping contributes a non-zero signal when \(\theta\) equals 90° and 270°. \(\langle m^2 \rangle\) is a function of the microwave \(h\) field distribution as well. However, as \(h_z\) is dominant in our sample, we are allowed to make the approximation that \(\langle m^2 \rangle\) is independent of \(\theta\). Thus, a linear combination of Eqs. (3) and (2b) can be used to describe the Lorentz amplitude as a function of \(\theta\). The dashed line in Fig. 3(b) indicates a good agreement between this theory and the experimental results.

The microwave \(h\) field components found through fitting the data in Figs. 3(a) and 3(b) to Eqs. (2) and (3) are listed in Table I.

Here, phases are measured with respect to the phase of the microwave current \(j_x\) in the Py. From this table, we see...
that the out-of-plane component of the microwave field $h_z$ is dominant, as was expected from our sample design, and that its relative is shifted slightly from $-\pi/2$, indicating that the spin rectification voltage produced by our sample will not have a pure dispersive line shape. We also see that $h_y$ has a non-negligible amplitude with respect to $h_z$ and a phase of approximately $10^\circ$ with respect to $j_z$, this indicates that $h_y$ will affect the FMR line shape of our sample as well.

Beyond allowing the microwave $h$ field distribution to be calculated, this analysis separates the DC voltages due to spin rectification and spin pumping as shown in Fig. 3(b) using a gray and black solid lines. The gray line shows that the voltage due to spin rectification crosses zero at each symmetric angle ($0^\circ$, $90^\circ$, $180^\circ$, and $270^\circ$) just like the dispersive component. But the spin pumping component does not disappear at $90^\circ$ and $270^\circ$, as highlighted by the arrows in Fig. 3(b). At those angles, the measured voltage represents a pure spin pumping signal. From this, it is clear that spin rectification is not an ignorable component in the Lorentz line shape. Such an angle dependent line shape analysis is suitable for all frequencies in this device.

It is worth noting that the Anomalous Hall Effect (AHE), in addition to AMR, contributes to spin rectification. The magnetoresistance change due to AHE in Py is two orders of magnitude smaller than that of AMR, therefore, AHE can be ignored in this work. Spin torque is another issue in such a Pt/Pt bilayer, which is induced by a microwave current flowing through the Pt layer via spin orbit interaction in Pt and detected through spin rectification. In this work, microwave current was sent through the signal line of the CPW rather than the Pt, hence, the Oersted field plays a far greater role than that of spin torque. As a secondary effect, it might slightly modify the calculated microwave $h$ distribution but not affect the spin rectification and spin pumping signals.

In this work, we have systematically studied line shape as a function of the external magnetic field $H$ orientation (for in plane geometries). We have demonstrated a method which can calculate the magnetic $h$ field distribution and distinguish spin pumping from spin rectification.

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<td>0.154</td>
<td>-0.033</td>
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<tr>
<td>Imaginary part</td>
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<td>Phase</td>
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References