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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 h 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 h field vector distribution, and distinguish spin pumping from spin rectification. © *2013 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4811482]

Spin pumping is a recently developed method for generating spin currents (others include DC injection and optical excitation) and has recently attracted much attention.[1–7] 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.[1–3,6] In similar samples, the spin rectification effect will also generate a DC voltage through anisotropic magnetoresistance (AMR) in the FM material.[8,9] 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;[4] this assumption works well in specially designed devices. However, this assumption demands that, when the external magnetic field is applied in plane to the bilayer, the microwave magnetic h fields parallel and perpendicular to the Pt/Py plane must have relative phases of zero and $\pm\pi/2$ (with respect to the microwave current in the Py), respectively.[11] These strict conditions will generally not be true for most Pt/Py samples.

In general samples, where the microwave h field distribution does not obey the conditions defined above, the DC voltage generated by spin rectification will contain elements of both Lorentz and dispersive line shapes,[9–11] this has been shown in studies of pure spin rectification in a single Py strip placed between the strips of a coplanar waveguide (CPW).[11] Azevedo *et al.* has also previously studied spin rectification and spin pumping in Pt/Py bilayers within rectangular microwave cavities where the h field distribution was well known.[2] In this work, we systematically study the FMR line shape of a Pt/Py bilayer integrated with a CPW in which the h field might be disturbed by the presence of the Pt/Py bilayer. By rotating the external magnetic field **H** in the Pt/Py bilayer plane, we obtained the microwave magnetic h 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.[7] 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 $20\,\mu\text{m} \times 2.5\,\text{mm}$. The sample resistance was $1070\ \Omega$ and its saturation magnetization $\mu_0 M_0$ 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

$$V = L\frac{\Delta H^2}{(H-H_0)^2+\Delta H^2} + D\frac{\Delta H(H-H_0)}{(H-H_0)^2+\Delta H^2}, \quad (1)$$

where H_0 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_x,[12] which can be deduced from

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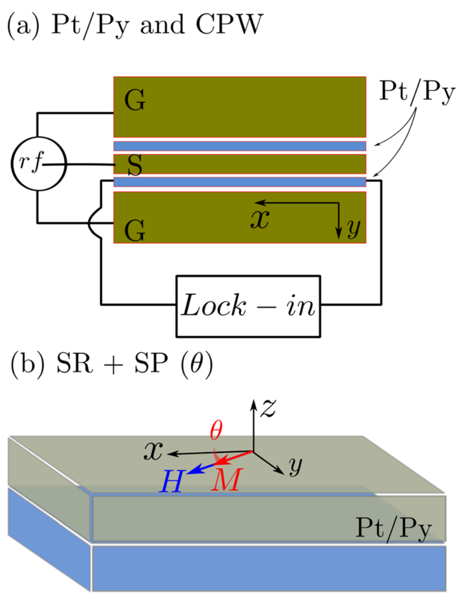

FIG. 1. (a) The Pt/Py bilayer was patterned in between the G and S lines of the CPW. (b) While the external magnetic field **H** is applied in the x-y plane, a DC voltage due to both spin rectification and spin pumping can be detected.

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

$$D_{SR} \propto \sin(2\theta)(A_L h_y^r \cos(\theta) - A_L h_x^r \sin(\theta) - A_T h_z^i), \quad (2a)$$

$$L_{SR} \propto \sin(2\theta)(-A_L h_y^i \cos(\theta) + A_L h_x^i \sin(\theta) - A_T h_z^r). \quad (2b)$$

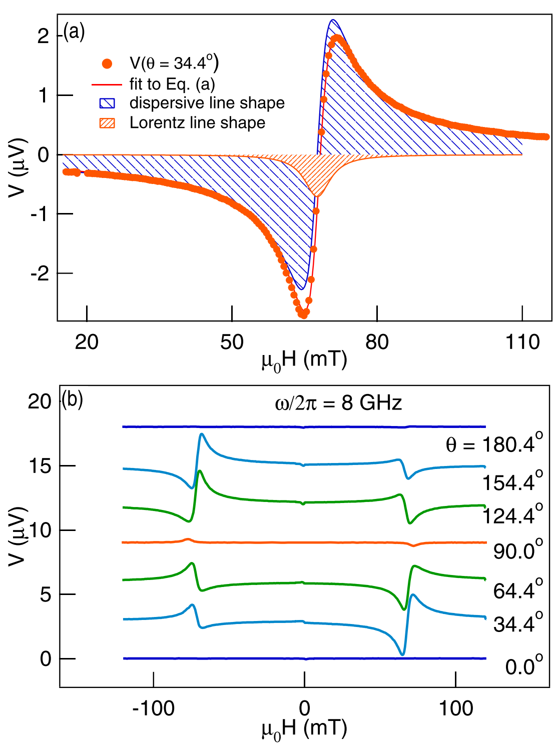

FIG. 2. (a) DC voltages were detected by sweeping the external magnetic field **H** at 8 GHz. The DC voltages as a function of the external magnetic field **H** were fitted to Eq. (1) with dispersive and Lorentz line shape components, which are, respectively, highlighted. (b) The DC voltages plotted as a function of θ and the external magnetic field **H**.

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 θ 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:

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

It is clear that spin pumping contributes a non-zero signal when θ 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 θ. Thus, a linear combination of Eqs. (3) and (2b) can be used to describe the Lorentz amplitude as a function of θ. 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

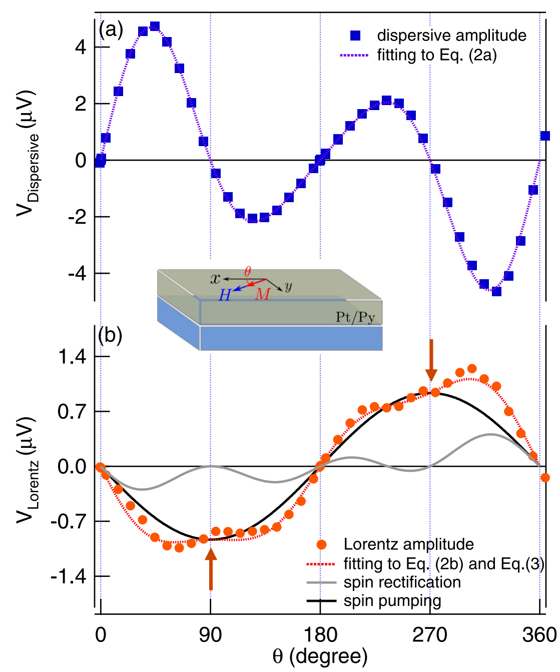

FIG. 3. At 8 GHz, the dispersive and Lorentz line shape components of the DC voltage as a function of θ are plotted in (a) and (b), respectively. The dispersive component in (a), which is a pure spin rectification signal, is seen to cross zero when θ equals to 0°, 90°, 180°, and 270°. The Lorentz component contains contributions from both spin rectification and spin pumping. The contribution due to spin rectification crosses zero at the same angles as (a), but the spin pumping contribution does not cross zero at θ of 90° and 270°.

TABLE I. The microwave h field distribution is found by fitting the data in Figs. 3(a) and 3(b) to Eqs. (2b) and (3). The values in this table are normalized against the amplitude of h_z. The real part is used to describe components whose phase is equal to that of the microwave current j_x, and imaginary part is used to describe components whose phase differs from j_x by $\pi/2$.

	h_x	h_y	h_z
Real part	0.006	0.154	−0.033
Imaginary part	0.006	0.027	0.999
	h_x	h_y	h_z
Amplitude	0.008	0.156	1.000
Phase	45.0°	9.9°	−88.1°

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° with respect to j_x, 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°, 90°, 180°, and 270°) just like the dispersive component. But the spin pumping component does not disappear at 90° and 270°, 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/Py bilayer, which is induced by a microwave current flowing through the Pt layer via spin orbit interaction in Pt and detected through spin rectification.[3] 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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[1]O. Mosendz, J. E. Pearson, F. Y. Fradin, G. E. W. Bauer, S. D. Bader, and A. Hoffmann, Phys. Rev. Lett. **104**, 046601 (2010).
[2]A. Azevedo, L. H. Vilela-Leão, R. L. Rodríguez-Suárez, A. F. Lacerda Santos, and S. M. Rezende, Phys. Rev. B **83**, 144402 (2011).
[3]L. Liu, T. Moriyama, D. C. Ralph, and R. A. Buhrman, Phys. Rev. Lett. **106**, 036601 (2011).
[4]Y. Tserkovnyak, A. Brataas, and G. E. W. Bauer, Phys. Rev. Lett. **88**, 117601 (2002).
[5]Y. Tserkovnyak, A. Brataas, G. E. W. Bauer, and B. I. Halperin, Rev. Mod. Phys. **77**, 1375 (2005).
[6]E. Saitoh, M. Ueda, H. Miyajima, and G. Tatara, Appl. Phys. Lett. **88**, 182509 (2006).
[7]Z. Feng, J. Hu, L. Sun, B. You, D. Wu, J. Du, W. Zhang, A. Hu, Y. Yang, D. M. Tang, B. S. Zhang, and H. F. Ding, Phys. Rev. B **85**, 214423 (2012).
[8]Y. S. Gui, N. Mecking, X. Zhou, G. Williams, and C.-M. Hu, Phys. Rev. Lett. **98**, 107602 (2007).
[9]N. Mecking, Y. S. Gui, and C.-M. Hu, Phys. Rev. B **76**, 224430 (2007).
[10]A. Wirthmann, X. Fan, Y. S. Gui, K. Martens, G. Williams, J. Dietrich, G. E. Bridges, and C.-M. Hu, Phys. Rev. Lett. **105**, 017202 (2010).
[11]M. Harder, Z. X. Cao, Y. S. Gui, X. L. Fan, and C.-M. Hu, Phys. Rev. B **84**, 054423 (2011).
[12]L. H. Bai, Y. S. Gui, A. Wirthmann, E. Recksiedler, N. Mecking, C.-M. Hu, Z. H. Chen, and S. C. Shen, Appl. Phys. Lett. **92**, 032504 (2008).