Determination of Penetration Depth of Transverse Spin Current in Ferromagnetic Metals by Spin Pumping

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Spin pumping in nonmagnetic/ferromagnetic metal multilayers is studied both theoretically and experimentally. We show that the line widths of the ferromagnetic resonance (FMR) spectrum depend on the thickness of the ferromagnetic metal layers, which must not be in resonance with the oscillating magnetic field. We also show that the penetration depths of the transverse spin current in ferromagnetic metals can be determined by analyzing the line widths of their FMR spectra. The obtained penetration depths in NiFe, CoFe, and CoFeB were 3.7, 2.5, and 12.0 nm, respectively. © 2008 The Japan Society of Applied Physics

Fig. 1. Schematic illustration of a nonmagnetic/ferromagnetic metal five-layer system. The magnetization of the F1 layer (m1) precesses around the z-axis with angle θ. The magnetization of the F2 layer (m2) is fixed with the z-axis. The precession of the magnetization in the F1 layer pumps the spin current \( I_{pump} \). The pumped spin current creates spin accumulation in the other layers, and the spin accumulation induces a backflow of spin current \( I_{backflow} \) across each N/F interface.

The field of current-driven magnetization dynamics (CDMD) has drawn enormous attention because of its potential applications to non-volatile magnetic random access memory and microwave devices. In the last decade much effort has been devoted to studying the physics and applications of CDMD both theoretically and experimentally.1–4 One of the most important quantities in CDMD is the penetration depth of the transverse spin current \( \lambda_t \), over which spin transfer torque is exerted for the magnetization of the free layer. However, there is a controversial issue regarding the penetration depth of the transverse spin current. One argument is based on the ballistic theory of electron transport, and its \( \lambda_t = \pi/|k_F^2 - k_r^2| \), which is on the order of the lattice constant in conventional ferromagnets such as Fe, Co, Ni, and their alloys.5,6 The other argument is based on the Boltzmann theory of electron transport, and its \( \lambda_t \) is on the order of a few nm.7 Urazhdin et al. analyzed the current-perpendicular-to-plane giant magnetoresistance of noncollinear magnetic multilayers using the extended twofold-resistance model and concluded that \( \lambda_t = 0.8 \) nm for permalloy.8 On the other hand, Chen et al. analyzed the critical current of the CDMD in the Co/Cu/Co trilayer system and concluded that \( \lambda_t = 3.0 \) nm for Co.9

The inverse process of CDMD is spin pumping, where spin current is generated by precession of magnetization in the ferromagnetic layer.6,10 Enhancement of the Gilbert damping constant due to spin pumping has been extensively studied, and spin diffusion lengths, i.e., penetration depths of spin current in nonmagnetic metals, have been obtained by analyzing the dependence of the enhancement of the Gilbert damping constant on the thickness of the nonmagnetic metal layer. In spin pumping, the direction of the magnetization vector of the pumped spin current is perpendicular to the direction of the precessing magnetization vector.10 Let us consider the nonmagnetic/ferromagnetic metal five-layer system shown in Fig. 1. Since the magnetization vector of the pumped spin current \( I_{pump} \) is perpendicular to the magnetization vector \( m_1 \) of the F1 layer and the precession angle \( \theta \) is very small (about 1 deg) in conventional ferromagnetic resonance (FMR) experiments, the dominant component of the pumped spin current is perpendicular to the magnetization vector \( m_2 \) of the F2 layer. Therefore, it would be possible to determine the penetration depth of the transverse spin current in the F2 layer if we could analyze the dependence of the enhancement of the Gilbert damping constant on the thickness of the F1 layer.

In this paper, we study spin pumping in five-layer systems shown in Fig. 1 both theoretically and experimentally. We extend Tserkovnyak’s theory of spin pumping by taking into account the finite penetration depth of the transverse spin current and show that the enhancement of the Gilbert damping constant due to spin pumping depends on the ratio of the penetration depth \( \lambda_t \) and the thickness \( d_2 \) of the F2 layer. Analyzing the experimental results we showed that the penetration depths of the transverse spin current in the Py, CoFe, and CoFeB layers are 3.7, 2.5, and 12.0 nm, respectively. The abbreviations CoFe, CoFeB, and Py hereafter refer to Co75Fe25, (Co55Fe50)50B20 and Ni80Fe20, respectively.

Let us begin with an introduction to the theory of spin pumping in the magnetic five-layer system shown in Fig. 1 with a finite penetration depth of the transverse spin current. The pumped spin current generated by precession of the magnetization \( m_1 \) of the F1 layer is given by

\[
I_{pump} = \frac{\hbar}{4\pi} \left( \sum_{F_1} j^{\pm}_{F_1} m_1 \times \frac{dm_1}{dt} + \sum_{F_2} j^{\pm}_{F_2} \frac{dm_1}{dt} \right),
\]

where \( \hbar \) is the Dirac constant and \( j^{\pm}_{F_1} \) is the real (imaginary) part of the mixing conductance.10 The pumped spin current creates spin accumulation in the other layers, and the spin accumulation induces a backflow of spin current across each N/F interface. Although the backflow is obtained from circuit theory,6,10 the penetration depth of the transverse spin current \( \lambda_t \) is assumed to be zero in this theory. Since we...
are interested in the effect of the penetration depth of the transverse spin current on spin pumping, we explicitly consider the diffusion of transverse spin accumulation in the ferromagnetic layer. The backflow of spin current flowing from the Ni layer to the F$_3$ layer is expressed as

$$f_{s}^{N_{i} \rightarrow F_{3}} = \frac{1}{4\pi} \left[ \frac{1}{S_{22}^{(1)}} \left[ \frac{\hat{s}_{0}^{2}}{S_{22}^{(1)}} \hat{m} \cdot (\mu_{N_{i}} - \mu_{F_{3}}^{L}) \hat{m} \right] + \frac{\hat{s}_{1}^{2}}{S_{22}^{(1)}} \hat{m} \times (\mu_{N_{i}} \times \hat{m}) + \frac{\hat{s}_{2}^{2}}{S_{22}^{(1)}} (\mu_{N_{i}} \times \hat{m}) \times \hat{m} \right] - \frac{t_{s}^{(1)}}{S_{22}^{(1)}} \left[ \frac{\hat{s}_{0}^{2}}{S_{22}^{(1)}} \hat{m} \cdot (\mu_{F_{3}}^{L} - \mu_{F_{3}}^{T}) \hat{m} \right] + \frac{\hat{s}_{1}^{2}}{S_{22}^{(1)}} \hat{m} \times (\mu_{F_{3}}^{L} \times \hat{m}) + \frac{\hat{s}_{2}^{2}}{S_{22}^{(1)}} (\mu_{F_{3}}^{L} \times \hat{m}) \times \hat{m} \right],$$

where $\hat{s}^{(1)} = (\hat{s}^{(0)} + \hat{s}^{(0)} \cdot \hat{m})/2$. The expression of the non-equilibrium spin accumulation in the Ni layer is given by

$$f_{s}^{N_{i} \rightarrow F_{3}} = \frac{1}{4\pi} \left[ \frac{1}{S_{22}^{(1)}} \left[ \frac{\hat{s}_{0}^{2}}{S_{22}^{(1)}} \hat{m} \cdot (\mu_{N_{i}} - \mu_{F_{3}}^{L}) \hat{m} \right] + \frac{\hat{s}_{1}^{2}}{S_{22}^{(1)}} \hat{m} \times (\mu_{N_{i}} \times \hat{m}) + \frac{\hat{s}_{2}^{2}}{S_{22}^{(1)}} (\mu_{N_{i}} \times \hat{m}) \times \hat{m} \right].$$

The spin accumulation can be expressed as a linear combination of $\exp(\pm i/\lambda_{sd}(F_{1}))$ and $\exp(\pm i/\lambda_{sd}(F_{2}))$, where $\lambda_{sd}(F_{1})$ is the longitudinal spin diffusion length. Here $\lambda_{sd}(F_{1})$ is the average of the exchange field and $D_{L}^{(1)}$ is the diffusion constant of spin-up (spin-down) electrons. The transverse spin accumulation is expressed as a linear combination of $\exp(i/\lambda_{t})$ and $\exp(\pm i/\lambda_{t})$, where $1/\lambda_{t} = \sqrt{(1/\lambda_{sd}(F_{1}))(1/\lambda_{sd}(F_{2}))}$. Therefore, we define the penetration depth of the transverse spin current $\lambda_{t}$ by $1/\lambda_{t} = \sqrt{(1/\lambda_{sd}(F_{1}))(1/\lambda_{sd}(F_{2}))}$. The transverse spin current in a ferromagnetic layer is expressed as

$$m \times (\hat{f}_{s}^{T} \times \hat{m}) = \frac{\partial}{\partial x} \frac{h S \hat{s}_{0}^{2}}{S_{22}^{(1)}} \mu_{F_{1}}.$$
The Gilbert damping constant is related to the line width of the FMR absorption spectrum via \[ \Delta B = \Delta B_0 + \frac{\hbar \omega}{2\sqrt{3\pi M_d}S} \left( \frac{g_{\parallel}^3}{g_{\parallel}^3 + g_{\perp}^3} \right), \]
where \( g_{\parallel}^3(k = 1, 2) \) is the real part of the renormalized mixing conductance of the \( k \)-th ferromagnetic layer. We should note that if we neglect the transverse spin accumulation in the ferromagnetic layer the mixing conductances are not renormalized, and that the line width \( \Delta B \) does not depend on the thickness of the \( F_2 \) layer.\(^{10}\) This is due to the fact that the dominant component of the pumped spin current is perpendicular to the magnetization vector \( m_2 \) of the \( F_2 \) layer in our experiment.

We performed FMR experiments on the three different \( N_1/F_1/N_2/F_2/N_3 \) five-layer systems shown in Fig. 1.\(^{14}\)
Nonmagnetic layers are made of Cu. The combinations of the ferromagnetic layers \( (F_1,F_2) \) of each system are (a) \( \text{CoFe,Py} \), (b) \( \text{Py,CoFe} \), and (c) \( \text{CoFe,CoFeB} \). The samples were deposited on Corning 1737 glass substrates using an rf magnetron sputtering system in an ultrahigh vacuum below \( 4 \times 10^{-6} \) Pa and cut to \( 5 \) mm. \( \text{Ar} \) pressure during deposition was 0.077 Pa. The thickness of all Cu layers is 5 nm. The thickness of \( F_1 \) layers is 5 nm for sample (a) and (b), and 10 nm for sample (c). The FMR measurements were carried out using an X-band microwave source (\( f = 9.4 \) GHz) at room temperature. The microwave power, modulation frequency, and modulation field are 1 mW, 10 kHz, and 0.1 mT, respectively. The precession angles of all samples are estimated to be 1 deg. The resistivity \( \rho_0 \) of Py, CoFe, and CoFeB are 241, 94, and 1252 \( \Omega \cdot \text{nm} \), respectively. The magnetostriction \( (\lambda \pi M) \) of Py and CoFe are 0.76 and 2.1 T, respectively. The gyromagnetic ratio is 1.8467 \( \times 10^11 \) Hz/T for all systems.

In Figs. 2(a), 2(b), and 2(c), the measured line widths of the FMR absorption spectra \( \Delta B \) are plotted with filled circles against the thickness of the \( F_2 \) layer, \( d_2 \). The solid lines are fit to the experimental data according to the theory with the finite penetration depth of the transverse spin current \( \lambda_t \). The dotted lines represent the case of \( \lambda_t = 0 \).

Parameters other than \( \lambda_t \) are determined as follows. The mixing conductances per unit area of the combinations \((g_{\parallel}^3,F_1)/S, g_{\perp}^3,F_2)/S\) are assumed to be (a) \((48.0,38.0)\), (b) \((15.2,17.0)\), and (c) \((48.0,128.0)\) nm\(^{-2}\). Although these values are determined by fitting, they have good agreement with the ab initio calculations.\(^{6}\) For simplicity, we assume that \( g_{\parallel}^3 = g_{\perp}^3 \) where values of \( g_{\parallel}^3/S \) of Py, CoFe, and CoFeB are taken to be 4.0, 6.0, and 0.8 nm\(^{-2}\), respectively. The longitudinal spin diffusion lengths are 5.5 nm for Py and 12 nm for CoFe and CoFeB, respectively.\(^{15,16}\) The polarization of conductance \( \beta \) is 0.73 for Py, 0.65 for CoFe, and 0.56 for CoFeB, respectively.\(^{15,17}\) The transverse spin diffusion lengths are given by \( L_{\parallel,\perp} = \lambda_{\parallel,\perp}/\sqrt{1 - \beta^2} \). We take \( g_{\parallel}^3/S = 1.0 \) nm\(^{-2}\), \( 2g_{\perp}^3/g_{\parallel}^3 = g_{\perp}^3/g_{\parallel}^3 \) and \( S = 20.0 \) nm\(^{-2}\) for all systems.\(^{5,10}\) The spin diffusion length and resistivity of Cu are taken to be 500 nm and 21 \( \Omega \cdot \text{nm} \).\(^{18}\)

The obtained values of \( \lambda_t \) are 3.7 nm for Py, 2.5 nm for CoFe, and 12.0 nm for CoFeB, respectively. Our results agree quite well with the prediction based on the Boltzmann theory of electron transport.\(^{7}\)

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