Penetration Depth of Transverse Spin Current in Ferromagnetic Metals

Tomohiro Taniguchi\textsuperscript{1,2}, Satoshi Yakata\textsuperscript{3}, Hiroshi Imamura\textsuperscript{1}, and Yasuo Ando\textsuperscript{4}

\textsuperscript{1}Nanotechnology Research Institute, National Institute of Advanced Industrial Science and Technology, Tsukuba, Ibaraki 305-8568, Japan
\textsuperscript{2}Institute of Applied Physics, University of Tsukuba, Tsukuba, Ibaraki 305-8573, Japan
\textsuperscript{3}Nanoelectronics Research Institute, National Institute of Advanced Industrial Science and Technology, Tsukuba, Ibaraki 305-8568, Japan
\textsuperscript{4}Department of Applied Physics, Graduate School of Engineering, Tohoku University, Sendai 980-8579, Japan

Abstract—The line width of the ferromagnetic resonance (FMR) spectrum of Cu/CoFeB/Cu/Co/Cu is studied. Analyzing the FMR spectrum by the theory of spin pumping, we determined the penetration depth of the transverse spin current in the Co layer. The obtained penetration depth of Co is 1.7 nm.

Index Terms—Ferromagnetic resonance, Spin Pumping, Transverse Spin Current, Gilbert damping

I. INTRODUCTION

There is great interest in the field of current-driven magnetization dynamics (CDMD) because of its potential applications to non-volatile magnetic random access memory and microwave devices. The concept of CDMD was first proposed by Slonczewski\textsuperscript{[1]} and independently by Berger\textsuperscript{[2]} in 1996. In the last decade, many experimental studies have shown the evidences of CDMD\textsuperscript{[3],[4]}.

Theoretical studies of CDMD have also been developed\textsuperscript{[5],[6]}. The origin of the CDMD has been understood as the transfer of spin angular momentum of the conducting electrons to the magnetization of the ferromagnetic metal. One of the most important quantities in CDMD is the penetration depth of the transverse (perpendicular to the magnetization) spin current \(\lambda_t\), over which the transfer of spin angular momentum is achieved. However, there is a controversial issue regarding the penetration depth of the transverse spin current. The ballistic theory of electron transport argues that \(\lambda_t\) is on the order of the lattice constant in conventional ferromagnets such as Fe, Co and Ni, and their alloys\textsuperscript{[7],[8]}. On the other hand, the Boltzmann theory of electron transport argues that \(\lambda_t\) is on the order of a few nm\textsuperscript{[9],[10],[11]}. However, only a few experimental measurements of the penetration depth has been reported\textsuperscript{[12],[13]}.

In our previous paper\textsuperscript{[14]}, we studied the line width of the ferromagnetic resonance (FMR) spectrum in a ferromagnetic(F)/nonmagnetic(N) metal five-layer system (\(N_1/F_1/N_2/F_2/N_3\)), and showed that the line width of the \(F_1\) layer depends on the thickness of the \(F_2\) layer due to spin pumping\textsuperscript{[15],[16]}. Analyzing the FMR spectrum, the penetration depth of the transverse spin current of NiFe, CoFe and CoFeB were obtained\textsuperscript{[14]}. Our result seems to support the Boltzmann theory of electron transport. However, we cannot compare our results with the results of\textsuperscript{[9],[10],[11]} directly since only the penetration depth of Co is studied in\textsuperscript{[9],[10],[11]}. In this paper, we study the line width of FMR spectrum of Cu/CoFeB/Cu/Co/Cu five-layer system, and determine the penetration depth of Co. The obtained penetration depth of Co, 1.7 nm, has good agreement with the results of\textsuperscript{[9],[10],[11]}.

II. THEORY

Spin pumping\textsuperscript{[15],[16]} is, in some sense, the reverse process of CDMD, where the precession of the magnetization in the ferromagnetic layer generates spin current flowing into the adjacent layers. In a ferromagnetic/nonmagnetic metal multi-layer system the Gilbert damping constant of the ferromagnetic layer is enhanced due to spin pumping. Analyzing the dependence of the Gilbert damping on the thickness of the nonmagnetic layer the spin diffusion length, i.e., the penetration depth of spin current in the nonmagnetic layer is determined.

The penetration depth of the transverse spin current of a ferromagnetic metal, \(\lambda_t\), is also determined in a similar way. Let us consider \(N_1/F_1/N_2/F_2/N_3\) metal five-layer system shown in Fig. 1, where \(\mathbf{m}_k\) \((k=1,2)\) is the unit vector along the magnetization of the \(k\text{-th}\) ferromagnetic layer. The magnetization of the \(F_1\) layer (\(\mathbf{m}_1\)) is in resonance with the oscillating magnetic field, and pumps spin current \(I_{\text{pump}}\)
flowing into the other layers. The precession axis of \( \mathbf{m}_1 \) is along the direction of the magnetization of the F\(_2\) layer (\( \mathbf{m}_2 \)). Since the magnetization vector of \( \mathbf{I}_{s}^{\text{pump}} \) is perpendicular to \( \mathbf{m}_1 \) [14] and the precession angle \( \theta \) is very small (about 1 deg), the dominant component of the magnetization vector of spin current flowing into the F\(_2\) layer is perpendicular to \( \mathbf{m}_2 \), i.e., the dominant component of the spin current flowing into the F\(_2\) layer is the transverse spin current. Thus, analyzing the dependence of the FMR spectrum of the F\(_1\) layer on the thickness of the F\(_2\) layer, the penetration depth of the transverse spin current of the F\(_2\) layer can be determined. However, the conventional theory of spin pumping assumes that the penetration depth of the transverse spin current is zero. Thus, we need to extend the theory of spin pumping by taking into account the finite penetration depth [14].

The spin current pumped from the F\(_1\) layer is given by [15]

\[
\mathbf{I}_s^{\text{pump}} = \frac{\hbar}{4\pi} \left( f_1^\dagger \mathbf{m}_1 \times \frac{d\mathbf{m}_1}{dt} + f_1 \mathbf{m}_1 \frac{d\mathbf{m}_1}{dt} \right),
\]

where \( \hbar \) is the Dirac constant and \( g_{1(i)}^\dagger \) is the real (imaginary) part of the mixing conductance. The pumped spin current creates spin accumulation in the other layers. The spin accumulation is given by

\[
\mu = \int d\varepsilon \text{Tr}[\hat{\sigma} \hat{f}],
\]

where \( \hat{\sigma} \) is the Pauli matrix and \( \hat{f} \) is the non-equilibrium distribution matrix in spin space. In general, the distribution matrix of a ferromagnetic layer, \( \hat{f}_F \), is given by \( \hat{f}_F = f_0 \mathbf{1} + f_1 \mathbf{m} \cdot \hat{\sigma} + f_2 \mathbf{1} \cdot \hat{\sigma} + f_3 \mathbf{t}_1 \cdot \hat{\sigma} + f_4 \mathbf{t}_2 \cdot \hat{\sigma} \), where \( \mathbf{1} \) is the 2 \times 2 unit matrix, \( f_0 = (f^\dagger + f^\dagger)/2 \) is the non-equilibrium charge distribution and \( f_2 = (f^\dagger - f^\dagger)/2 \) is the difference in non-equilibrium distribution between spin-up (\( f^\dagger \)) and spin-down (\( f^\dagger \)) electrons. \( (\mathbf{t}_1, \mathbf{t}_2, \mathbf{m}) \) is a set of orthogonal unit vectors in spin space where \( \mathbf{m} \) is the unit vector parallel to the magnetization vector. \( f_2 \) and \( f_3 \) are the non-equilibrium distribution of the transverse spin components. Spin accumulation in a nonmagnetic layer is defined in a similar way.

The spin accumulation induces a backflow of spin current. The backflow of spin current flowing from the N\(_i\) layer to the F\(_k\) layer is expressed in terms of the spin accumulation as

\[
\mathbf{I}_{s_i \rightarrow F_k} = \frac{1}{4\pi} \left[ \begin{array}{c}
2g_{1(F_k)}^\dagger g_{1(F_k)}^\dagger \\
g_{1(F_k)}^\dagger + g_{1(F_k)}^\dagger
\end{array} \right] (\mathbf{m}_k \cdot (\mathbf{\mu}_{N_i} - \mathbf{\mu}_{F_k})) \mathbf{m}_k
\]

\[
+ g_{1(F_k)}^\dagger \mathbf{m}_k \times (\mathbf{\mu}_{N_i} \times \mathbf{m}_k) + g_{1(F_k)}^\dagger \mathbf{\mu}_{N_i} \times \mathbf{m}_k
\]

\[
- t_1^\dagger (\mathbf{m}_k \times (\mathbf{\mu}_{F_k} \times \mathbf{m}_k) - \mathbf{\mu}_{F_k} \times \mathbf{m}_k),
\]

where \( \mathbf{\mu}_{N_i} \) and \( \mathbf{\mu}_{F_k} \) are the spin accumulation of the N\(_i\) and the F\(_k\) layer, respectively. \( g_{1(11)}^\dagger \) is the spin-up (spin-down) conductance and \( t_1^\dagger \) is the real (imaginary) part of the transmissin mixing conductance defined at the F/N interface. In the conventional theory of spin pumping, the penetration depth of the transverse spin current is assumed to be zero, and the last two terms in (3) is neglected [8].

The spin current given by (1) and (3) satisfies the boundary conditions of the continuity of the spin current. In general, the current operator in spin space is given by [9]

\[
\hat{j} = \frac{1}{e} (\hat{C} \frac{\partial V}{\partial x} - \hat{D} \frac{\partial \hat{n}}{\partial x}),
\]

where \( e(>0) \) is the absolute value of electron charge and \( V \) is the applied voltage. Since we are interested in the FMR line width, we assume \( V = 0 \). \( \hat{C}, \hat{D} \) and \( \hat{n} \) are the 2 \times 2 matrices representing the conductivity, the diffusion constant and the density of the non-equilibrium electron, respectively. The conductivity and the diffusion constant are expressed as

\[
\hat{C} = c_0 (1 + 3m \cdot \hat{\sigma}), \quad \hat{D} = d_0 (1 + \beta m \cdot \hat{\sigma}),
\]

where \( c_0 = (\sigma^1 + \sigma^{-1})/2 \), \( d_0 = (D^1 + D^{-1})/2 \), \( \beta = (\sigma^1 - \sigma^{-1})/\sigma^1 + \sigma^{-1} \) and \( \alpha = (D^1 - D^{-1})/(D^1 + D^{-1}) \). \( \sigma^1 \) and \( D^1 \) are the conductivity and the diffusion constant of spin-up (spin-down) electrons, respectively. \( \beta \) and \( \gamma \) are the polarization of the spin dependent conductivity and diffusion constant, respectively. The conductivity and the diffusion constant satisfy the Einstein relation \( c = e^2 N \hat{D} \), where \( N \) is the density of states. For simplicity, we assume that \( \beta = \gamma \) in this paper. The distribution \( \hat{f} \) and the density \( \hat{n} \) are related with each other via

\[
\text{Tr}[\hat{\sigma} \hat{n}] = \int d\varepsilon \text{Re} \left[ \text{Tr}[\hat{\sigma} \hat{N} \hat{f}] \right].
\]
References [10,11] show that the order of $\lambda_f$ is a few nm for NiFe and Co. The exchange interaction, which determines $\lambda_f$, does not give any contribution to $\lambda_{sd(F_1)}$, i.e., there’s no relation between $\lambda_f$ and $\lambda_{sd(F_1)}$. If the order of $\lambda_{sd(F_1)}$ is a few nm, for example NiFe, $\lambda_f \simeq \lambda_{sd(F_1)}$. On the other hand, for Co $\lambda_{sd(F_1)} \gg \lambda_f$, and therefore $\lambda_f \ll \lambda_{sd(F_1)}$.

The spin current at the $F_2/N_2$ interface is given by $I_{s,N_2}^{\uparrow \downarrow} = \langle \hat{g}_{s,F_2}^{\uparrow \downarrow} \rangle (m_2 \cdot \mu_{N_2}) m_2$.

Solving the diffusion equations of spin accumulations of the $N_2$ and $F_2$ layers, (6) and (7), with these boundary conditions, the backflow at the $N_2/F_2$ interface can be expressed as [13]

$$I_s^{N_2 \rightarrow F_2} = \frac{1}{4\pi} \left[ \hat{g}_{s,F_2}^{\uparrow \downarrow} (m_2 \cdot \mu_{N_2}) m_2 \right]$$

where the conductance $\hat{g}_{s,F_2}^{\uparrow \downarrow}$ depends on the ratio $d_2/\lambda_{sd(F_1)}$, where $d_2$ is the thickness of the $F_2$ layer. Similarly, the renormalized mixing conductances, $\hat{g}_{s,F_2}^{\uparrow \downarrow}$ and $\hat{g}_{s,F_2}^{\downarrow \uparrow}$, depend on the ratio $d_2/l_{\uparrow \downarrow}(F_2)$. If the thickness of the $N_2$ layer is thin enough compared to its spin diffusion length, $\hat{g}_{s,F_2}^{\uparrow \downarrow}$ is equal to $g^\ast$ given in [14], and $\hat{g}_{s,F_2}^{\downarrow \uparrow}$ is given by

$$\left( g_{s,F_2}^{\uparrow \downarrow} g_{s,F_2}^{\downarrow \uparrow} \right) = \frac{1}{\Delta} \begin{pmatrix} K_1 & K_2 \\ -K_2 & K_1 \end{pmatrix} \left( g_{s,F_2}^{\downarrow \uparrow} g_{s,F_2}^{\uparrow \downarrow} \right),$$

where $\Delta = K_1^2 + K_2^2$. $K_1$ and $K_2$ are given by

$K_1 = 1 + t_{\uparrow \downarrow}^{\uparrow \downarrow} \eta_i + t_{\downarrow \uparrow}^{\downarrow \uparrow} \eta_i$, \hspace{1cm} (11)

$K_2 = -t_{\uparrow \downarrow}^{\uparrow \downarrow} \eta_i + t_{\downarrow \uparrow}^{\downarrow \uparrow} \eta_i$, \hspace{1cm} (12)

where $\eta_i = \text{Re}(\text{Im} \eta)$ and $\eta = \{g^\ast \tanh (d_2/l_{\uparrow \downarrow}) \}^{-1}$, where $g^\ast = \hbar S/(2e^2 \rho_{F_2} l_{\uparrow \downarrow})$, and $\rho_{F_2}$ is the resistivity of the $F_2$ layer. The mixing conductance of the $F_1$ layer in [1] and [3] is also replaced by the renormalized mixing conductance.

The spin pumping modifies the Landau-Lifshitz-Gilbert (LLG) equation of the magnetization of the $F_1$ layer as

$$\frac{dm_1}{dt} = -\gamma m \times B_{eff} + \tau + \alpha_0 m_1 \times \left( \frac{dm_1}{dt} \right),$$

where $B_{eff}$ is the effective magnetic field, $\gamma$ is the gyromagnetic ratio and $\alpha_0$ is the intrinsic Gilbert damping constant. $\tau$ is the additional torque due to the spin pumping given by

$$\tau = \frac{\gamma}{MS d_1} m_1 \times \left\{ (I_{s,pump} - I_{s,N_2 \rightarrow F_1}) \times m_1 \right\},$$

where $M$ is the saturated magnetization of the $F_1$ layer and $d_1$ is the thickness of the $F_1$ layer. We assume that the spin relaxation in the $N_2$ layer is so weak that the spin current in the $N_2$ layer is conserved, i.e., $I_s^{pump} - I_s^{N_2 \rightarrow F_1} = I_s^{N_2 \rightarrow F_2}$. Then the dynamics of the magnetization of the $F_1$ layer is affected by the $F_2$ layer. We notice that the effects of the $N_1$ and $N_3$ layers are quite small because, as mentioned below, the thickness of these layers are thin enough compared to its spin diffusion length in our experiments. The LLG equation is rewritten as [14],[15],[18]

$$\frac{dm_1}{dt} = -\gamma_{eff} m_1 \times B_{eff} + \frac{\gamma_{eff}}{\gamma} (\alpha_0 + \alpha') m_1 \times \left( \frac{dm_1}{dt} \right),$$

where (\gamma_{eff}/\gamma) and $\alpha'$ is the enhancement of the gyromagnetic ratio and the Gilbert damping due to the spin pumping, respectively. Assuming that $g_{11}^{\uparrow \downarrow} \gg g_i^{\uparrow \downarrow}$, in the limit of $\theta \rightarrow 0$, $\alpha'$ is reduced as

$$\alpha' \simeq \frac{\gamma \hbar}{4\pi M d_1 S} g_{11}^{\uparrow \downarrow} g_{11}^{\downarrow \uparrow},$$

and (\gamma_{eff}/\gamma) \approx 1. We should note that if we neglect the penetration depth of the transverse spin current in the ferromagnetic layer the mixing conductances are not renormalized, and that the enhancement of the Gilbert damping constant, $\alpha'$, does not depend on the thickness of the $F_2$ layer. This is because the dominant component of the pumped spin current is perpendicular to the magnetization of the $F_2$ layer.

III. EXPERIMENT

We performed FMR experiments on Cu(5nm)/CoFeB(5nm)/(Cu(5nm)/Co(d2)/Cu(10nm) five-layer system shown in Fig. [1] [16], where CoFeB layer corresponds to the $F_1$ layer and Co layer corresponds to the $F_2$ layer. Figure 2 shows the dependence of the derivative of the FMR spectrum of CoFeB on the thickness of Co, $d_2$. The width of the peak to peak in Fig. 2 namely the linewidth of the FMR spectrum $\Delta B$, is a linear function of the Gilbert damping constant [19]:

$$\Delta B = \Delta B_0 + 4\pi f \sqrt{3\gamma},$$

where $f$ is the frequency of the oscillating magnetic field. The line width of CoFeB depends on the thickness of Co through $\alpha'$, as shown in Fig. 2. Thus, we can determine the penetration depth of the transverse spin current of Co by the line width of CoFeB. The enhancement of the gyromagnetic ratio does not give any contributions to the line width.

The sample was 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 nm$^2$. The Ar pressure during deposition was 0.077 Pa. The FMR measurement was carried out using an X-band microwave source ($f = 9.4 \text{GHz}$) at room temperature. The microwave power, modulation frequency, and modulation field are 1 mW, 10 kHz, and 0.1 mT, respectively. The precession angle of the magnetization of the $F_1$ layer was estimated to be 1 deg. The resistivity of CoFeB
and Co are 1252 Ω·nm and 210 Ω·nm [20], respectively. The magnetization (4πM) and the gyromagnetic ratio of CoFeB are 1.66 T and 1.846×10¹¹ Hz/T, respectively.

A Cu layer typically shows an enhanced (111) orientation and the Co layer on it also shows an induced (111) texture. Thus, the Co layer is considered to be (111) texture.

In Fig. 3 the measured line width of the FMR, ΔB, of CoFeB layer is plotted with full circles against the thickness of Co layer, ds. The solid line is a fit to the experimental data according to the theory with the finite penetration depth of the transverse spin current λt. The dotted line is the calculated line width assuming λt = 0. If the Co film is not continuous but consists of Co islands, the thickness of the Co island is somewhat thicker than the nominal thickness. However, the effect of the Co islands is not so significant because the important quantity in our analysis is the mean thickness which is almost same as the nominal thickness.

The best fitting parameters are as follows. The real part of the mixing conductances per unit area, g↑↑↓↓/S, of CoFeB and Co are 128 nm⁻² and 20 nm⁻², respectively. Although these values are determined by fitting, they have good agreement with ab initio calculations [8]. For simplicity, we assume that t↑↑↓↓= t↑↓↑↓, where the values of t↑↑↓↓/S of CoFeB and Co are 0.8 nm⁻² and 6.0 nm⁻², respectively. The spin diffusion length of CoFeB and Co layer are 12 nm and 38 nm, respectively [20],[21]. The polarization of the conductance β are 0.56 for CoFeB and 0.31 for Co [20],[21]. We take g↑↑↑↓=0.99 nm⁻² and 2g↑↑↑↓/(g↑↑↑↓+g↓↓↓↓)S = 20 nm⁻² both CoFeB and Co [15]: these are not important parameters for fitting. The spin diffusion length and resistivity of Cu are taken to be 500 nm and 21 Ω·nm [22].

The obtained value of the penetration depth of Co is λe = 1.7 nm. References [9],[10],[11] estimate λ1 = √Tλ1, and predict that λ2 of Co with (111) texture is 1.1 nm. Thus, we have good agreement with [9],[10],[11].

IV. Conclusion

In conclusion, we study the line width of the FMR spectrum of Cu/CoFeB/Cu/Co/Cu five-layer system. The line width of the CoFeB layer depends on the thickness of the Co layer due to spin pumping. We extend the conventional theory of spin pumping by taking into account the finite penetration depth of the transverse spin current of the Co layer, and analyze the experimental data. The obtained penetration depth of the Co layer is 1.7 nm, which has good agreement with the Boltzmann theory of electron transport.

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