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Penetration Depth of Transverse Spin Current in Ferromagnetic Metals

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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 [1] and independently by Berger [2] in 1996. In the last decade, many experimental studies have shown the evidences of CDMD [3], [4].

Theoretical studies of CDMD have also been developed [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 $\lambda_{\rm t}$, 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 $\lambda_{\rm t}$ is on the order of the lattice constant in conventional ferromagnets such as Fe, Co and Ni, and their alloys [7], [8]. On the other hand, the Boltzmann theory of electron transport argues that $\lambda_{\rm t}$ is on the order of a few nm [9]–[11]. However, only a few experimental measurements of the penetration depth has been reported [12], [13].

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

II. Theory

Spin pumping [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, $\lambda_{\rm t}$, is also determined in a similar way. Let us consider $\rm N_1/F_1/N_2/F_2/N_3$ 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-th ferromagnetic layer. The magnetization of the $\rm F_1$ layer $(\mathbf{m}_1)$ is in resonance with the oscillating magnetic field, and pumps spin current $\mathbf{I}_s^{\rm pump}$ flowing into the other layers. The precession axis of $\mathbf{m}_1$ is along the direction of the magnetization of the $\rm F_2$ layer $(\mathbf{m}_2)$. Since the magnetization vector of $\mathbf{I}_s^{\rm pump}$ is perpendicular to $\mathbf{m}_1$ [14] and the precession angle θ is very small (about 1 deg), the dominant component of the magnetization vector of spin current flowing into the $\rm F_2$ layer is perpendicular to $\mathbf{m}_2$, i.e., the dominant component of the spin current flowing into the $\rm F_2$ layer is the transverse spin current. Thus, analyzing the dependence of the FMR spectrum of the $\rm F_1$ layer on the thickness of the $\rm F_2$ layer, the penetration depth of the transverse spin current of the $\rm F_2$ 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 $\rm F_1$ layer is given by [15]

$$\mathbf{I}_s^{\rm pump} = \frac{\hbar}{4\pi}\left(g_{\rm r(F_1)}^{\uparrow\downarrow}\mathbf{m}_1\times\frac{{\rm d}\mathbf{m}_1}{{\rm d}t} + g_{\rm i(F_1)}^{\uparrow\downarrow}\frac{{\rm d}\mathbf{m}_1}{{\rm d}t}\right) \qquad (1)$$

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where $\hbar$ is the Dirac constant and $g_{\mathrm{r(i)}}^{\uparrow\downarrow}$ 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

$$\boldsymbol{\mu} = \int_{\varepsilon_{\mathrm{F}}} \mathrm{d}\varepsilon \mathrm{Tr}[\hat{\boldsymbol{\sigma}}\hat{f}] \tag{2}$$

where $\hat{\boldsymbol{\sigma}}$ 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, $\hat{f}_{\mathrm{F}}$, is given by $\hat{f}_{\mathrm{F}} = f_0\hat{1} + f_z\mathbf{m}\cdot\hat{\boldsymbol{\sigma}} + f_x\mathbf{t}_1\cdot\hat{\boldsymbol{\sigma}} + f_y\mathbf{t}_2\cdot\hat{\boldsymbol{\sigma}}$, where $\hat{1}$ is the 2×2 unit matrix, $f_0 = (f^{\uparrow} + f^{\downarrow})/2$ is the non-equilibrium charge distribution and $f_z = (f^{\uparrow} - f^{\downarrow})/2$ is the difference in non-equilibrium distribution between spin-up $(f^{\uparrow})$ and spin-down $(f^{\downarrow})$ 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_x and f_y 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

$$\begin{aligned}\mathbf{I}_s^{\mathrm{N}_i\to\mathrm{F}_k} &= \frac{1}{4\pi}\Bigg[\frac{2g_{(\mathrm{F}_k)}^{\uparrow\uparrow}g_{(\mathrm{F}_k)}^{\downarrow\downarrow}}{g_{(\mathrm{F}_k)}^{\uparrow\uparrow}+g_{(\mathrm{F}_k)}^{\downarrow\downarrow}}\{\mathbf{m}_k\cdot(\boldsymbol{\mu}_{\mathrm{N}_i}-\boldsymbol{\mu}_{\mathrm{F}_k})\}\mathbf{m}_k \\ &\quad + g_{\mathrm{r}(\mathrm{F}_k)}^{\uparrow\downarrow}\mathbf{m}_k\times(\boldsymbol{\mu}_{\mathrm{N}_i}\times\mathbf{m}_k) + g_{\mathrm{i}(\mathrm{F}_k)}^{\uparrow\downarrow}\boldsymbol{\mu}_{\mathrm{N}_i}\times\mathbf{m}_k \\ &\quad - t_{\mathrm{r}(\mathrm{F}_k)}^{\uparrow\downarrow}\mathbf{m}_k\times(\boldsymbol{\mu}_{\mathrm{F}_k}\times\mathbf{m}_k) - t_{\mathrm{i}(\mathrm{F}_k)}^{\uparrow\downarrow}\boldsymbol{\mu}_{\mathrm{F}_k}\times\mathbf{m}_k\Bigg]\end{aligned} \tag{3}$$

where $\boldsymbol{\mu}_{\mathrm{N}_i}$ and $\boldsymbol{\mu}_{\mathrm{F}_k}$ are the spin accumulation of the N_i and the F_k layer, respectively. $g^{\uparrow\uparrow(\downarrow\downarrow)}$ is the spin-up (spin-down) conductance and $t_{\mathrm{r(i)}}^{\uparrow\downarrow}$ is the real (imaginary) part of the transmission 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]

$$\hat{j} = \frac{1}{e}\hat{C}\frac{\partial V}{\partial x} - \hat{D}\frac{\partial \hat{n}}{\partial x} \tag{4}$$

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 2×2 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 $\hat{C} = C_0(\hat{1} + \beta\mathbf{m}\cdot\hat{\boldsymbol{\sigma}})$ and $\hat{D} = D_0(\hat{1} + \beta'\mathbf{m}\cdot\hat{\boldsymbol{\sigma}})$, where $C_0 = (\sigma^{\uparrow} + \sigma^{\downarrow})/2$, $D_0 = (D^{\uparrow} + D^{\downarrow})/2$, $\beta = (\sigma^{\uparrow} - \sigma^{\downarrow})/(\sigma^{\uparrow} + \sigma^{\downarrow})$ and $\beta' = (D^{\uparrow} - D^{\downarrow})/(D^{\uparrow} + D^{\downarrow})$. $\sigma^{\uparrow(\downarrow)}$ and $D^{\uparrow(\downarrow)}$ are the conductivity and the diffusion constant of spin-up (spin-down) electrons, respectively. β and β' are the polarization of the spin dependent conductivity and diffusion constant, respectively. The conductivity and the diffusion constant satisfy the Einstein relation $\hat{C} = e^2\hat{N}\hat{D}$, where $\hat{N}$ is the density of states. For simplicity, we assume that $\beta = \beta'$ in this paper. The distribution $\hat{f}$ and the density $\hat{n}$ are related with each other via

$$\mathrm{Tr}[\hat{\boldsymbol{\sigma}}\hat{n}] = \int_{\varepsilon_{\mathrm{F}}} \mathrm{d}\varepsilon \mathrm{Re}[\mathrm{Tr}[\hat{\boldsymbol{\sigma}}\hat{N}\hat{f}]]. \tag{5}$$

The spin current is given by $\mathbf{I}_s = (\hbar S/2)\mathrm{Re}[\mathrm{Tr}[\hat{\boldsymbol{\sigma}}\hat{j}]]$, where S is the cross section area. Using (2), (4) and (5), the spin current $\mathbf{I}_s$ is expressed in terms of spin accumulation $\boldsymbol{\mu}$. The spin current in a nonmagnetic metal is expressed in a similar way, but $\beta = \beta' = 0$.

The diffusion equation of the spin accumulation is obtained by the continuity of the charge and spin current. In a nonmagnetic metal, the spin accumulation $\boldsymbol{\mu}_{\mathrm{N}}$ obeys the diffusion equation given by [17]

$$\frac{\partial^2}{\partial x^2}\boldsymbol{\mu}_{\mathrm{N}} = \frac{1}{\lambda_{\mathrm{sd(N)}}^2}\boldsymbol{\mu}_{\mathrm{N}} \tag{6}$$

where $\lambda_{\mathrm{sd(N)}}$ is the spin diffusion length of the nonmagnetic metal. The spin accumulation can be expressed as a linear combination of $\exp(\pm x/\lambda_{\mathrm{sd(N)}})$. The longitudinal spin accumulation in a ferromagnetic metal, $\boldsymbol{\mu}_{\mathrm{F}}^{\mathrm{L}} = (\mathbf{m}\cdot\boldsymbol{\mu}_{\mathrm{F}})\mathbf{m}$, also obeys the diffusion equation, and is expressed as a linear combination of $\exp(\pm x/\lambda_{\mathrm{sd(F_L)}})$, where $\lambda_{\mathrm{sd(F_L)}}$ is the longitudinal spin diffusion length.

We assume that the transverse spin accumulation in a ferromagnetic metal, $\boldsymbol{\mu}_{\mathrm{F}}^{\mathrm{T}} = \mathbf{m}\times(\boldsymbol{\mu}_{\mathrm{F}}\times\mathbf{m})$, obeys the following equation [9]:

$$\frac{\partial^2}{\partial x^2}\boldsymbol{\mu}_{\mathrm{F}}^{\mathrm{T}} = \frac{1}{\lambda_J^2}\boldsymbol{\mu}_{\mathrm{F}}^{\mathrm{T}}\times\mathbf{m} + \frac{1}{\lambda_{\mathrm{sd(F_T)}}^2}\boldsymbol{\mu}_{\mathrm{F}}^{\mathrm{T}} \tag{7}$$

where $\lambda_J = \sqrt{(D^{\uparrow} + D^{\downarrow})\hbar/(2J)}$ is the spin coherence length [8] and $\lambda_{\mathrm{sd(F_T)}} = \lambda_{\mathrm{sd(F_L)}}/\sqrt{1-\beta^2}$ is the transverse spin diffusion length. J represents the strength of the exchange field. The transverse spin accumulation is expressed as a linear combination of $\exp(\pm x/l_+)$ and $\exp(\pm x/l_-)$, where $1/l_{\pm} = \sqrt{(1/\lambda_{\mathrm{sd(F_T)}}^2) \mp (\mathrm{i}/\lambda_J^2)}$. Therefore, we define the penetration depth of the transverse spin current as

$$\frac{1}{\lambda_{\mathrm{t}}} = \mathrm{Re}\left[\frac{1}{l_+}\right]. \tag{8}$$

References [10] and [11] show that the order of λ_J is a few nm for NiFe and Co. The exchange interaction, which determines λ_J, does not give any contribution to $\lambda_{\mathrm{sd(F_L)}}$, i.e., there's no relation between λ_J and $\lambda_{\mathrm{sd(F_L)}}$. If the order of $\lambda_{\mathrm{sd(F_L)}}$ is a few nm, for example NiFe, $\lambda_{\mathrm{t}} \simeq \lambda_{\mathrm{sd(F_L)}}$. On the other hand, for Co $\lambda_{\mathrm{sd(F_L)}} \gg \lambda_J$, and therefore $\lambda_{\mathrm{t}} \ll \lambda_{\mathrm{sd(F_L)}}$.

The spin current at the $\mathrm{F}_2/\mathrm{N}_2(\mathrm{N}_3)$ interface is given by $\mathbf{I}_s^{\mathrm{N}_2\to\mathrm{F}_2}(-\mathbf{I}_s^{\mathrm{N}_3\to\mathrm{F}_2})$. Solving the diffusion equations of spin accumulations of the N_3 and F_2 layers, (6) and (7), with these boundary conditions, the backflow at the $\mathrm{N}_2/\mathrm{F}_2$ interface can be expressed as [13]

$$\begin{aligned}\mathbf{I}_s^{\mathrm{N}_2\to\mathrm{F}_2} &= \frac{1}{4\pi}\Big[\tilde{g}_{(\mathrm{F}_2)}^{*}(\mathbf{m}_2\cdot\boldsymbol{\mu}_{\mathrm{N}_2})\mathbf{m}_2 \\ &\quad + \tilde{g}_{\mathrm{r}(\mathrm{F}_2)}^{\uparrow\downarrow}\mathbf{m}_2\times(\boldsymbol{\mu}_{\mathrm{N}_2}\times\mathbf{m}_2) + \tilde{g}_{\mathrm{i}(\mathrm{F}_2)}^{\uparrow\downarrow}\boldsymbol{\mu}_{\mathrm{N}_2}\times\mathbf{m}_2\Big]\end{aligned} \tag{9}$$

where the conductance $\tilde{g}^*_{(\mathrm{F}_2)}$ depends on the ratio $d_2/\lambda_{\mathrm{sd}(\mathrm{F_L})}$, where d_2 is the thickness of the F_2 layer. Similarly, the renormalized mixing conductances, $\tilde{g}^{\uparrow\downarrow}_{\mathrm{r,i}(\mathrm{F}_2)}$, depend on the ratio $d_2/l_{+(\mathrm{F}_2)}$. If the thickness of the N_3 layer is thin enough compared to its spin diffusion length, $\tilde{g}^*_{(\mathrm{F}_2)}$ is equal to g^* given in [14], and $\tilde{g}^{\uparrow\downarrow}_{\mathrm{r,i}(\mathrm{F}_2)}$ are given by

$$\begin{pmatrix} \tilde{g}^{\uparrow\downarrow}_{\mathrm{r}(\mathrm{F}_2)} \\ \tilde{g}^{\uparrow\downarrow}_{\mathrm{i}(\mathrm{F}_2)} \end{pmatrix} = \frac{1}{\Delta}\begin{pmatrix} K_1 & K_2 \\ -K_2 & K_1 \end{pmatrix}\begin{pmatrix} g^{\uparrow\downarrow}_{\mathrm{r}(\mathrm{F}_2)} \\ g^{\uparrow\downarrow}_{\mathrm{i}(\mathrm{F}_2)} \end{pmatrix} \tag{10}$$

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

$$K_1 = 1 + t^{\uparrow\downarrow}_{\mathrm{r}}\eta_{\mathrm{r}} + t^{\uparrow\downarrow}_{\mathrm{i}}\eta_{\mathrm{i}} \tag{11}$$

$$K_2 = -t^{\uparrow\downarrow}_{\mathrm{r}}\eta_{\mathrm{i}} + t^{\uparrow\downarrow}_{\mathrm{i}}\eta_{\mathrm{r}} \tag{12}$$

where $\eta_{\mathrm{r(i)}} = \mathrm{Re(Im)}\eta$ and $\eta = \{g_{\mathrm{t}} \tanh(d_2/l_+)\}^{-1}$, where $g_{\mathrm{t}} = hS/(2e^2\rho_{\mathrm{F}_2} l_+)$, and ρ_{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

$$\frac{\mathrm{d}\mathbf{m}_1}{\mathrm{d}t} = -\gamma\mathbf{m} \times \mathbf{B}_{\mathrm{eff}} + \boldsymbol{\tau} + \alpha_0 \mathbf{m}_1 \times \frac{\mathrm{d}\mathbf{m}_1}{\mathrm{d}t} \tag{13}$$

where $\mathbf{B}_{\mathrm{eff}}$ is the effective magnetic field, γ is the gyromagnetic ratio and α_0 is the intrinsic Gilbert damping constant. $\boldsymbol{\tau}$ is the additional torque due to the spin pumping given by

$$\boldsymbol{\tau} = \frac{\gamma}{MSd_1}\mathbf{m}_1 \times \{(\mathbf{I}^{\mathrm{pump}}_s - \mathbf{I}^{\mathrm{N}_2\to\mathrm{F}_1}_s) \times \mathbf{m}_1\} \tag{14}$$

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., $\mathbf{I}^{\mathrm{pump}}_s - \mathbf{I}^{\mathrm{N}_2\to\mathrm{F}_1}_s = \mathbf{I}^{\mathrm{N}_2\to\mathrm{F}_2}_s$. 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 layer 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 (13) is rewritten as [14], [15], [18]

$$\frac{\mathrm{d}\mathbf{m}_1}{\mathrm{d}t} = -\gamma_{\mathrm{eff}}\mathbf{m}_1 \times \mathbf{B}_{\mathrm{eff}} + \frac{\gamma_{\mathrm{eff}}}{\gamma}(\alpha_0 + \alpha')\mathbf{m}_1 \times \frac{\mathrm{d}\mathbf{m}_1}{\mathrm{d}t} \tag{15}$$

where $(\gamma_{\mathrm{eff}}/\gamma)$ and α' is the enhancement of the gyromagnetic ratio and the Gilbert damping due to the spin pumping, respectively. Assuming that $g^{\uparrow\downarrow}_{\mathrm{r}} \gg g^{\uparrow\downarrow}_{\mathrm{i}}$, in the limit of $\theta \to 0$, α' is reduced as

$$\alpha' \simeq \frac{\gamma\hbar}{4\pi M d_1 S}\frac{\tilde{g}^{\uparrow\downarrow}_{\mathrm{r}(\mathrm{F}_1)}\tilde{g}^{\uparrow\downarrow}_{\mathrm{r}(\mathrm{F}_2)}}{\tilde{g}^{\uparrow\downarrow}_{\mathrm{r}(\mathrm{F}_1)} + \tilde{g}^{\uparrow\downarrow}_{\mathrm{r}(\mathrm{F}_2)}} \tag{16}$$

and $(\gamma_{\mathrm{eff}}/\gamma) \simeq 1$. 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, α', 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.

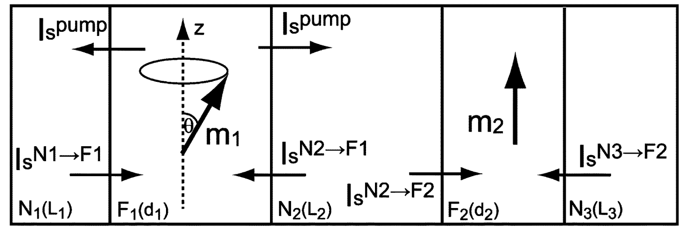

Fig. 1. Schematic illustration of a nonmagnetic/ferromagnetic metal five-layer system. $L_i (i = 1, 2, 3)$ is the thickness of the i-th nonmagnetic layer and $d_k (k = 1, 2)$ is the thickness of the k-th ferromagnetic layer. The magnetization $\mathbf{m}_1$ is in resonance and precess around the z-axis with the angle θ. The magnetization $\mathbf{m}_2$ is fixed along the z-axis. $\mathbf{I}^{\mathrm{pump}}_s$ and $\mathbf{I}^{\mathrm{N}\to\mathrm{F}}_s$ are pumped spin current and backflow of spin current, respectively.

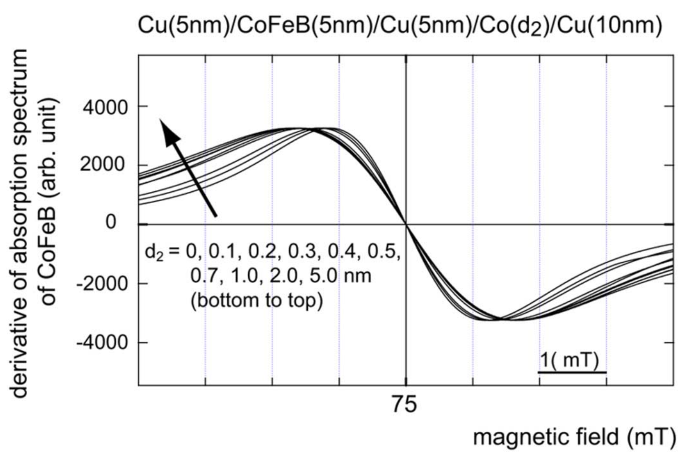

Fig. 2. The dependence of derivative of the FMR spectrum of CoFeB on the thickness of Co layer, d_2. The center of the horizontal axis, 75 mT, is the resonance magnetic field of CoFeB.

III. Experiment

We performed FMR experiments on Cu(5 nm)/CoFeB(5 nm)/Cu(5 nm)/Co(d_2)/Cu(10 nm) 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. Fig. 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 line width of the FMR spectrum ΔB, is a linear function of the Gilbert damping constant [19]:

$$\Delta B = \Delta B_0 + \frac{4\pi f}{\sqrt{3}\gamma}(\alpha_0 + \alpha') \tag{17}$$

where f is the frequency of the oscillating magnetic field. The line width of CoFeB depends on the thickness of Co through α', 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 4×10^{-6} Pa and cut to 25 mm^2. The Ar pressure during deposition was 0.077 Pa. The FMR measurement was carried out using an X-band microwave source ($f = 9.4$ [GHz]) at room temperature. The microwave power, modulation frequency, and modulation field are 1 mW, 100 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

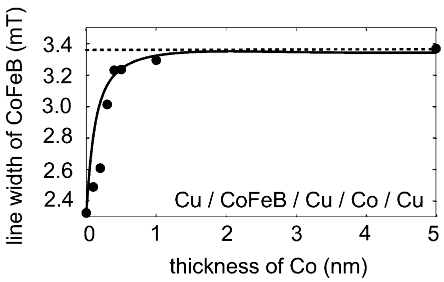

Fig. 3. The dependence of the FMR spectrum, ΔB, of CoFeB layer on the thickness of Co layer, d_2. The filled circles represent experimental data and solid line is fit to the experimental data according to the theory with the finite penetration depth of the transverse spin current in Co, $\lambda_{\rm t}$. The dotted line represents the case of $\lambda_{\rm t} = 0$.

1252 Ω·nm and 210 Ω·nm [20], respectively. The magnetization $(4\pi M)$ and the gyromagnetic ratio of CoFeB are 1.66 T and 1.846×10^{11} 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, d_2. The solid line is a fit to the experimental data according to the theory with the finite penetration depth of the transverse spin current $\lambda_{\rm t}$. The dotted line is the calculated line width assuming $\lambda_{\rm t} = 0$. If the Co film is not continuous but consists of a 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, $g_{\rm r}^{\uparrow\downarrow}/S$, 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 the *ab initio* calculations [8]. For simplicity, we assume that $t_{\rm r}^{\uparrow\downarrow} = t_{\rm i}^{\uparrow\downarrow}$, where the values of $t_{\rm r,i}^{\uparrow\downarrow}/S$ 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 $g_{\rm i}^{\uparrow\downarrow}/S = 1.0$ nm^{-2} and $2g^{\uparrow\uparrow}g^{\downarrow\downarrow}/(g^{\uparrow\uparrow} + g^{\downarrow\downarrow})S = 20$ 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 $\lambda_{\rm t} = 1.7$ nm. References [9]–[11] estimate $\lambda_{\rm t} = \sqrt{2}\lambda_J$, and predict that λ_J of Co with (111) texture is 1.1 nm. Thus, we have good agreement with [9]–[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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References

[1] J. C. Slonczewski, "Current-driven excitation of magnetic multilayers," *J. Magn. Magn. Mater.*, vol. 159, pp. L1–L7, 1996.
[2] L. Berge, "Emission of spin waves by a magnetic multilayer traversed by a current," *Phys. Rev. B*, vol. 54, pp. 9353–9358, 1996.
[3] S. I. Kiselev *et al.*, "Microwave oscillations of a nanomagnet driven by a spin-polarized current," *Nature*, vol. 425, pp. 380–383, 2003.
[4] A. Deac *et al.*, "Spin transfer effects in exchange-biased spin-valves for current-perpendicular-to-plane magnetoresistive heads," *J. Magn. Magn. Mater.*, vol. 290–291, pp. 42–47, 2005.
[5] J. Z. Sun, "Spin-current interaction with a monodomain magnetic body: A model study," *Phys. Rev. B*, vol. 62, pp. 570–578, 2000.
[6] J. Grollier *et al.*, "Field dependence of magnetization reversal by spin transfer," *Phys. Rev. B*, vol. 67, p. 174402, 2003.
[7] M. D. Stiles and A. Zhangwill, "Anatomy of spin-transfer torque," *Phys. Rev. B*, vol. 66, p. 014407, 2002.
[8] A. Brataas, G. E. W. Bauer, and P. J. Kelly, "Non-collinear magneto-electronics," *Phys. Rep.*, vol. 427, pp. 157–255, 2006.
[9] S. Zhang, P. M. Levy, and A. Fert, "Mechanisms of spin-polarized current-driven magnetization switching," *Phys. Rev. Lett.*, vol. 88, p. 236601, 2002.
[10] A. Shpiro, P. M. Levy, and S. Zhang, "Self-consistent treatment of nonequilibrium spin torques in magnetic multilayers," *Phys. Rev. B*, vol. 67, p. 104430, 2003.
[11] J. Zhang, P. M. Levy, S. Zhang, and V. Antropov, "Identification of transverse spin currents in noncollinear magnetic structures," *Phys. Rev. Lett.*, vol. 93, p. 256602, 2004.
[12] S. Urazhdin, R. Loloee, and W. P. Pratt Jr., "Noncollinear spin transport in magnetic multilayers," *Phys. Rev. B*, vol. 71, p. 100401(R), 2005.
[13] W. Chen, M. J. Rooks, N. Ruiz, J. Z. Sun, and A. D. Kent, "Spin transfer in bilayer magnetic nanopillars at high fields as a function of free-layer thickness," *Phys. Rev. B*, vol. 74, p. 144408, 2006.
[14] T. Taniguchi, S. Yakata, H. Imamura, and Y. Ando, "Determination of penetration depth of transverse spin current in ferromagnetic metals by spin pumping," *Appl. Phys. Express*, vol. 1, p. 031302, 2008.
[15] Y. Tserkovnyak, A. Brataas, G. E. W. Bauer, and B. I. Halperin, "Nonlocal magnetization dynamics in ferromagnetic heterostructures," *Rev. Mod. Phys.*, vol. 77, pp. 1375–1421, 2005.
[16] S. Mizukami, Y. Ando, and T. Miyazaki, "Effect of spin diffusion on Gilbert damping for a very thin permalloy layer in Cu/permalloy/Cu/Pt films," *Phys. Rev. B*, vol. 66, p. 104413, 2002.
[17] T. Valet and A. Fert, "Theory of the perpendicular magnetoresistance in magnetic multilayers," *Phys. Rev. B*, vol. 48, pp. 7099–7113, 1993.
[18] T. Taniguchi and H. Imamura, "Enhancement of the Gilbert damping constant due to spin pumping in noncollinear ferromagnet/nonmagnet/ferromagnet trilayer systems," *Phys. Rev. B*, vol. 76, p. 092402, 2007.
[19] S. V. Vonsovskii, "Ferromagnetic resonance," *Israel Program for Scientific Translations Ltd., Jerusalem*, pp. 66–70, 1964, Chap. II,.
[20] L. Piraux, S. Dubois, A. Fert, and L. Belliard, "The temperature dependence of the perpendicular giant magnetoresistance in Co/Cu multilayered system," *Eur. Phys. J. B*, vol. 4, pp. 413–420, 1998.
[21] H. Oshima *et al.*, "Perpendicular giant magnetoresistance of CoFeB/Cu single and dual spin-valve films," *J. Appl. Phys.*, vol. 91, pp. 8105–8107, 2002.
[22] J. Bass and W. P. Pratt Jr., "Spin-diffusion length in metals and alloys, and spin-flipping at metal/metal interfaces: An experimentalist's review," *J. Phys.: Condens. Matter*, vol. 19, p. 183201, 2007.

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