Quantifying spin mixing conductance in F/Pt (F = Ni, Fe, and Ni$_{81}$Fe$_{19}$) bilayer film

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Abstract. The spin-mixing conductances in F/Pt (F = Ni, Fe, and Ni$_{81}$Fe$_{19}$) bilayer films were quantified from the peak-to-peak linewidth of ferromagnetic resonance (FMR) spectra based on the model of the spin pumping. When the Pt layer is attached to the F layer, we found the enhancement of the FMR linewidth due to the spin pumping. The experimental results show that the spin-mixing conductances in F/Pt (F = Ni, Fe, and Ni$_{81}$Fe$_{19}$) bilayer films have the same order of magnitude, showing that spin injection efficiency in the spin pumping is almost identical in these films.

1. Introduction

There has been a rapidly growing interest in the field of spintronics, which manipulates the electron’s spin degree of freedom in addition to the charge degree of freedom [1, 2]. In the field of spintronics, methods for generating and detecting spin currents, a flow of electron spins in a solid, are essential for spin-based magnetic memories and computing devices [3-5].

In a ferromagnetic/paramagnetic bilayer film, the spin pumping induced by ferromagnetic resonance (FMR) is an efficient method to realize a pure spin-current injection into the paramagnetic layer from the ferromagnetic layer; when the magnetic field is applied to the film, the magnetization precession in the ferromagnetic metal pumps a spin current into the adjacent paramagnetic metal [6-12]. The pumped spin currents $J_s$ induced by the spin pumping is described as

$$J_s = \frac{h}{4\pi} \left( g_r \uparrow \downarrow \mathbf{m} \times \frac{d\mathbf{m}}{dr} \right).$$

Here, $\mathbf{m}$ is a unit vector of magnetization, $g_r$ is real part of the spin-mixing conductance [13]. $g_r$ is essential parameter to investigate the spin pumping experimentally. In this paper, we quantify $g_r$ in F/Pt (F = Ni, Fe, and Ni$_{81}$Fe$_{19}$) bilayer films.

2. Experimental Procedure

Figure 1(a) shows a schematic illustration of the sample used in the present study. The samples are plane F films and F/Pt films where, F = Ni, Fe, and Ni$_{81}$Fe$_{19}$. The 10-nm thick Pt layer was sputtered in Ar gas atmosphere on a thermally oxidized Si substrate and then the 10-nm thick F layer was
deposited with an electron beam evaporator. We measured the FMR spectra in all samples using the electron spin resonance spectroscopy.

During the measurement, the sample is placed at the center of a TE$_{011}$ cavity at which the magnetic-field component of the microwave mode is maximized while the electric-field component of the microwave mode is minimized [14]. The microwave mode with a frequency of $f = 9.44$ GHz exists in the cavity, and the external magnetic field $\mathbf{H}$ along the film plane is applied to the sample. The microwave power (100 mW) is much lower than the saturation of the FMR absorption for the present sample. All the experiments were performed at room temperature.

![Figure 1](image)

**Figure 1.** (a) A schematic illustration of the sample used in the present study. We used Ni, Fe, and Ni$_{81}$Fe$_{19}$ for the ferromagnetic layer. $\mathbf{H}$ is the external magnetic field. (b) FMR spectrum for the Fe film. $I$, $H_{\text{FMR}}$, and $\Delta H$ denote the microwave absorption intensity, the resonance field, and the peak-to-peak linewidth, respectively.

### 3. Results and Discussion

Figures 2(a), 2(b), and 2(c) show the FMR spectra $dI(H)/dH$ for the Ni, Fe, and Ni$_{81}$Fe$_{19}$ single layer films under the 100 mW microwave excitation, where $I$ represents the microwave absorption intensity. Figures 2(d), 2(e), and 2(f) show the FMR spectra $dI(H)/dH$ for the $F$/Pt ($F = \text{Ni, Fe, and Ni}_{81}\text{Fe}_{19}$) bilayer films under the 100 mW microwave excitation.

From the FMR spectra, we can estimate the damping constant $\alpha$ using the relation $\alpha = (\sqrt{3}\gamma / 4\pi f)\Delta H$, where $\Delta H$ is defined as shown in figure 1(b) [4]. Here, $\gamma$ represents the gyromagnetic ratio. The saturation magnetization $4\pi M_s$ can also be obtained from the resonance condition when $\mathbf{H}$ is applied along the film plane:

$$\left( \frac{\omega}{\gamma} \right)^2 = (H_{\text{FMR}} + 4\pi M_s)H_{\text{FMR}},$$

(2)

where $\omega = 2\pi f$ [15].

When attaching the Pt layer to the ferromagnetic layer, the FMR linewidth $\Delta H$ is enhanced, e.g., $\Delta H$ extracted from figures 2(a) and 2(d) are $\Delta H_{\text{Ni}} = 26.3$ mT for Ni and $\Delta H_{\text{Ni/Pt}} = 27.3$ mT for Ni/Pt, respectively. The additional contribution to $\alpha$ is attributed to the spin-current emission induced by the spin pumping. We define the additional damping constant as $\Delta\alpha$ as $\Delta\alpha = \alpha_{F/Pt} - \alpha_r$, where $\alpha_{F/Pt}$ and $\alpha_r$ are the damping constant for the $F$/Pt ($F = \text{Ni, Fe, and Ni}_{81}\text{Fe}_{19}$) bilayer films and the $F$ films, respectively. Using $\Delta\alpha$, $g_{\uparrow\downarrow}$ is expressed by

$$g_{\uparrow\downarrow} = \frac{4\pi M_s d_{\text{FM}}}{4\hbar} \Delta\alpha,$$

(3)
where $d_{FM}$ is the thickness of the ferromagnetic layer [13]. Here, in the $F$/Pt ($F =$ Ni, Fe, and Ni$_{81}$Fe$_{19}$) bilayer films, the Pt layer acts as a spin sink, since the thickness of the Pt layer is comparable to the spin diffusion length $\lambda$ of Pt $\lambda = 7$ nm [13, 16].

In table 1, we calculate the values of $g_{\uparrow\downarrow}$ for the $F$/Pt ($F =$ Ni, Fe, and Ni$_{81}$Fe$_{19}$) bilayer films obtained from figure 2 using equation (3). We also show the values of $\Delta\alpha$, $4\pi M_s$, and $\gamma$ for these films. Table 1 indicates that the spin-mixing conductances at the $F$/Pt ($F =$ Ni, Fe, and Ni$_{81}$Fe$_{19}$) interface have the same order of magnitude, showing that spin injection efficiency in the spin pumping is almost identical in these films.

4. Conclusion

The spin-mixing conductances were quantified in $F$/Pt ($F =$ Ni, Fe, and Ni$_{81}$Fe$_{19}$) bilayer films. From the FMR spectra using the model of the spin pumping, we found the spin-mixing conductances in $F$/Pt ($F =$ Ni, Fe, and Ni$_{81}$Fe$_{19}$) bilayer films have the same order of magnitude. This shows that spin injection efficiency in the spin pumping is almost identical in these films.
Table 1. The values of $\gamma$, $4\pi M_s$, $\Delta \alpha$, and $g_{\uparrow \downarrow}^{(1)}$ for the F/Pt ($F = \text{Ni}, \text{Fe}, \text{and} \text{Ni}_{81}\text{Fe}_{19}$) bilayer films. The values of $g_{\uparrow \downarrow}^{(1)}$ are calculated from figure 2 using equation (3). The spin-mixing conductances at the F/Pt ($F = \text{Ni}, \text{Fe}, \text{and} \text{Ni}_{81}\text{Fe}_{19}$) interface have the same order of magnitude.

|       | $\gamma$ (T$^{-1}$s$^{-1}$) | $4\pi M_s$ (T) | $\Delta \alpha$ | $g_{\uparrow \downarrow}^{(1)}$ (m$^{-2}$) |
|-------|----------------------------|----------------|-----------------|-----------------------------------------|
| Ni    | $1.85 \times 10^{11}$     | 0.218          | $3 \times 10^{-3}$ | $3 \times 10^{18}$                        |
| Fe    | $1.84 \times 10^{11}$     | 1.60           | $3 \times 10^{-4}$ | $2 \times 10^{18}$                        |
| Ni$_{81}$Fe$_{19}$ | $1.85 \times 10^{11}$    | 0.787          | $8 \times 10^{-4}$ | $3 \times 10^{18}$                        |

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