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Irreversible magnetic-field dependence of ferromagnetic resonance and inverse spin Hall effect voltage in CoFeB/Pt bilayer

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ABSTRACT

Magnetic field (H) sweeping direction dependences of the mixed voltage V_{mix} induced by the inverse-spin Hall effect(ISHE) and spin-rectified effect (SRE) in a CoFeB (5 nm)/Pt (10 nm) bilayer structure are investigated using the ferromagnetic resonance in the TE mode cavities and coplanar waveguide methods. Conventionally, the magnitude of ISHE voltage V_{ISH} (symmetric) excluding the SRE (antisymmetric component) was unavoidably separated from the fitting curve of V_{mix} (a sum of a symmetric and an antisymmetric part) for one direction of H-source. By studying the ratio of the two voltage parts with the bi-directional H sweeping, the optimized V_{ISH} (no SRE condition) value which also include a well-defined spin Hall angle can be obtained via the linear response relation of ISHE and SRE components.

1. Introduction

The spin Hall effect (SHE) [1] is a phenomenon of the generation of pure spin current J_s, which is the flow of electron spins without the flow of charge current J_c. Research on the SHE has a great potential for developing applied spintronic devices [2,3]. The SHE coverts J_c to J_s in the perpendicular direction through spin-orbit coupling (SOC) in ferromagnets [4]. The efficiency of the charge-spin conversion is determined using the spin Hall angle θ_{SH} [5]. For example, high values of θ_{SH} are reported for the $\mathrm{Bi_2Se_3}(0.43)$ [6], β-Ta(-0.15) [7], and $\beta-\mathrm{W}(-0.3)$ [8]. For attaining high performance and reliability in the applications of spin devices in comparison to conventional spin-based devices [7], it is practically important to use a high and reliable θ_{SH}, thus solving the issue of write impedance and consequently minimizing the writing energy of a three-terminal SHE device. The θ_{SH} can be precisely quantified before application to spintronic devices. An accurate θ_{SH} is essential in order to employ the SHE in spintronic devices [9–11].

Many studies on the θ_{SH} use a reverse phenomenon of the SHE, such as the inverse-spin Hall effect (ISHE). The J_s is converted to a J_c via ISHE as [12]

$$J_c = \theta_{SH}(2e/\hbar)J_s \times \sigma \tag{1}$$

where e, $\hbar$, and σ denote the elementary charge, Dirac constant, and spin-polarization vector of the J_s, respectively. The spin pumping effect driven by the ferromagnetic resonance (FMR) is widely used to generate the J_s in a ferromagnet (FM)/normal metal (NM) bilayer structure [9–12]. Note that the θ_{SH}, which is related to the spin-orbit interaction of the NM material, can be obtained from the measured ISHE voltage V_{ISH} (transform from the J_c). However, the mixed voltage V_{mix} in the measurement boundaries of the microwave (MW) cavity and coplanar waveguide (CPW) involve not only the V_{ISH} but also the spin-rectified effect (SRE) voltage V_{SR} [12,13]. The inexplicit V_{SR} contains the anisotropic magnetoresistance (AMR) [13] contributions and/or anomalous Hall effect (AHE) [12] in the FM. The unwanted SRE can be interfered by obtaining a reasonable θ_{SH} value. Numerous studies are performed to exclude the SRE so as to attain a more accurate θ_{SH} value [9–13]. For example, placing the sample at the center of a MW cavity where the MW magnetic field is maximized and the MW electric field is minimized, will result in the suppression of the AHE contribution [14]. In addition, the extent of AHE contribution is the selection issues of suitable MW modes despite locating the cavity center [9]. The condition of FM/NM interface is very important to retain the Js under the spin pumping phenomenon [15]. Furthermore, the minimized SRE achieved using the TE mode cavity can be satisfied using a thick NM layer and the parallel direction between the external magnetic field H and width axis of the sample [11]. However, it is difficult because the different θ_{SH} values come from the origin and correlation between the

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ISHE and SREs in the bilayer sample.

In this study, the H sweeping direction dependences of the FMR spectra and $V_{\mathrm{mix}}(H)$ from the ISHE and SRE in CoFeB (5 nm)/Pt (10 nm) sample are experimentally investigated using the TE$_{102}$/TE$_{011}$ mode cavities [9] and new CPW method like a cavity configuration. The hysteretic behavior of $V_{\mathrm{mix}}(H)$ can be shown based on the linear decreasing function of relative V_{ISH} versus V_{SR}. Finally, the optimized V_{ISH} ((x,y)-coordinate point $= (V_{\mathrm{SR}},V_{\mathrm{ISH}}) = (0,V_{\mathrm{ISH}}{}^{0})$) which also convert into a well-defined θ_{SH} can be obtained by the extrapolation of V_{ISH} vs. V_{SR} plot.

2. Experimental results

Fig. 1(a) and (b) show the measurements of the FMR in the CoFeB/Pt bilayer structure. The bilayer sample with a 5-nm-thick CoFeB layer and a 10-nm-thick Pt layer is sputtered on thermally oxidized Si substrate. The dimension of the sample was 1 mm (width) × 2 mm (length). The H is applied perpendicular to the direction across the sample of the length axis. The increased H sweep direction (from a low to high value) is represented as H^+ i.e., by using a superscript plus sign. On the other hand, the decreased H sweep direction (from a high to low value) is represented as H^- i.e., by using a superscript minus sign. When the FMR experiment is performed using the cavity, the sample was placed at the center of a resonant cavity where the magnetic field of the MW is maximized and the electric field of the MW is minimized. The MW frequency f_{MW} and power P_{MW} are 9.371 GHz and 10 mW, respectively, in the TE$_{102}$ mode cavity. For the H^+ case, the resonance field $H_0{}^+$ is 889.6 Oe and the peak-to-peak line width (ΔH^+) is 53.57 Oe. For the H^- case, the $H_0{}^-$ is 886 Oe and the ΔH^- is 57.35 Oe. The f_{MW} and P_{MW} are 9.46 GHz and 10 mW, respectively, in the TE$_{011}$ mode cavity. For the H^+ case, the $H_0{}^+$ is 982 Oe and ΔH^+ is 61.99 Oe. For the H^- case, the $H_0{}^-$ is 981.1 Oe and the ΔH^- is 62.77 Oe. The FMR signals for the $H^{+(-)}$ cases have a difference of $H_0{}^{+(-)}$ and $\Delta H^{+(-)}$ due to the hysteretic behavior of magnetization dynamics and spin-relaxation process in the ferromagnetic/non-magnetic systems. Fig. 2(a) shows the in-plane $H^{+(-)}$ dependence of the normalized M_{eff} ($= m/M_{\mathrm{s}}$, where m and M_{s} are the magnetic moment and the saturation magnetization, respectively) value in the CoFeB/Pt sample. The difference of M_{eff} for the $H^{+(-)}$ can be shown at each $H_0{}^{+(-)}$ point. After all, the hysteretic resonance-phenomenon can occur to the FM/NM bilayer due to the deficient or unsaturated M_{eff}. A few discrepancies of between $H_0{}^+(\Delta H^+)$ and $H_0{}^-(\Delta H^-)$ caused by the different path of magnetization for the $H^{+(-)}$.

Fig. 2(b) and (c) show the $H^{+(-)}$ dependence of $V_{\mathrm{mix}}{}^{\pm}(H)$ measured for the CoFeB/Pt sample under the FMR condition. Two electrodes were contacted with both ends of the dumbbell-shaped Pt layer. To separate the ISHE component from the $V_{\mathrm{mix}}{}^{\pm}(H)$ spectra, the spectral line of $V_{\mathrm{mix}}{}^{\pm}(H)$ is well fitted using the following equation: [12]

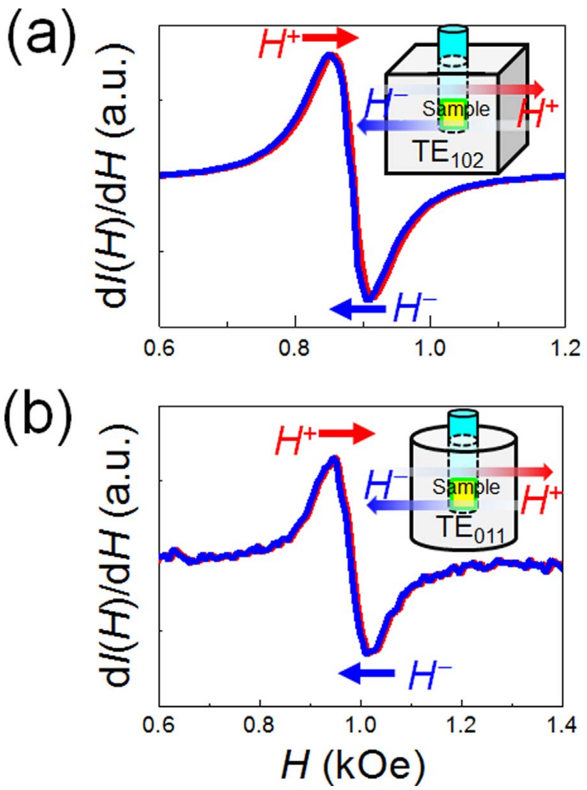

Fig. 1. Experimental FMR data in the (a) TE$_{102}$ mode cavity and (b) TE$_{011}$ mode cavity. The red arrow represents the increased H sweep direction (H^+), and the blue arrow represents the decreased H sweep direction (H^-). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

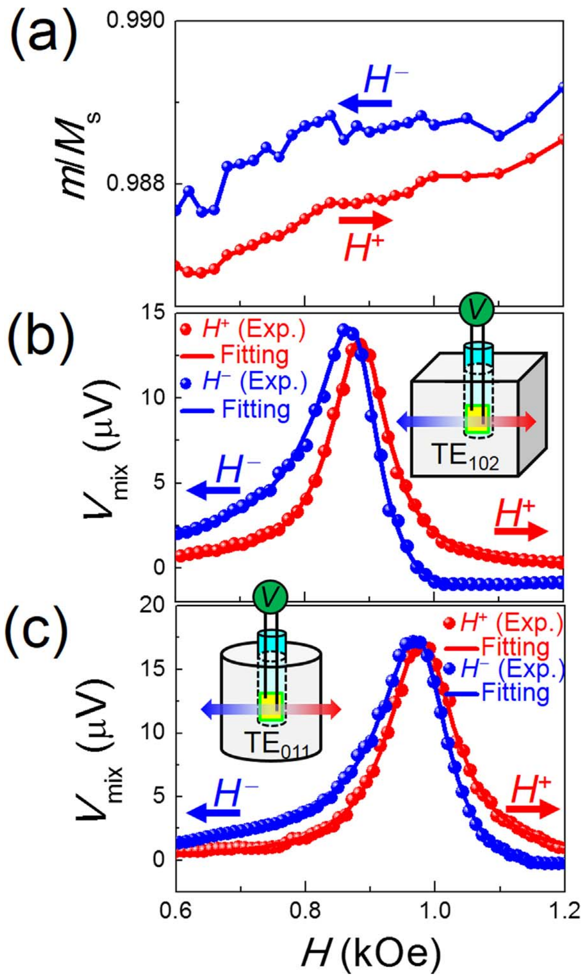

Fig. 2. In-plane $H^{+(-)}$ dependences of the (a) relative magnetization(m/M_{s}), (b) measured V_{mix} in the TE$_{102}$ mode cavity(rectangular cavity), and (c) measured V_{mix} in the TE$_{011}$ mode cavity(cylindrical cavity). The red (blue) dots and lines are the H^+ (H^-) case. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)