SIGNIFICANT INFLUENCE OF DC CURRENT ON SPIN TORQUE FERROMAGNETIC RESONANCE

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I. Introduction

Spin Hall effect is a key phenomenon to manipulate magnetization via spin angular momentum transfer from a heavy metal into an adjacent ferromagnetic metal. The efficiency of spin current generation from electric current flowing in a heavy metal, so called spin Hall angle, has been demonstrated for several heavy metals such as Pt, Ta, W [1, 2]. In spin torque ferromagnetic resonance (ST-FMR) excited by the spin Hall effect in such a ferromagnetic metal/heavy metal bilayers, a voltage output can be obtained as follows:

$$V = {}^{k}\!/_{\Delta}[SF_S(H_{res}) + AF_A(H_{res})], \tag{1}$$

where k, Δ, S, A, F_S, F_A and H_{res} are the coefficient related to resistance, the half width at half maximum of the resonant peak, the coefficient of symmetric part of voltage signal, the coefficient of asymmetric part of voltage signal and the Lorentzian and anti-Lorentzian functions of the resonant field H_{res}, respectively. If the damping torque can be compensated with the spin torque due to spin Hall effect, it is possible to develop a microwave oscillation. So far, many studies have been performed to fully understand the spin dynamics in ST-FMR [3, 4]. However, there are still many issues under debate, being related with underlying physics. In this study, we found unexpected behavior of the Lorentzian part of ST-FMR caused by adding a dc current to the excitation rf current.

II. Experimental

We prepared a NiFe (5 nm)/Pt (8 nm) bilayer on a sapphire substrate by using rf-sputtering and fabricated it into rectangular devices of 6 μm in length and 1 μm in width. ST-FMR measurements were performed with the combination of a signal generator and a lock-in amplifier. The frequency was fixed at 12 GHz, and an external magnetic field was applied (swept from 0 to 2.8 kOe). Dc currents up to 4.15×10^{11} A/m^2 were applied in Pt, in addition to the rf current through a bias-tee.

III. Results and discussion

Fig. 1(a) shows dc current dependence of the output voltage of ST-FMR at $\theta = 10^\circ$, which can be separated into symmetric and asymmetric Lorentzian components, as shown in Figs. 1(b) and 1(c), respectively. Here, θ corresponds to the angle between the applied magnetic field and the current direction. The shape of resonant signal significantly changes as the magnitude of dc current increase, which would be an unexpected behavior in the current understanding of ST-FMR. In Figs. 1(b) and 1(c), it turns out that it is due to the contribution of the symmetric part of the signal, which corresponds to the effect of the spin Hall spin transfer toque in Pt. As dc current is varied from $+4.15\times10^{11}$ A/m^2 to -4.15×10^{11} A/m^2, the symmetric part of ST-FMR in Fig.1(b) shows a decrease of the signal amplitude at the resonant field and then a sign change occurs. This in contrast to the behavior that the asymmetric part does not show any significant dependence to dc current, as shown in Fig. 1(c). Interestingly, these dependences can cause the change in the evaluated spin Hall angle η of Pt, as shown in Fig. 2, although spin Hall angle that is a physical quantity specific to the material should be constant.

Figs. 3(a) and (b) show *kS and kA* of the symmetric and asymmetric parts, respectively, as a function of *θ, □□□□□□□□□□□□□.* We firstly checked the dc current dependence of *kS* and *kA* at each angle (not shown here) and these data were fitted with $kS = k_0 + k_1 I_{dc} + k_2 I^2_{dc}$ and $kA = k_0 + k_1 I_{dc} + k_2 I^2_{dc}$, respectively.

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k_0 and k_2 of both of kS and kA can be fitted by sin2θcosθ, which can be attributed to the anisotropy magnetoresistance (AMR) because the voltage signals appear based on the AMR of the device. On the other hand, k_1, especially of kS, can be fitted by sin2θ, which can not be explained by the conventional understanding of ST-FMR. This unconventional behavior of k_1 may make us take it into account that out-of-plane magnetization dynamics occurs via unknown torques beyond the model described in Eq. (1). Another possibility is that the observation can simply be explained by the inverse spin Hall effect.

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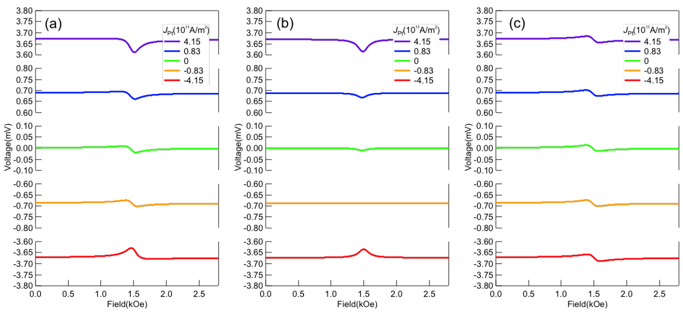

Fig. 1. ST-FMR spectra of a NiFe (5 nm)/Pt (8 nm) bilayer at θ = 10˚; (a) fitted curves, (b) symmetric component and (c) asymmetric component.

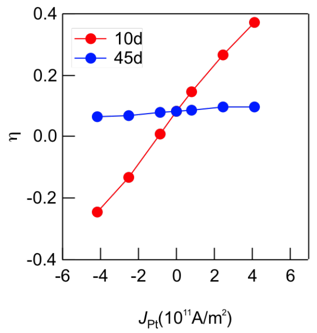

Fig. 2. Spin Hall angles evaluated for Pt at θ = 10˚ and 45˚.

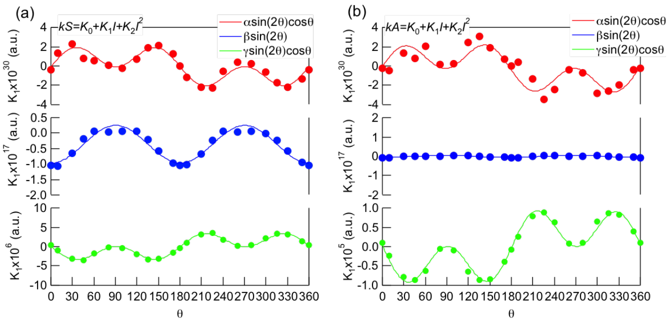

Fig. 3. (a) kS and (b) kA as a function of θ.