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Measurement of effective magnetic field via spin Hall effect in a Pt/Co/Pt trilayer structure

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1. Introduction

Magnetization control and reversal exclusively by electrical means have been demonstrated in heavy metal (Pt, Ta) and magnetic (Fe, Co) multi-layered structures which may play an important role in the development of next generation memory, and logic devices [1-7]. One of the effects owing to these phenomena is a spin current originating from heavy metal layers with a strong spin-orbit interaction exerting a spin torque on the local magnetization due to the spin Hall effect [6,7]. In the present experiment we attempt to measure the effective magnetic field resulting from the torque induced by the spin Hall effect in a Pt/Co/Pt trilayer film.

A Pt film exhibits the spin Hall effect where an applied in plane electrical current induces a spin current into the perpendicular direction. In a Pt/Co/Pt layered film, the spin current exerts a torque into the adjacent magnetic Co layer which results in an effective magnetic field on the magnetization (hereafter referred to as effective field). The torque from the spin current acting on the magnetic layer is expected to match Slonczewski spin current torque dynamics indicating that the spin current in the vertical direction *z* axis polarized transversely along the *y* axis will exert an effective field along the direction of the electrical current *x* axis[8,9]. Here M_s is the saturation magnetization,

$$\tau = \frac{\hbar}{2eM_s t} J_S(\hat{m}\times(\hat{\sigma}\times\hat{m})) \qquad (1)$$

e electrical charge, *t* thickness of the magnetic layer, *m* magnetization unit vector of the Co film, σ electron spin polarization by spin Hall effect and J_s is the spin current. While the spin Hall torques exerted downward from the top and upward from the bottom are opposite in polarity, their relative strengths can be adjusted by altering the Pt layer thickness as shown in Fig. 1(a). Pt layer thicknesses close to the spin diffusion length (assumed to be 1.4 nm in this experiment [8]) will have their spin Hall torques suppressed due to spin diffusion. It is then expected that a net spin Hall torque can exist in a Pt/Co/Pt system by setting one Pt layer thickness close to the spin diffusion length and another to the bulk thickness [6,8]. Due to similar interfaces on the Co layer, the Rashba effect is assumed to be cancel out.

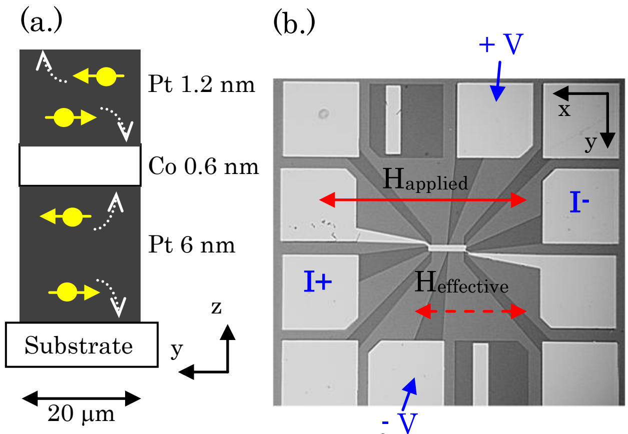

Fig. 1 (a) Cross section structure of the sample. Electrons scatter in the vertical direction due to their spins indicated by the broken white arrows resulting in a spin current on the middle cobalt layer. The spin current in the top layer is suppressed due to spin diffusion resulting in a contribution from only the bottom layer. (b) The Hall bar structure is 80 μm along the x direction and 20 μm along the y direction. AC and DC sources are applied at the ±I terminals while all voltage measurements are taken at the ±V terminals.

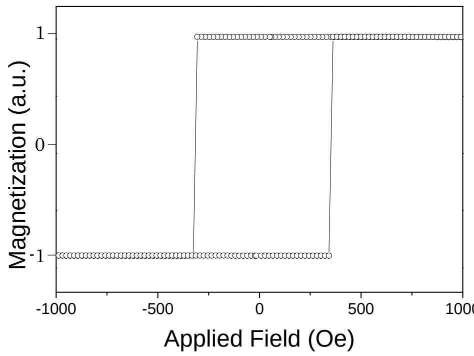

Fig. 2 The perpendicular magnetic anisotropy of the film is confirmed through 4 terminal DC and Hall voltage measurements as a function of the out of plane applied field.

Experiment

A Pt (6 nm)/Co (0.6 nm)/Pt (1.2 nm) film was fabricated by RF magnetron sputtering onto a sili-

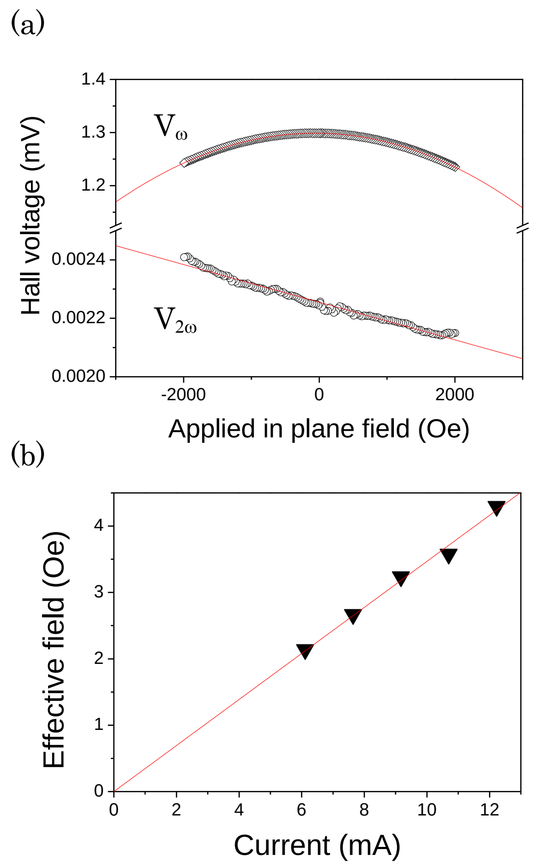

Fig. 3 (a) First and Second harmonic AC voltage measurements with fitted second and first order derivatives respectively (red lines). Effective field is determined by the ratio of these two values. (b) Effective field and applied current dependence.

con oxide substrates with an Ar pressure of 0.2 Pa and deposition rates of 0.02 nm/s for Pt and Co. These films were then patterned into 20 μm × 80 μm Hall bar structures by several photolithography processes (Fig. 1(b)) and the perpendicular magnetic anisotropy is initially confirmed through a 4 terminal DC anomalous Hall voltage measurement with an out of plane *z* direction sweeping field (Fig. 2). To measure the effective field resulting from the spin Hall torque, an AC current at 330 Hz is applied longitudinally (I+ and I- in Fig. 1(b)) and a magnetic field is swept along the *y* direction from a positive to a negative field. Two lock-in amplifiers are used to measure the 1st harmonic signal V_ω corresponding to the tilting of the magnetization due to the external applied field and the 2nd harmonic signal $V_{2\omega}$ corresponding to the magnetization tilting due to the spin Hall torque from the applied AC current [3,10]. The effective field resulting from

$$\mathrm{H_{SHE}} = -2\frac{\partial V_{2\omega}}{\partial H_{Applied}} \Bigg/ \frac{\partial^2 V_\omega}{\partial H^2_{Applied}} \qquad (2)$$

the spin Hall torque can be calculated using those two measured values with the relation.

The first and second harmonic transverse Hall voltages exhibit a parabolic and linear relation respectively for an AC current amplitude of 12 mA (Fig. 3(a)). Through polynomial and linear fitting, the 2nd derivative V_ω was determined to be 3.0×10^{-11} V/Oe^2 and the first derivative of $V_{2\omega}$ were found to be 6.44×10^{-11} V/Oe resulting in an effective field of 4.29 Oe from Eq. (2). The effective fields increases linearly with the applied current amplitudes in Fig. 3(b) from which we find the effective field per current density equivalent to 53 Oe per 10^8A/cm^2. This result is significantly smaller than the 2300 Oe per 10^8A/cm^2 in a Ta/CoFeB/MgO film [2] and 10,000 Oe per 10^8A/cm^2 in a Pt/Co/AlOx film [4]. Structural inversion asymmetry resulting from different interfaces of magnetic layer allows the possibility of the Rashba spin orbit interaction which in combination with the spin Hall torque may be responsible for the perceived larger effective fields in the heavy metal / ferromagnet / metal oxide films reported [2],[4].

Conclusion

We obtained an effective field of 53 Oe per 10^8 A/cm^2 in a Pt (6 nm)/Co (0.6 nm)/Pt (1.2 nm) with 20 μm × 80 μm Hall bar structure by AC current induced magnetization tilting. Films with varying layer thicknesses and materials will be measured to further investigate the current induced effective field.

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