Spin-torque induced magnetization switching and oscillation in half-metallic Co₂MnSi-based CPP-GMR devices

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1. Introduction

Half-metallic ferromagnets (HMFs), which possess perfectly spin-polarized conduction electrons due to the semiconducting gap in either the up- or down-spin channel at the Fermi level, are attracting much interest in spintronics because they are expected to enhance and elicit various spin-dependent phenomena and improve the performance of applications. Recently, several Co-based full-Heusler compounds, a class of HMFs, such as Co₂MnSi (CMS), Co₂MnGe, and Co₂FeAl_{0.5}Si_{0.5}, have been applied as ferromagnetic electrodes in magnetic tunnel junctions and current-perpendicular-to-plane (CPP) giant magnetoresistance (GMR) devices, and large MR ratios due to high spin-polarization have been reported successfully.[1-4] According to the analysis based on the Valet-Fert model, a reason of high MR ratio is high bulk and interface spin-asymmetry of electron scatterings originated from a high spin-polarization. [3,4]

Not only MR ratio but also spin-torque induced phenomena such as spin-torque induced magnetization switching (SIMS) and magnetization oscillation (STO) are attractive to be investigated in the magnetoresistive devices using half-metallic electrodes. It is expected to decrease a critical current density (J_C) of SIMS by using half-metallic electrodes because of high spin-injection efficiency. It is also promising to enhance a microwave output power of STO because the output power of STO is proportional to the square of MR ratio. Thus, the purpose of present study is to investigate SIMS and STO in the CMS-based CPP-GMR devices.

2. Experimental method

A fully epitaxial CMS/Ag/CMS film was prepared using an ultra-high vacuum (UHV)-compatible magnetron sputtering system ($P_{base} < 1 \times 10^{-7}$ Pa). First, a Cr (5 nm)/Ag (40 nm) buffer was deposited on a MgO (001) single-crystal substrate at RT to improve the surface flatness. A 40-nm-thick CMS lower layer was grown on the buffer at RT using a Co_{43.7}Mn_{28.0}Si_{28.4} alloy target followed by in situ annealing at 500°C to promote chemical ordering. After the sample was cooled to RT, a 5-nm-thick Ag spacer and a 5-nm-thick CMS upper layer were deposited. Then, the upper CMS layer was also annealed at 500°C. Finally, the film was capped by a Ag (2 nm)/Au (5 nm) protective layer. The film was patterned into a CPP-GMR pillar with an ellipsoidal shape (0.06 \times 0.11 μ m2) using electron beam lithography and Ar ion milling. The milling was stopped at around the interface between the lower CMS layer and the Ag spacer using secondary ion mass spectroscopy to induce large shape magnetic anisotropy in only the upper CMS layer. In this device structure, the upper and lower CMS layers, respectively, behave as hard and soft layers against an external magnetic field (H_{ext}) , and as free and fixed layers against the STT given by a electric current. In this study, positive current I is defined as the direction of electron flows from the upper to the lower CMS layer. For the measurement of STO, the CPP-GMR device was connected to a circuit with a two-terminal rf probe, and I_{dc} was applied through a bias tee. The output rf voltage was amplified by a preamplifier and was monitored in the frequency domain by a spectrum analyzer.

3. Experimental Result

3.1 SIMS in the CMS/Ag/CMS CPP-GMR device

R-I measurements in a CMS(40 nm)/Ag/CMS(5 nm) structure show a clear spin-transfer torque induced magnetization switching (as shown in Fig. 1). It is clearly found that the critical switching currents for AP to P states (I_{AP-P}) and P to AP states (I_{P-AP}) is remarkably asymmetric. A critical switching current is inverse-proportional to the spin-injection efficiency $g(\theta)$, where θ is relative angle between the magnetizations of two ferromagnets. In a CPP-GMR structure, $g(\theta)$ is expressed as



Fig. 1 *R-I* curve for a CMS/Ag/CMS CPP-GMR device using dc current and under no effective magnetic field.

$$g(\theta) = \left[-4 + \frac{1}{4}(P^{-\frac{1}{2}} + P^{\frac{1}{2}})^3(3 + \cos\theta)\right]^{-1}$$

where g becomes 1/4 and infinite at P = 1 in the case of $\theta = 0$ and π , respectively. Thus, observed large asymmetry of critical switching currents between I_{AP-P} and I_{P-AP} indicates large spin-polarization P in CMS electrode and much larger spin-injection efficiency in AP state $g(\pi)$. Note that, decrease of R over 2.2 mA is caused by rotation of agnetization toward P-state in thick CMS layer due to the large spin-injection efficiency in AP-state. The critical current density of SIMS without the effect of thermal fluctuation by Joule heating (J_{c0}) was estimated using pulse current with different durations from 10 µs – 100 ms. The estimated J_{c0} were relatively higher than we expected; 5.7 x 10⁷ and 1.7 x 10⁷A/cm² in P and AP configuration, respectively, which may be mainly due to the relatively thick free CMS layer thickness.

3.2 STO in the CMS/Ag/CMS CPP-GMR device

The H_{ext} dependence of rf spectra in the CMS/Ag/CMS is shown in Fig. 2(a). I_{dc} was fixed at 6.0 mA. Only f_0 was observed at 175 Oe $\leq H_{ext} \leq$ 300 Oe, and it showed a redshift with H_{ext} . At $H_{ext} \ge 400$ Oe, $2f_0$ appeared in addition to f_0 , and these frequencies gradually increased with H_{ext} . The peak frequencies of f0 and $2f_0$ as a function of H_{ext} are summarized in Fig. 2(b). The ferromagnetic resonance (FMR) frequency ($f_{\rm FMR}$) under $H_{\rm ext}$ applied in the in-plane hard magnetization direction was calculated using Kittel's equation. The calculated result shown in the dashed line in Fig. 2(b) qualitatively explains the experimental results. At $H_{\text{ext}} = H_{\text{sat}}$ (~ 400Oe from the MR curve), both free and fixed layer magnetizations are aligned in parallel, which is why $2f_0$ appeared at $H_{\text{ext}} \ge H_{\text{sat}}$. Note that the positive I_{dc} stimulates the rf oscillation in the thinner CMS layer, $2f_0$ is exactly twice f_0 , and the intensity change in f_0 and $2f_0$ with H_{ext} depends on the relative angle between two CMS layers. These facts support the conclusion that the two observed peaks are not due to two non-uniform modes, modes from the thick CMS layers, or coupled modes, but originate from the uniform FMR mode in the thin CMS layer.

The output power of rf oscillation P_{out} as a function of H_{ext} is shown in Fig. 2(c). Although the H_{ext} dependence is complicated, high $P_{out} > 1$ nW was achieved at low H_{ext} . For example, $P_{out} = 1.1$ nW at $H_{ext} = 125$ Oe, the spectrum of which is shown in the inset of Fig. 2(c). From the value of P_{out} for the fundamental peak (P_{out}^{Fund}) , the precession angle $(\Delta\theta)$ of rf oscillation was roughly estimated by using, $P_{out}^{Fund}/P_{in} \approx \left\{ \left((R_{AP} - R_P)R(\theta_0) / R_{AP}R_P \right)^2 (\Delta\theta/2)^2 \sin^2\theta_0 \right\} / 8$ where P_{in} is the input power. By using $\theta_0 = 38^\circ$, which was

where P_{in} is the input power. By using $\theta_0 = 38^\circ$, which was calculated from the MR curve, $\Delta\theta$ was found to be ~8.6°. In addition to the high power oscillation, a narrow linewidth of 35 MHz was observed, which is one order of magnitude smaller than that reported for MgO-based STOs with high resistance and high MR ratio.[5-7] The estimated damping magnetic α from the linewidth was 0.002, which is compa-



Fig. 2 (a) Rf spectra measured at different H_{ext} . For clarity, spectra are shifted vertically. (b) Peak frequencies of f_0 (circles) and $2f_0$ (squares) as function of H_{ext} . Dashed line in (b) denotes calculated results. (c) Output power as function of H_{ext} . Rf spectra at $H_{\text{ext}} = 125$ Oe are shown in inset. I_{de} was fixed at 6.0 mA. H_{ext} was applied in short-axis direction of ellipsoidal pillar.

rable to that obtained from a previous FMR measurement. [8] A striking feature of the CMS-based STO is the large output power due to the large MR effect. We have demonstrated $P_{out} = 1.1$ nW in this study, which is much larger than the output power reported in spin-valve-type devices with conventional ferromagnetic layers[9-11] and is comparable to that obtained in point-contact devices using the out-of-plane precession mode. [12]

3. Conclusions

In this study, spin-torque induced magnetization switching and oscillation was investigated in the CMS/Ag/CMS CPP-GMR device. Large asymmetry of critical current density between P and AP states, which indicated a high spin-injection efficiency, was observed in the measurement of SIMS. Large STO output power of 1.1nW due to high MR ratio was confirmed despite a small precession angle of 8.6°.

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