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ABSTRACT

Charge-current-induced torque effects on the magnetization dynamics of ferromagnetic/metal bilayer is interesting from the aspect of fundamental physics as well as the applications in spintronic devices. The torque-induced variation of damping constant of magnetization can be foreseen from the change of the linewidth of ferromagnetic resonance spectrum. The Oersted torque ($\tau_{Oe}$) and current-induced torque ($\tau_{C}$) are induced by charge current; while the spin-orbit torque ($\tau_{SO}$) and field-like torque ($\tau_{FL}$) are induced by spin current. However, the torque effects often were hindered due to the heating-induced artifacts. In this work, we particularly pay attention to minimize the Joule heating effects in order to investigate the intrinsic torque effects in cobalt (Co)/platinum (Pt) bilayer with an applied charge current ranging from ~60 to 60 mA. In this range, the Oersted field is estimated as 0.25 Oe which is much smaller than the experimental result of $\Delta H$, (~0.7 Oe), implying some contribution from the spin-current induced field like torque. The current-polarization-induced asymmetry of linewidth $\Delta W$, $\Delta W \equiv [W(+J_{c}) - W(-J_{c})]$, increases from 0 to 0.15 with $J_{c}$ changing from 0 to 60 mA, which is attributed to the spin-orbit torque.

INTRODUCTION

Ferromagnetic resonance (FMR) is a powerful tool to analyze the torque effects on magnetic materials. The underlying physics is that the torque changes the magnetization relaxation time, which is reflected from the variation of FMR linewidth ($W$) and resonance field ($H_{r}$). Under the FMR condition, the magnetic dynamic behavior can be described by the Landau-Lifshitz-Gilbert equation.2–4 Injecting a charge current into the structure of ferromagnetic material (FM)/nonmagnetic material (NM) bilayer might induce various kinds of torque on the magnetization and modify the Landau-Lifshitz-Gilbert equation. One of them is the Oersted torque ($\tau_{Oe} \approx \hat{M} \times H_{Oe}$) induced by the Ampere’s law.6–11 Another one is the current-induced torque ($\tau_{C} \approx \hat{M} \times H_{j}$) generated by the out-of-plane charge-current gradient, which may switch the magnetization and moves the domain wall.12–14 The charge current can also be transformed to spin current via spin-orbit coupling in the NM layer and induces the spin torque effects in the FM layer, including the spin-orbit torque ($\tau_{SO} \approx \hat{M} \times (\hat{\sigma} \times \hat{M})$) and field-like torque ($\tau_{FL} \approx \hat{M} \times \hat{\sigma}$).1–3,9–11,14–19 In particular, the $\tau_{FL}$ effect is related to the interface of FM/NM.7 The overall torque effects can be categorized into two types according to two different directions: parallel (for example, $\tau_{SO}$) and perpendicular (for example, $\tau_{FL}$, $\tau_{C}$, and $\tau_{r}$) to the damping torque. An illustration of the different torque effects on magnetization is shown in Fig. 1(a). The three torques ($\tau_{FL}$, $\tau_{C}$, and $\tau_{r}$) enhance the precession angle of magnetization and are analogous to the effect of magnetic field, which can be detected from the variation of $H_{r}$. On the other hand, the $\tau_{SO}$ drives the magnetization toward or away from the equilibrium position depending on the direction of the injected charge current, which can be detected from the variation of $W$ with injecting different direction of $J_{c}$.

The related subject of electric-current-driven torque effects has been studied on Py/Pt, YIG/Pt and Pb/Pt bilayer structures using...
the FMR technique previously, but only the \( \tau_{\text{SO}} \) effect was discussed because of the heating effect.\(^{14-16} \) A strong Joule heating effect was inevitably produced by injecting the current during the course of measuring FMR spectra, which enhanced the fluctuations of magnetization and concealed the contribution from \( \tau_{\text{FL}}, \tau_{\text{Oe}} \) and \( \tau_{\text{C}} \) effect. If one wishes to understand the complete picture of torque effects, the elimination of thermal effect is essential. In addition, the way to distinguish different types of torque effects is by injecting \( \pm J \) on the plane of the film along the two directions: transverse \([\text{as shown in Fig. 1(b)]}\) and parallel \([\text{as shown in Fig. 1(c)]}\) to the applied magnetic field. According to the theory,\(^{3,20} \) the \( \tau_{\text{SO}} \) only occurs in the transversal configuration.

In this work, we inject a charge current with two opposite directions into a cobalt (Co)/platinum (Pt) bilayer and study the torque effects by analyzing the variation of the current-dependent linewidth \( W(J) \) and resonance field \( H_r(J) \) of the FMR spectra. The Joule heating is monitored with a thermocouple attached onto the sample. It is found that the heating effect is not significant in the range of \( J \leq 60 \) mA and the torque effects could be clearly observed within this range.

EXPERIMENT

The Co (10 nm) and Pt (10 nm) thin films are deposited on a Si(100) substrate by two sputtering systems (CVT TFS-4700 and Quorum Q150TS, respectively) at room temperature. The deposition pressure of Co and Pt are \( 2.5 \times 10^{-3} \) and \( 5.0 \times 10^{-3} \) Torr, and the rate are 1.62 and 2.17 Å/sec, respectively. The surface area and resistivity of the substrate is \( 1.5 \times 3 \) mm\(^2\) and 3000 Ω-cm, respectively. The FMR spectrum is obtained with a ferromagnetic resonance system (Bruker EMX). The sample is placed at the center of TE\(_{002}\) microwave (MW) cavity, where the magnetic field \( (h_{\text{rf}}) \) along the x-axis of the MW is maximum and the electric field \( (e_{\text{ac}}) \) along the z-axis of the MW is minimum. The spectra are detected by sweeping the external magnetic field \( H \) from 100 to 1200 Oe. The frequency and power of the MW are 9.8 GHz and 5.0 mW, respectively. The schematic diagrams of current input and temperature measurement under two different sample configurations are shown in Fig. 1(b) and (c) with "I" representing the current source and "V" the voltmeter. The FMR spectra are obtained with an applied charge current ranging from \(-160 \) to \(160 \) mA provided by a Keithley 2400 meter. The temperature of sample is measured with a K-type thermocouple.

RESULT

Typical FMR spectra with an injected \( J \) of 0 mA (black curve), +60 mA (red dash curve) and −60 mA (blue dash-dot curve) in the transversal configuration are plotted in Fig. 1(d). The linewidth \( W \) and intensity \( I \) are obtained by fitting the integrated FMR spectra to the Lorentz function. The value of \( W \) is 74.25 Oe, 70.21 Oe and 70.06 Oe at \( J = 0 \) mA, +60 mA and −60 mA respectively. The value of \( H_r \) is 572.0 Oe, 577.7 Oe, and 578.4 Oe at \( J = 0 \) mA, +60 mA and −60 mA respectively. A magnified view around the peaks of the FMR spectra is shown in the inset of Fig. 2(a), indicating a clear shift of FMR spectrum. The change of \( W \) by switching the direction of the
current indicates that the damping of magnetization is dependent on the direction of $J_c$.

In this work, $W^*$ and $I^*$ are the normalized linewidth and intensity of FMR spectrum to the values at $J_c = 0$, defined by $W^*(J_c) \equiv [W(J_c)/W(0)]$ and $I^* \equiv |I(J_c)/I(0)|$, respectively. The experimental results of $W^*(J_c)$ and $I^*(J_c)$ in the transverse and parallel configuration are shown in Fig. 2(a) and (b), respectively. It is noted that 100 mA is the turning point for the distinct behaviors of $W^*$ and $I^*$ for both configurations. Figure 2(a) shows the data for transverse configuration, indicating that $W^*$ is reduced while $I^*$ is enhanced with $J_c$ increasing from 0 to 100 mA. In contrast, $W^*$ is enhanced and $I^*$ is reduced with $J_c$ increasing from 100 to 160 mA. Figure 2(b) displays the result in the parallel configuration, showing a similar behavior but with higher values of $W^*$ and $I^*$.

The heating effect enhances the fluctuations of magnetization and thus the $W$. $\Delta T$ is defined as the temperature difference from the starting time of measurement to the end of measurement ($\Delta T \equiv T_{\text{end}} - T_{\text{start}}$). The current dependencies of $\Delta W$ [$\Delta W \equiv W(J_c) - W(0)$] and $\Delta W$ with two different configurations are shown in Fig. 3(a) and Fig. 3(b), respectively. Figure 3(a) shows that $\Delta W$ first changes slowly, then drops suddenly at $J_c = 60$ mA in both configurations. The current dependency of $\Delta T$ and $\Delta W$ is opposite, indicating an inverse correlation between these two parameters. The overall data indicates that in the range of $J_c = 0$ to 60 mA, $\Delta W$ increases from 0 to 0.15 Oe with $\Delta T$ increasing by 5 °C in the transverse configuration; while $\Delta W$ decreases from 0 to −0.09 Oe with $\Delta T$ increasing from 8 °C in the parallel configuration. In the range of $J_c = 60$ to 160 mA, $\Delta W$ decreases from 0.15 to −8.06 Oe with $\Delta T$ increasing by 42 °C with transverse direction, and $\Delta W$ decreases from −0.09 to −13.22 Oe with $\Delta T$ increasing 58 °C in the parallel configuration. Based on the results from Fig. 3(a) and (b), it is evident that the heating effect is not significant in the range of $J_c$ between −60 and 60 mA in both configurations.

According to the theory,$^{3,20}$ $\tau_{SO}$ can only occur in the transverse configuration and it can be detected by analyzing the data of $\Delta W$. Figure 4(a) shows an asymmetrical curve of $W(J_c)$ with transverse configuration and the dash line marks a horizontal level to display the asymmetry of data at $J_c$. The variation of $\Delta W$ is shown in Fig. 4(b). It increases from 0 to 0.15 Oe with $J_c$ increasing from 0 to 60 mA and the red line is the linear fitting result. In the transverse configuration, the non-zero $\Delta W$ is due to the $\tau_{SO}$ effect, which manipulates the local magnetization toward ($J_c > 0$) or away ($J_c < 0$) from equilibrium direction.

The contribution of $\tau_{\text{TR}}$, $\tau_{0e}$ and $\tau_{C}$ are observed from the variation of $H_r$. $\Delta H_r \equiv H_r(0) - H_r(J_c)$. The current-induced torque is due to charge current gradient in Co layer, which does not change the sign with changing the direction of current. While the Oersted torque and field-like torque will change the sign with changing the direction of current. The value of $\Delta H_r$ is 6 Oe and the FMR spectra are shown in the Fig. 1(d). The Oersted field is estimated using $\frac{\partial j}{\partial n_{NM}}$ and the field is 0.25 Oe with applying $J_c = 60$ mA [Refs. 2 and 5]. The difference of $H_r$ between ±60 mA is 0.7 Oe and this value is larger than the calculation result (0.25 Oe). The reason may be that there is contribution from the Oersted torque and spin-current-induced field like torque. However, the $\tau_{\text{TR}}$ can be neglected in our Co/Pt system because the $\tau_{\text{TR}}$ is smaller than the $\tau_{0e}$ in the thick FM samples. Accordingly, the shift of resonance field is mainly due to the $\tau_{C}$ effect in our Co/Pt bilayer. The $\tau_{C}$ enhances the precession angle of magnetization and increase the magnetization relaxation time (reduces $W$).

**CONCLUSION**

In conclusion, the charge-current-driven torque effects in a Co/Pt bilayer are analyzed by the FMR technique. The heating effect is negligible in the range of $|J_c|$ from 0 to 60 mA. In this range, a current-induced modulation of FMR spectrum is experimentally observed, which may be due to the charge current gradient in Co layer. On the other hand, the asymmetrical part of $W(J_c)$ is found only under the transverse configuration, which is originated from the spin-orbit torque. The spin-orbit torque manipulates the local magnetization toward ($J_c > 0$) or away ($J_c < 0$) from the equilibrium direction.
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