Spin-orbit torques originating from bulk and interface in Pt-based structures

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The origin of spin-orbit torques in prototypical Pt-based spintronic devices strongly depends on the choice of the ferromagnetic layer. We show that, in a Pt/Ni bilayer, the bulk spin Hall effect in the Pt layer is responsible for both damping-like and field-like torques. In contrast, the interfacial spin-orbit coupling dominates the damping-like torque in a Pt/Fe bilayer, where the Ni layer is replaced with Fe, despite the strong spin Hall effect in the Pt layer. The reason for this is that the strong spin-orbit coupling at the Pt/Fe interface generates the sizable damping-like torque, while it suppresses the damping-like torque arising from the bulk through the dissipation of the spin Hall current at the interface. Although the bulk spin Hall effect plays a minor role in the generation of the damping-like torque in the Pt/Fe bilayer, the bulk effect is significant in the generation of the field-like torque, which arises from a rotation of the spin direction of the spin Hall current at the Pt/Fe interface. We found that the direction of the field-like torque originating from the spin Hall effect is opposite between the Pt/Ni and Pt/Fe bilayers. This difference is attributed to the opposite sign of the imaginary part of the spin-mixing conductance due to different spin-dependent potentials at the Pt/Ni and Pt/Fe interfaces. These results show that the bulk spin-orbit torques, as well as the interfacial spin-orbit torques, can be controlled by the interface engineering.

I. INTRODUCTION

Current-induced spin-orbit torques provide a promising strategy for the electrical manipulation of magnetization in metals, semiconductors, and insulators [1–10]. The efficient manipulation of magnetization through the spin-orbit torques offers a path for ultralow power, fast nonvolatile magnetic memory and logic technologies [11]. The spin-orbit torques arise from the transfer of orbital angular momentum from the lattice to the spin system, which results from spin-orbit coupling in the bulk and at the interface of heavy-metal/ferromagnet (HM/FM) bilayers [1].

The bulk spin-orbit coupling in the HM causes carriers with opposite spins to scatter in opposite directions. The spin dependent scattering generates a spin current from a charge current, which is known as the spin Hall effect [18–28]. In the HM/FM bilayer, the angular momentum carried by the spin Hall current is transferred to the magnetization through the spin-transfer mechanism [1]. This angular momentum transfer induces a torque on the magnetization, which is expressed as \( \tau_{DL} = \tau_{DL} \mathbf{m} \times (\mathbf{\sigma} \times \mathbf{m}) \), where \( \mathbf{m} \) is the magnetization unit vector, \( \mathbf{\sigma} \) is the unit vector along the spin polarization direction of the spin current, and \( \tau_{DL} \) is the magnitude of the torque. The torque of this form is referred to as a damping-like torque. The transfer of the angular momentum is generally imperfect at the interface partly because of a small component of the spins that rotate when they reflect from the interface [29]. The spin rotation at the interface gives rise to a torque in the form of \( \tau_{FL} = \tau_{FL} \mathbf{\sigma} \times \mathbf{m} \), which is referred to as a field-like torque.

The interfacial spin-orbit coupling in the HM/FM bilayer also generates the damping-like and field-like torques. At the interface with broken inversion symmetry, the spin-orbit coupling lifts the electron-spin degeneracy, and the spin angular momentum is locked on the linear momentum \( \mathbf{m} \). Because of the spin-momentum locking, a charge current flowing parallel to the interface generates a nonzero spin accumulation [30–31]. This process, called the Rashba-Edelstein or inverse spin galvanic effect, exerts a torque on the magnetization through the exchange coupling at the HM/FM interface [31]. Since the interfacial Rashba spin-orbit effective field induces the rotation of the spin accumulation, both field-like and damping-like torques can be generated by the current-induced spin accumulation and exchange coupling [3–35]. Although in this scenario, carriers are assumed to be confined to the two-dimensional interface, in the HM/FM bilayer, carriers are not confined but can be scattered across the interface. In this situation, the interfacial spin-orbit coupling can also generate an interfacial spin current that flows away from the FM/HM interface through interfacial spin-orbit scattering. The interfacial spin-orbit scattering generates both damping-like and field-like torques [32].

Understanding the physics behind the generation of the spin-orbit torques is essential for the development of spin-orbitronic devices, as well as the fundamental understanding of spin-dependent transport in condensed matter. A wide range of experiments have demonstrated that the spin-orbit torques can be manipulated by materials and interface engineering in Pt-based structures [10–42], where the spin-orbit torques are generally attributed to the strong spin-orbit coupling of Pt, the most widely studied source of spin currents. However, despite this progress, the origin of the spin-orbit torques is still unclear and controversial even in the prototypical spin-orbitronic device. A typical example is the field-like
torque in Pt/Ni-Fe-alloy bilayers \cite{41,42,46,47}. The reported values vary significantly for the same system and even the sign, as well as the magnitude, is inconsistent in literature, implying an important role of the spin-orbit coupling and electronic structure of the FM layer in the generation of the spin-orbit torques.

In this paper, we show that the origin of the spin-orbit torques in the standard Pt/FM bilayer strongly depends on the choice of the FM. We found that the bulk spin Hall effect is responsible for both damping-like and field-like torques in a Pt/Ni bilayer. In contrast, in a Pt/Fe bilayer, the interfacial spin-orbit coupling is the dominant mechanism of the damping-like torque, while both bulk and interfacial spin-orbit coupling contribute to the field-like torque. We also found that the sign of the field-like torque originating from the bulk spin Hall effect in the Pt layer is opposite between the Pt/Ni and Pt/Fe bilayers, which can be attributed to the opposite sign of the imaginary part of the spin-mixing conductance. Although the strong spin-orbit coupling of the Pt layer is expected to play an essential role in the prototypical Pt-based structure, these results demonstrate that the spin-orbit torques are quite sensitive to the electronic structure of the FM layer. These results provide a crucial piece of information for a fundamental understanding of the spin-orbit torques.

II. EXPERIMENTAL METHOD

We investigated the spin-orbit torques in Pt/Ni and Pt/Fe bilayers using spin torque ferromagnetic resonance (ST-FMR). The sample structure is Ti(2)/Pt(\textit{d}_\text{Pt})/FM(\textit{d}_\text{FM})/SiO\textsubscript{2}(5), where the numbers in the parentheses represent the thickness in the unit of nm [see Fig. 1(a)]. \textit{d}_\text{Pt} and \textit{d}_\text{FM} are the thickness of the Pt and FM layers, respectively. The films were deposited on thermally oxidized Si/SiO\textsubscript{2}(100) substrates using RF-magnetron sputtering, where the base pressure was around 1 \times 10^{-6} Pa. The 2-nm-thick Ti layer was sputtered on the substrate, and then the Pt layer was sputtered on the adhesion Ti layer, where the deposition rate of Ti (Pt) was 0.01 (0.03) nm/s. On the Pt layer, the FM layer (FM = Ni and Fe) was sputtered, where the deposition rate of Ni (Fe) was 0.04 (0.02) nm/s. To avoid the natural oxidation of the FM layer, the 5-nm-thick SiO\textsubscript{2} was sputtered on the FM layer, where the deposition rate was 0.01 nm/s. All the sputtering processes were conducted in the 5N-purity argon atmosphere of 0.4 Pa at room temperature.

To measure the ST-FMR, the Pt/FM films were patterned into rectangular shapes (10 \mu m \times 150 \mu m) with Ti(2)/Pt(60) electrodes using the conventional photolithography and lift-off technique. For the ST-FMR measurement, we applied an RF current with the frequency \textit{f} along the longitudinal direction of the Pt/FM bilayer and an external magnetic field \textbf{H} at the angle of 45° from the longitudinal direction, as shown in Fig. 1(a). The RF current generates out-of-plane and in-plane torques due to the spin-orbit torques and an Oersted field, which drive the magnetization precession under the FMR condition. The precession of the magnetization leads to the oscillation of the resistance of the device through the anisotropic magnetoresistance (AMR) of the FM layer. In the bilayer, the mixing of the RF current and oscillating resistance induces DC voltage \textit{V}_{DC}. We measured \textit{V}_{DC} for the Pt/FM bilayers using a bias tee and a nano-voltmeter at room temperature, as shown in Fig. 1(a).

The ST-FMR voltage \textit{V}_{DC} can be decomposed into two components \cite{48}:

\[
\textit{V}_{DC} = A \frac{W(\mu_0 H - \mu_0 H_{\text{FMR}})}{(\mu_0 H - \mu_0 H_{\text{FMR}})^2 + W^2} + S \frac{W}{(\mu_0 H - \mu_0 H_{\text{FMR}})^2 + W^2},
\]

where \textit{W} is the spectral width and \textit{H}_{\text{FMR}} is the FMR field. The symmetric \textit{S} and anti-symmetric \textit{A} components are produced by the out-of-plane and in-plane effective fields, respectively. Here, the out-of-plane effective field is the damping-like effective field \textit{H}_{DL} and the

![FIG. 1.](image-url)

(a) The schematic illustration of the experimental set up of the ST-FMR measurement for the Pt/FM (FM = Ni and Fe) bilayers. (b) The magnetic field \textit{H} dependence of the DC voltage \textit{V}_{DC} for the Pt(7.4)/Ni(4) (upper) and Pt(7.4)/Fe(4) (lower) bilayers measured with the RF power of 24.7 dBm. The RF frequency was varied from \textit{f} = 4 to 9 GHz for the Pt/Ni film and from \textit{f} = 8 to 16 GHz for the Pt/Fe film.
FIG. 2. The magnetic field $H$ dependence of the DC voltage $V_{\text{DC}}$ for the (a) Pt(1.5)/Ni($d_{\text{FM}}$) at $f$ = 6 GHz, (b) Pt(7.4)/Ni($d_{\text{FM}}$) at $f$ = 6 GHz, (c) Pt (1.5)/Fe($d_{\text{Ni}}$) at $f$ = 12 GHz, and (d) Pt(7.4)/Fe($d_{\text{FM}}$) at $f$ = 12 GHz. The solid circles are the experimental data and the solid curves are the fitting result using Eq. (1). (e) The $1/d_{\text{FM}}$ dependence of $1/\xi_{\text{FMR}}$ for the Pt/Ni and Pt/Fe bilayers, where $d_{\text{FM}}$ is the thickness of the FM layer and $\xi_{\text{FMR}}$ is the FMR spin-torque efficiency. The solid circles are the experimental data and the solid lines are the fitting result using Eq. (3).

in-plane effective field is the sum of the Oersted field $H_{\text{Oe}}$ due to the current flow in the Pt layer and the field-like effective field $H_{\text{FL}}$. The damping-like and field-like torque efficiencies per applied electric field $E$, defined as

$$\xi_{\text{DL(FL)}}^E = \frac{2e}{h} \frac{\mu_0 M_s d_{\text{FM}} H_{\text{DL(FL)}}}{E},$$

(2)

can be determined by measuring the ST-FMR for devices with different $d_{\text{FM}}$ using [49].

$$\frac{1}{\xi_{\text{FMR}}} = \frac{1}{\xi_{\text{DL}}} \left( \frac{1 + \frac{h}{\rho_{\text{Pt}}}}{\mu_0 M_s d_{\text{FM}} \rho_{\text{Pt}}} \right),$$

(3)

where $e$ is the elementary charge, $h$ is the Dirac constant, $\rho_{\text{Pt}}$ is the electric resistivity of the Pt layer, and $M_s$ is the saturation magnetization.

$$\xi_{\text{FMR}} = \frac{S e \mu_0 M_s d_{\text{FM}} \rho_{\text{Pt}}}{A} \sqrt{1 + \frac{M_{\text{eff}}}{H_{\text{FMR}}}},$$

(4)

is the FMR spin torque generation efficiency, where $M_{\text{eff}}$ is the effective demagnetization field.

III. RESULTS AND DISCUSSION

A. Spin-torque ferromagnetic resonance

Figure 1(b) shows the magnetic field $H$ dependence of the DC voltage $V_{\text{DC}}$ for the Pt(7.4)/Ni(4) and Pt(7.4)/Fe(4) bilayers at various RF current frequencies $f$. This result shows that the FMR field $H_{\text{FMR}}$ changes systematically by changing $f$, which is consistent with the Kittel formula: $2\pi f = \gamma \sqrt{\mu_0 H_{\text{FMR}}/\mu_0 H_{\text{FMR}} + \mu_0 M_{\text{eff}}}$, where $\gamma$ is the gyromagnetic ratio.

In Figs. 2(a) and 2(b), we show the $V_{\text{DC}}$ spectra at $f$ = 6 GHz for the Pt(1.5)/Ni($d_{\text{FM}}$) and Pt(7.4)/Ni($d_{\text{FM}}$) bilayers with various $d_{\text{FM}}$, respectively. We also show the $V_{\text{DC}}$ spectra at $f$ = 12 GHz for the Pt(1.5)/Fe($d_{\text{FM}}$) and Pt(7.4)/Fe($d_{\text{FM}}$) bilayers in Figs. 2(c) and 2(d), respectively. All the measured $V_{\text{DC}}$ spectra are consistent with Eq. (1). We note that the sign of the anti-symmetric component $A$ is opposite between the Pt(1.5)/Ni and Pt(7.4)/Ni bilayers [see Figs. 2(c) and 2(d)]. We also note that the sign of the FMR spin-torque efficiency is opposite between the Pt(1.5)/Fe and Pt(7.4)/Fe bilayers.

To determine the damping-like and field-like efficiencies, $\xi_{\text{DL}}^E$ and $\xi_{\text{FL}}^E$, we plot $1/\xi_{\text{FMR}}$ as a function of $1/d_{\text{FM}}$ for the Pt/FM bilayers in Fig. 2(e), where $\xi_{\text{FMR}}$ was obtained by fitting the measured $V_{\text{DC}}$ using Eq. (1). The $1/\xi_{\text{FMR}}$ is linear to $1/d_{\text{FM}}$ in all the devices, consistent with Eq. (3). This result shows that the sign of the intercept of the linear relation is positive in all the devices, consistent with Eq. (3). In contrast to the same sign of the intercept, the sign of the slope is opposite between the Pt/Ni and Pt/Fe bilayers. The values of $\xi_{\text{DL}}^E$ and $\xi_{\text{FL}}^E$, obtained by fitting the data with Eq. (3), are listed in Table I.

The result in Table I shows that the damping-like efficiency $\xi_{\text{DL}}^E$ in the Pt($d_{\text{Pt}}$)/Ni bilayer is clearly enhanced by increasing $d_{\text{Pt}}$, while $\xi_{\text{DL}}^E$ in the Pt($d_{\text{Pt}}$)/Fe bilayer is almost independent of $d_{\text{Pt}}$. The choice of the FM layer also strongly affects the field-like torque. Even the sign of $\xi_{\text{FL}}^E$ is reversed by changing the FM layer from Ni to Fe. These results indicate that different mechanisms dominate the generation of the damping-like and field-like torques in the Pt/Ni and Pt/Fe bilayers.
TABLE I. The summarized parameters for the Pt/Ni and Pt/Fe bilayers, determined by the ST-FMR measurement. $\xi_{DL}^E$ and $\xi_{DL}^F$ are the damping-like and field-like torque efficiencies for applied electric field $E$, respectively. $K_s$ and $\mu_0 M_s$ are the interfacial perpendicular magnetic anisotropy energy density and the saturation magnetization in the FM layer, respectively, determined by fitting the FM-thickness dependence of the effective demagnetization field using Eq. 9. $\text{Re}[G_{\text{eff,tot}}^{E}]$ is the total effective spin mixing conductance, determined by fitting the FM-thickness dependence of the effective Gilbert magnetic damping $\alpha_{\text{eff}}$ using Eq. 10. The errors are the standard deviation determined by the fitting.

| Sample            | $\xi_{DL}^E$ (10$^3$Ω$^{-1}$cm$^{-1}$) | $\xi_{DL}^F$ (10$^3$Ω$^{-1}$cm$^{-1}$) | $K_s$ (mJ/m$^2$) | $\mu_0 M_s (T)$ | $\text{Re}[G_{\text{eff,tot}}^{E}]$ (10$^3$Ω$^{-1}$m$^{-2}$) |
|-------------------|--------------------------------------|--------------------------------------|------------------|-----------------|---------------------------------------------------------------|
| Pt(1.5)/Ni        | 0.61 ± 0.10                          | 0.17 ± 0.02                          | 0.05 ± 0.05      | 0.47 ± 0.05     | 1.32 ± 0.58                                                   |
| Pt(7.4)/Ni        | 2.65 ± 0.24                          | 0.85 ± 0.12                          | 0.13 ± 0.02      | 0.49 ± 0.02     | 1.76 ± 0.20                                                   |
| Pt(1.5)/Fe        | 1.75 ± 0.55                          | –0.05 ± 0.10                         | 1.41 ± 0.09      | 2.07 ± 0.03     | 3.42 ± 0.38                                                   |
| Pt(7.4)/Fe        | 2.00 ± 0.05                          | –2.20 ± 0.09                         | 1.23 ± 0.37      | 1.92 ± 0.13     | 3.56 ± 0.88                                                   |

B. Damping-like torque

The measured damping-like torque efficiency $\xi_{DL}^E$ can be decomposed into $d_{Pt}$-dependent $\xi_{DL,dep}^E(d_{Pt})$ and $d_{Pt}$-independent $\xi_{DL, indep}^E(d_{Pt})$ components: $\xi_{DL}^E(d_{Pt}) = \xi_{DL,dep}^E(d_{Pt}) + \xi_{DL, indep}^E$. The strong dependence of $\xi_{DL}^E$ on $d_{Pt}$ in the Pt/Ni bilayer indicates $\xi_{DL}^E(d_{Pt}) \sim \xi_{DL,dep}^E(d_{Pt})$. One of the source of $\xi_{DL, dep}^E(d_{Pt})$ is the bulk spin Hall effect in the Pt layer. Although the damping-like torque due to the interfacial spin current originating from interfacial spin-orbit scattering also increases with $d_{Pt}$ [34, 51], we first assume that the spin-orbit coupling at the Pt/Ni interface is not significant and neglect the contribution from this mechanism. Here, the damping-like torque efficiency due to the bulk spin Hall effect in the simplest drift-diffusion model is expressed as $\xi_{DL, SHE}^E(d_{Pt}) = [1 - \text{sech}(d_{Pt}/\lambda_{eff})] \sigma_{SHE}^E$, where $\sigma_{SHE}^E = \sigma_{SHE} \varepsilon$ is the effective spin Hall conductivity of the Pt layer, where $\sigma_{SHE}$ is the spin Hall conductivity and $\varepsilon$ represents the strength of the spin memory loss at the interface ($\varepsilon \leq 1$). $\lambda_{eff}$ is the effective spin diffusion length in the Pt layer, which is assumed to be independent of the thickness, for simplicity [51]. We note that the observed change of the damping-like torque efficiency, $\xi_{DL}^E(d_{Pt} = 7.4)/\xi_{DL}^E(d_{Pt} = 1.5) = 4.3$, is consistent with this model; we obtain $\xi_{DL, SHE}^E(d_{Pt} = 7.4)/\xi_{DL, SHE}^E(d_{Pt} = 1.5) = 4.2$ when $\lambda_{eff} = 2$ nm [51]. This result is consistent with the assumption that the bulk spin Hall effect dominates the observed damping-like torque. We also note that $\sigma_{SHE}^E = 2.8 \times 10^3$ Ω$^{-1}$cm$^{-1}$, obtained by assuming $\xi_{DL}^E(d_{Pt}) = \xi_{DL, SHE}^E(d_{Pt})$, does not exceed the intrinsic spin Hall conductivity of Pt [40]. This suggests that the $d_{Pt}$-dependent damping-like torque arising from the interfacial spin-orbit scattering is not significant in the observed $\xi_{DL}^E(d_{Pt})$. These results show that the observed damping-like torque in the Pt/Ni bilayer is dominated by the bulk spin Hall effect in the Pt layer.

In contrast to the Pt/Ni bilayer, the damping-like torque in the Pt/Fe bilayer is dominated by the interfacial spin-orbit coupling. As shown in Table I, $\xi_{DL}^E$ in the Pt/Fe bilayer is almost independent of $d_{Pt}$: $\xi_{DL}^E(d_{Pt}) \sim \xi_{DL, indep}^E$ and $\xi_{DL,dep}^E(d_{Pt}) \sim 0$. This result indicates that the damping-like torque in the Pt/Fe bilayer cannot be attributed to the bulk spin Hall effect despite the strong spin Hall effect in the Pt layer. The negligible $\xi_{DL, SHE}^E(d_{Pt})$ and sizable $\xi_{DL, indep}^E$ demonstrates the important role of the interfacial spin-orbit coupling in the Pt/Fe bilayer. In the presence of the strong spin-orbit coupling at the interface, most of the spin current generated by the spin Hall effect in the Pt layer is dissipated at the interface and cannot be transferred to the Fe layer. Because of the interface spin loss, the damping-like torque due to the spin-transfer mechanism induced by the spin Hall effect, $\xi_{DL, SHE}^E(d_{Pt})$, is ineffective. In this situation, the damping-like torque arising from the interfacial spin-orbit coupling can be more significant than that arising from the bulk spin-orbit coupling. Here, the interfacial spin current generated by the interfacial spin-orbit scattering is not the dominant source of the observed $\xi_{DL}^E$ because the damping-like torque due to this mechanism depends on $d_{Pt}$, as with the damping-like torque due to the bulk-generated spin current [34, 51]. A sizable damping-like torque can be produced by the interfacial spin-orbit coupling through the intrinsic mechanism, which can present in the two-dimensional limit and does not require the spin transport across the interface [32, 33, 34].

C. Magnetic anisotropy and effective spin mixing conductance

The results on the damping-like torque efficiency show the significant role of the interfacial spin-orbit coupling in the Pt/Fe bilayer. The strong spin-orbit coupling at the Pt/Fe interface is also supported by the magnetic anisotropy and magnetic damping. The interface magnetic anisotropy can be evaluated from the $1/d_{FM}$ dependence of $\mu_0 M_{eff}$, determined by fitting the measured...
\( f \) dependence of \( H_{\text{FMR}} \) using the Kittel formula \([52]\):

\[
\mu_0 M_{\text{eff}} = \mu_0 M_s - \frac{2K_s}{M_s} \frac{1}{d_{\text{FM}}},
\]

where \( K_s \) and \( M_s \) are the interface perpendicular magnetic anisotropy energy density and the saturation magnetization, respectively. In Fig. 3(a), we show the \( 1/d_{\text{FM}} \) dependence of \( \mu_0 M_{\text{eff}} \). By fitting the data using Eq. 5, we obtained \( K_s \) for the Pt/Ni and Pt/Fe films, as in Table I. The result shows that the magnitude of \( K_s \) at the Pt/Fe interface is an order of magnitude larger than that at the Pt/Ni interface, suggesting that the interfacial spin-orbit coupling at the Pt/Fe interface is stronger than that at the Pt/Ni interface \([53]\).

The magnetic damping, affected by the interfacial spin-orbit coupling, is also clearly different between the Pt/Ni and Pt/Fe bilayers. In Fig. 3(b), we show \( 1/d_{\text{FM}} \) dependence of the effective Gilbert damping \( \alpha_{\text{eff}} \) for the Pt/Ni and Pt/Fe bilayers. The effective Gilbert damping \( \alpha_{\text{eff}} \) was determined by fitting the measured \( f \) dependence of the ST-FMR linewidth \( W \) using \( W = W_0 + (2\pi\alpha_{\text{eff}}/\gamma)f \), where \( W_0 \) is the inhomogeneous linewidth. Figure 3(b) shows that \( \alpha_{\text{eff}} \) is linear to \( 1/d_{\text{FM}} \), which is consistent with the damping enhancement due to the spin pumping \([48]\). The spin pumping refers to the generation of spin currents by precessing magnetization. The spin-current emission from the FM layer by the spin pumping enhances the magnetic damping of the Pt/FM bilayer, since the spin-current emission depletes the magnetization of the angular momentum in the FM layer. The effective Gilbert magnetic damping \( \alpha_{\text{eff}} \) in the presence of the spin pumping is expressed as \([42]\):

\[
\alpha_{\text{eff}} = \alpha_{\text{int}} + \text{Re}[G_{\text{eff, tot}}] \frac{g\mu_B h}{4\pi e^2 M_s} \frac{1}{d_{\text{FM}}},
\]

where \( \alpha_{\text{int}} \) is the intrinsic magnetic damping of the FM layer, \( \text{Re}[G_{\text{eff, tot}}] \) is the real part of a total effective spin mixing conductance, \( g \) is the g-factor, \( \mu_B \) is the Bohr magneton, and \( h \) is the Planck constant. \( \text{Re}[G_{\text{eff, tot}}] \) consists of two components: \( \text{Re}[G_{\text{eff, tot}}] = \text{Re}[G_{\text{eff}}^\dagger] + G_{\text{SML}} \), where \( G_{\text{eff}}^\dagger \) is the effective spin mixing conductance, which characterizes the spin relaxation in the bulk of the Pt layer, and \( G_{\text{SML}} \) characterizes the strength of the spin memory loss at the Pt/FM interface. In Table I, we show \( \text{Re}[G_{\text{eff, tot}}^\dagger] \) for the Pt/FM bilayers, extracted by fitting the \( 1/d_{\text{FM}} \) dependence of \( \alpha_{\text{eff}} \) in Fig. 3(b) using Eq. 6. The values listed in Table I indicate that \( \text{Re}[G_{\text{eff, tot}}^\dagger] \) of the Pt/Fe bilayer is more than two-times larger than that of the Pt/Ni bilayer.

The large value of \( \text{Re}[G_{\text{eff, tot}}]^\dagger \) in the Pt/Fe bilayer evidences the strong spin-orbit coupling at the Pt/Fe interface \([54]\). Under the assumption of the drift-diffusion spin transport, \( \text{Re}[G_{\text{eff, tot}}]^\dagger \) is expressed as \([53, 50]\):

\[
\text{Re}[G_{\text{eff, tot}}^\dagger] = \frac{\text{Re}[G_{\text{eff, tot}}^\dagger]}{1 + \text{Re}[G_{\text{P}t/FM}]/G_{\text{Pt}} \tanh (d_{\text{Pt}}/\lambda_s)}.
\]

Next, we discuss the field-like torque in the Pt/Ni and Pt/Fe bilayers. Here, the measured field-like torque efficiency \( \zeta_{\text{FL}}^E \) can also be decomposed into \( d_{\text{Pt}} \)-dependent

\[\text{FIG. 3. (a) The } 1/d_{\text{FM}} \text{ dependence of the effective demagnetization field } \mu_0 M_{\text{eff}}, \text{ where } d_{\text{FM}} \text{ is the thickness of the FM layer. The dotted lines are the linear fitting result. (b) The effective magnetic damping } \alpha_{\text{eff}} \text{ as a function of } 1/d_{\text{FM}}. \text{ The dotted lines are the linear fitting result.} \]
versed by replacing the Ni with Fe in spite of the fact that the field-like torque efficiency is independent of the Pt-layer thickness, as shown in Table I. The strong dependence of \( \xi_{\text{FL}} \) on \( d_{\text{P}} \) suggests \( \xi_{\text{FL}}^{E}(d_{\text{P}}) \sim \xi_{\text{FL}}^{E}(d_{\text{P}}) \), indicating that the bulk spin Hall effect dominates the field-like torque in the Pt/Ni bilayer. The field-like torque due to the bulk spin Hall effect is also roughly proportional to \( 1 - \text{sech}(d_{\text{P}}/\lambda_{\text{eff}}) \) [28].

The observed change of the field-like torque efficiency is \( \xi_{\text{FL}}^{E}(d_{\text{P}} = 7.4)/\xi_{\text{FL}}^{E}(d_{\text{P}} = 1.5) = 5.0 \), which is roughly consistent with the \( 1 - \text{sech}(d_{\text{P}}/\lambda_{\text{eff}}) \) dependence, as well as the damping-like torque efficiency \( \xi_{\text{DL}}^{E} \). This result indicates that the bulk spin Hall effect, as well as the damping-like torque, is the bulk spin Hall effect in the Pt/Ni bilayer.

In the Pt/Fe bilayer, the field-like torque efficiency is enhanced by two times by increasing \( d_{\text{P}} \), although the damping-like torque is almost independent of \( d_{\text{P}} \). Because of the strong spin-orbit coupling at the Pt/Fe interface, the field-like torque is expected to generate a sizable field-like torque. Since \( \xi_{\text{FL, dep}}^{E}(d_{\text{P}}) \) and \( \xi_{\text{FL, indep}}^{E} \) mainly originate from the bulk spin Hall effect and interfacial spin-orbit coupling, respectively, the \( d_{\text{P}} \)-dependent observed \( \xi_{\text{FL}}^{E} \) indicates that the bulk spin Hall effect, as well as the interfacial effect, contributes to the field-like torque in the Pt/Fe bilayer. The separation of the bulk and interface contributions from this data based on the established model requires to assume various parameters, such as the real and imaginary parts of the spin mixing conductance and the spin Hall conductivity [29, 50], making the analysis less reliable. Thus, we use an alternative approach to roughly estimate the bulk and interface contributions to the field-like torque. We assume that \( \xi_{\text{FL, dep}}^{E}(d_{\text{P}}) \) in the Pt/Fe bilayer follows the simplified \( d_{\text{P}} \) dependence, \( \xi_{\text{FL, dep}}^{E}(d_{\text{P}}) = [1 - \text{sech}(d_{\text{P}}/\lambda_{\text{eff}})]\xi_{\text{FL, dep}}^{E, 0} \), as with the case of the Pt/Ni bilayer. This allows us to obtain \( \xi_{\text{FL, indep}}^{E} = -0.6 \times 10^{3} \) \( \Omega^{-1} \) \( \text{cm}^{-1} \), originating from the interface, and \( \xi_{\text{FL, dep}}^{E} = -1.7 \times 10^{3} \) \( \Omega^{-1} \) \( \text{cm}^{-1} \), originating from the bulk spin Hall effect in the Pt layer. For the calculation, we used \( \xi_{\text{FL, dep}}^{E}(d_{\text{P}} = 7.4)/\xi_{\text{FL, dep}}^{E}(d_{\text{P}} = 1.5) = 4.2 \) for \( \lambda_{\text{eff}} = 2 \) nm with the measured values of \( \xi_{\text{FL}}^{E}(d_{\text{P}} = 1.5) \) and \( \xi_{\text{FL}}^{E}(d_{\text{P}} = 7.4) \). Since this result is a rough estimation, we only focus on the sign of the field-like torque below.

The above results show that the sign of the \( d_{\text{P}} \)-dependent field-like torque efficiency \( \xi_{\text{FL, dep}}^{E}(d_{\text{P}}) \) is reversed by replacing the Ni with Fe in spite of the fact that the sign of the spin-orbit torques in the Pt/Ni and Pt/Fe bilayers.

\begin{table}[h]
\centering
\caption{The summary of the dominant mechanism and the sign of the spin-orbit torques in the Pt/Ni and Pt/Fe bilayers. \( \xi_{\text{DL, bulk}}^{E} \) and \( \xi_{\text{DL, interface}}^{E} \) are the damping-like (field-like) torque efficiencies per applied electric field originating from the bulk (interface) spin-orbit coupling, respectively. In the Pt/Ni bilayer, both damping-like and field-like torques are mainly generated by the bulk spin-orbit coupling. In the Pt/Fe bilayer, the interfacial spin-orbit coupling is the dominant mechanism of the damping-like torque, while both bulk and interfacial spin-orbit coupling contribute to the field-like torque. The sign of \( \xi_{\text{FL}}^{E} \) is opposite between the Pt/Ni and Pt/Fe bilayers.

| System | Damping-like torque | Field-like torque |
|--------|---------------------|------------------|
| Pt/Ni  | \( \xi_{\text{DL, bulk}}^{E} > 0 \) | \( \xi_{\text{FL, bulk}}^{E} > 0 \) |
| Pt/Fe  | \( \xi_{\text{DL, interface}}^{E} > 0 \) | \( \xi_{\text{FL, bulk}}^{E} < 0 \), \( \xi_{\text{FL, interface}}^{E} < 0 \) |
\end{table}

In summary, we investigated the damping-like and field-like torque efficiencies in the Pt/Ni and Pt/Fe bilayers with different Pt-layer thicknesses to reveal the origin of the spin-orbit torques in the Pt-based structures [see Table II]. The damping-like torque efficiency in the Pt/Ni and Pt/Fe bilayers is comparable when the Pt thickness
is much larger than the spin diffusion length. By decreasing the Pt thickness, the damping-like torque efficiency in the Pt/Ni bilayer is decreased noticeably, while that in the Pt/Fe bilayer is almost unchanged. This result indicates that different mechanisms dominate the generation of the damping-like; the damping like torque in the Pt/Ni bilayer and the Pt/Fe bilayer originates from the bulk spin-orbit coupling and the interfacial spin-orbit coupling, respectively. This demonstrates that the interfacial spin-orbit coupling in the Pt-based structure is sensitive to the choice of the ferromagnetic layer. In the Pt/Fe bilayer, where the interfacial spin-orbit coupling is stronger than in the Pt/Ni bilayer, the bulk of the Pt layer plays a minor role despite the strong bulk spin Hall effect in the Pt layer. The reason for this is that most of the spin current generated by the spin Hall effect in the Pt layer is dissipated at the Pt/Fe interface due to the strong interfacial spin-orbit coupling, which makes the spin-transfer mechanism of the bulk origin inefficient in the Pt/Fe bilayer. The strong interface spin memory loss due to the strong spin-orbit coupling at the Pt/Fe interface is supported by the exceptionally large effective spin mixing conductance. In the Pt/Ni bilayer, the field-like torque, as well as the damping-like torque, is dominated by the bulk spin-orbit coupling. We note that the direction of the field-like torque originating from the bulk spin Hall effect in the Pt layer is opposite between the Pt/Ni and Pt/Fe bilayers. The opposite sign of the field-like torque originating from the bulk spin-orbit coupling indicates that the sign of the imaginary part of the spin mixing conductance is opposite at the Pt/Ni and Pt/Fe interfaces. These results show that the bulk spin-orbit torques, as well as the interfacial spin-orbit torques, can be controlled by the interface engineering.

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