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

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We investigate spin-orbit torques in prototypical Pt-based spintronic devices. We find that, in Pt/Ni and Pt/Fe bilayers, the dampinglike torque efficiency depends on the thickness of the Pt layer. We also find that the dampinglike torque efficiency is almost identical in the Pt/Ni and Pt/Fe bilayers despite the stronger spin memory loss at the Pt/Fe interface. These results suggest that although the dominant source of the dampinglike torque is the bulk spin Hall effect in the Pt layer, a sizable dampinglike torque is generated by the interface in the Pt/Fe bilayer due to the stronger interfacial spin-orbit coupling. In contrast to the dampinglike torque, whose magnitude and sign are almost identical in the Pt/Ni and Pt/Fe bilayers, the fieldlike torque strongly depends on the choice of the ferromagnetic layer. The sign of the fieldlike 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. These results demonstrate that the spin-orbit torques are quite sensitive to the electronic structure of the ferromagnet layer.

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I. INTRODUCTION

Current-induced spin-orbit torques provide a promising strategy for the electrical manipulation of magnetization in metals, semiconductors, and insulators [1–16]. The efficient manipulation of magnetization through the spin-orbit torques offers a path for ultralow power, fast nonvolatile magnetic memory, and logic technologies [17]. 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 $\tau_{\text{DL}} = \tau_{\text{DL}} \mathbf{m} \times (\boldsymbol{\sigma} \times \mathbf{m})$, where $\mathbf{m}$ is the magnetization unit vector, $\boldsymbol{\sigma}$ is the unit vector along the spin-polarization direction of the spin current, and τ_{DL} is the magnitude of the torque. The torque of this form is referred to as a dampinglike 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 $\tau_{\text{FL}} = \tau_{\text{FL}} \boldsymbol{\sigma} \times \mathbf{m}$, which is referred to as a fieldlike torque.

The interfacial spin-orbit coupling in the HM/FM bilayer also generates the dampinglike and fieldlike 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 [30,31]. Because of the spin-momentum locking, a charge current flowing parallel to the interface generates a nonzero spin accumulation [32,33]. 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 [2,34,35]. Since the interfacial Rashba spin-orbit effective field induces the rotation of the spin accumulation, both fieldlike and dampinglike torques can be generated by the current-induced spin accumulation and exchange coupling [5,36–40]. 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 dampinglike and fieldlike torques [41].

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 has demonstrated that the spin-orbit torques can be manipulated by materials and interface engineering in Pt-based structures [42–47], where the spin-orbit

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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 fieldlike torque in Pt/Ni-Fe-alloy bilayers [43,44,48,49]. The reported values vary significantly for the same system and even the sign, as well as the magnitude, is inconsistent in the 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 find that the dampinglike torque efficiency depends on the thickness of the Pt layer in Pt/Ni and Pt/Fe bilayers. We also find that the dampinglike torque efficiency is almost identical in the Pt/Ni and Pt/Fe bilayers despite the stronger spin memory loss at the Pt/Fe interface. These results suggest that although the dominant source of the dampinglike torque is the bulk spin Hall effect in the Pt layer, a sizable dampinglike torque is generated by the interface in the Pt/Fe bilayer due to the stronger interfacial spin-orbit coupling. We also find that the sign of the fieldlike 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 (STFMR). The sample structure was Ti(2)/Pt(d_{Pt})/FM(d_{FM})/SiO₂(5), where the numbers in parentheses represent the thickness in units of nanometers [see Fig. 1(a)]. In addition, d_{Pt} and d_{FM} are the thicknesses of the Pt and FM layers, respectively. The films were deposited on thermally oxidized Si/SiO₂(100) substrates using RF-magnetron sputtering, where the base pressure was around 1×10^{-5} 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 SiO₂ 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 STFMR, the Pt/FM films were patterned into rectangular shapes ($10 \times 150 \mu\text{m}^2$) with Ti(2)/Pt(60) electrodes using the conventional photolithography and lift-off technique. For the STFMR measurement, we applied an RF current with the frequency f along the longitudinal

FIG. 1. (a) Schematic illustration of the experimental setup of the STFMR measurement for the Pt/FM (FM = Ni and Fe) bilayers. (b) Magnetic field H dependence of the DC voltage V_{DC} for the Pt(7.4)/Ni(4) (upper) and Pt(7.4)/Fe(4) (lower) bilayers measured with an RF power of 24.7 dBm. The RF frequency was varied from $f = 4$ to 9 GHz for the Pt/Ni film and from $f = 8$ to 16 GHz for the Pt/Fe film. The measurement of the STFMR for the Pt/Ni film at higher f requires higher H , which limits the f range in the present study.

direction of the Pt/FM bilayer and an external magnetic field $\mathbf{H}$ at an 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 conduction. 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 V_{DC} . We measured V_{DC} for the Pt/FM bilayers using a bias tee and a nanovoltmeter at room temperature, as shown in Fig. 1(a). Here the phase of the RF current is almost constant in the STFMR devices because the wavelength of the RF current with a frequency of 4–16 GHz is much larger than the length of the devices, $150 \mu\text{m}$. In fact, a previous study demonstrated that the phase of the magnetization precession driven by an RF current is almost constant in a STFMR device with a width of $100 \mu\text{m}$ and a length of $400 \mu\text{m}$ [50], supporting that the current nonuniformity is negligible in the present study.

The STFMR voltage V_{DC} can be decomposed into two components [51]

$$V_{\text{DC}} = A \frac{W(\mu_0 H - \mu_0 H_{\text{FMR}})}{(\mu_0 H - \mu_0 H_{\text{FMR}})^2 + W^2} + S \frac{W^2}{(\mu_0 H - \mu_0 H_{\text{FMR}})^2 + W^2}, \quad (1)$$

where W is the spectral width and H_{FMR} is the FMR field. The symmetric S and antisymmetric A components are produced by the out-of-plane and in-plane effective fields, respectively. Here the out-of-plane effective field is the dampinglike effective field H_{DL} and the in-plane effective field is the sum of the Oersted field H_{Oe} due to the current flow in the Pt layer and the fieldlike effective field H_{FL} . The dampinglike and fieldlike torque efficiencies per applied electric field E , defined as

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

can be determined by measuring the STFMR for devices with different d_{FM} using [52]

$$\frac{1}{\xi_{\text{FMR}}} = \frac{1}{\xi_{\text{DL}}^E} \left(\frac{1}{\rho_{\text{Pt}}} + \frac{\hbar}{e \mu_0 M_s d_{\text{FM}} d_{\text{Pt}}} \right), \quad (3)$$

where e is the elementary charge, $\hbar$ is the Dirac constant, ρ_{Pt} is the electric resistivity of the Pt layer, M_s is the saturation magnetization, and

$$\xi_{\text{FMR}} = \frac{S}{A} \frac{e \mu_0 M_s d_{\text{FM}} d_{\text{Pt}}}{\hbar} \sqrt{1 + \frac{M_{\text{eff}}}{H_{\text{FMR}}}} \quad (4)$$

is the FMR spin-torque generation efficiency, where M_{eff} is the effective demagnetization field. The resistivity ρ_{Pt} of the Pt layer in the Pt/FM bilayers was determined by the standard four-probe method for single Pt films, sputtered on the Ti layer, where the sheet resistance of the Ti layer was orders of magnitude larger than that of the Pt layer. The resistivity of the Pt layer was $\rho_{\text{Pt}} = 65.6 \mu\Omega \text{ cm}$ for $d_{\text{Pt}} = 1.5 \text{ nm}$ and $\rho_{\text{Pt}} = 23.0 \mu\Omega \text{ cm}$ for $d_{\text{Pt}} = 7.4 \text{ nm}$. The increase of the resistivity induced by decreasing the thickness d_{Pt} can be attributed to the surface scattering, rather than a possible discontinuity of the Pt layer. In fact, the difference in the resistivity between the Pt layers with $d_{\text{Pt}} = 1.5$ and 7.4 nm is in good agreement with that reported previously, where the drift-diffusion model is consistent with the experimental result for Pt/Co bilayers with $1.2 \text{ nm} < d_{\text{Pt}} < 15 \text{ nm}$ [53].

III. RESULTS AND DISCUSSION

A. Spin-torque ferromagnetic resonance

In Fig. 1(b) we show the magnetic field H dependence of the DC voltage V_{DC} for the Pt(7.4)/Ni(4) and Pt(7.4)/Fe(4) bilayers. We first characterize the DC voltage V_{DC} for the Pt/FM devices by measuring RF current power P , magnetic field angle θ , and RF current frequency f dependence of the STFMR.

Figures 2(a) and 2(b) show the RF power P dependence of the STFMR signal for the Pt(7.4)/Fe(5) and Pt(7.4)/Ni(4) bilayers, where the symmetric S and antisymmetric A components of V_{DC} were obtained by fitting the measured V_{DC} using Eq. (1). This result shows that both symmetric S and antisymmetric A components are proportional to P , indicating that the STFMR is in the linear response regime. We also note that the FMR field H_{FMR} is independent of the applied microwave power P as shown in Figs. 2(b) and 2(c). The negligible change of H_{FMR} shows that the sample heating due to the microwave application and absorption barely affects the magnetic properties of the STFMR devices.

FIG. 2. The RF power P dependence of the symmetric S (upper) and antisymmetric A (lower) components of the DC voltage V_{DC} for (a) the Pt(7.4)/Fe(5) bilayer at an RF of $f = 10 \text{ GHz}$ and (b) the Pt(7.4)/Ni(4) bilayer at $f = 7 \text{ GHz}$. The solid lines are the linear fitting result. Also shown is the RF power P dependence of the change ratio of the FMR field $\Delta H_{\text{FMR}} = [H_{\text{FMR}}(P) - \bar{H}_{\text{FMR}}]/\bar{H}_{\text{FMR}}$ for the (c) Pt(7.4)/Ni(4) and (d) Pt(7.4)/Fe(5) bilayers, where $\bar{H}_{\text{FMR}}$ represents the averaged value of $H_{\text{FMR}}(P)$.

In Figs. 3(a) and 3(b) we show the magnetic field angle θ dependence of the symmetric S and antisymmetric A voltage, where the in-plane external magnetic field $\mathbf{H}$ was applied at the angle of θ from the longitudinal direction of the Pt/Fe

FIG. 3. The S and A components of the STFMR spectra as a function of the in-plane magnetic field angle θ for (a) the Pt(7.4)/Fe(5) film at $f = 12 \text{ GHz}$ and (b) the Pt(7.4)/Ni(4) film at $f = 6 \text{ GHz}$. Here the in-plane external magnetic field $\mathbf{H}$ was applied at an angle of θ from the longitudinal direction. (c) The RF f dependence of the FMR spin-torque generation efficiency ξ_{FMR} from $f = 4$ to 16 GHz for the Pt(7.4)/Fe(5) and from $f = 4$ to 9 GHz for the Pt(7.4)/Ni(5) bilayers.

FIG. 4. Magnetic field H dependence of the DC voltage V_{DC} for (a) Pt(1.5)/Ni(d_{Ni}) at $f = 6$ GHz, (b) Pt(7.4)/Ni(d_{Ni}) at $f = 6$ GHz, (c) Pt(1.5)/Fe(d_{Fe}) at $f = 12$ GHz, and (d) Pt(7.4)/Fe(d_{Fe}) at $f = 12$ GHz. The closed circles are the experimental data and the solid curves are the fitting result using Eq. (1). (e) The $1/d_{FM}$ dependence of $1/\xi_{FMR}$ for the Pt/Ni and Pt/Fe bilayers, where d_{FM} is the thickness of the FM layer and ξ_{FMR} is the FMR spin-torque efficiency at $f = 9$ GHz for the Pt/Ni bilayer and $f = 16$ GHz for the Pt/Fe bilayer. The closed circles are the experimental data and the solid lines are the fitting result using Eq. (3).

and Pt/Ni devices. In both films, S and A are proportional to $\cos \theta \sin 2\theta$, consistent with previous results [54]. This result indicates that the contribution from an out-of-plane Oersted field is negligible in the observed voltage, supporting that the RF current flow is uniform in the STFMR devices.

The STFMR spectra at various frequencies f are shown in Fig. 1(b). This result shows that the FMR field H_{FMR} changes systematically by changing f , which is consistent with the Kittel formula $2\pi f = \gamma \sqrt{\mu_0 H_{FMR}(\mu_0 H_{FMR} + \mu_0 M_{eff})}$, where γ is the gyromagnetic ratio. From the measured V_{DC} , we calculated the FMR spin-torque generation efficiency ξ_{FMR} at each f using Eq. (4). The f dependence of ξ_{FMR} for the Pt/FM bilayers is shown in Fig. 3(c). Figure 3(c) shows that ξ_{FMR} is almost independent of f in the Pt/Ni bilayer, while ξ_{FMR} is independent of f only at higher frequency in the Pt/Fe bilayer. Here the STFMR predicts that ξ_{FMR} is independent of f [51]. The result for the Pt/Ni bilayer is consistent with this prediction, showing that the measured V_{DC} is dominated by the STFMR for the Pt/Ni bilayer. The f dependence of ξ_{FMR} for the Pt/Fe bilayer at the higher frequency is also consistent with the prediction of the STFMR. In contrast, ξ_{FMR} at the lower frequency for the Pt/Fe bilayer cannot be entirely attributed to the STFMR. In the Pt/Fe bilayer, the increase of ξ_{FMR} at the lower frequency can be attributed to additional contributions, including thermal effects and the inverse spin Hall effect induced by spin pumping; because of the smaller AMR of the Pt/Fe film, compared to that of the Pt/Ni film, these additional effects can contribute to the observed S in the Pt/Fe film. Since these contributions decrease with increasing f [55], these additional contributions become negligible and the STFMR dominates the measured ξ_{FMR} at higher frequency f , resulting in the f -independent ξ_{FMR} in the Pt/Fe film. The negligible contribution from the spin pumping and thermal effects at the higher frequency is also supported by the $1/d_{FM}$ dependence of $1/\xi_{FMR}$ as described below. In the following, we discuss the STFMR measured at the RF f where ξ_{FMR} is almost independent of f to neglect the contribution from the spin pumping and thermal effects.

In the following discussion, we neglect the spin-orbit torques arising from the FM/SiO₂ interface since, in the Pt/FM/oxide structure, the contribution from the FM/SiO₂

interface to the spin-orbit torques is negligible compared to that from the Pt bulk and/or the Pt/FM interface [56].

B. Spin-torque efficiencies

In Figs. 4(a) and 4(b) we show the V_{DC} spectra at $f = 6$ GHz for the Pt(1.5)/Ni(d_{FM}) and Pt(7.4)/Ni(d_{FM}) bilayers with various d_{FM} , respectively. We also show the V_{DC} spectra at $f = 12$ GHz for the Pt(1.5)/Fe(d_{FM}) and Pt(7.4)/Fe(d_{FM}) bilayers in Figs. 4(c) and 4(d), respectively. All the measured V_{DC} spectra are consistent with Eq. (1). We note that the sign of the antisymmetric component A is opposite between the Pt(1.5)/Fe and Pt(7.4)/Fe bilayers [see Figs. 4(c) and 4(d)]. We also note that in the Pt(7.4)/Fe(d_{FM}) film, the sign of A is reversed by decreasing d_{FM} from 3 nm to 2 nm. The sign changes are induced by the competition between the Oersted field H_{Oe} and fieldlike effective field H_{FL} , since $A \propto H_{Oe} + H_{FL}$.

To determine the dampinglike and fieldlike torque efficiencies ξ_{DL}^E and ξ_{FL}^E , we plot $1/\xi_{FMR}$ at $f = 9$ GHz for the Pt/Ni bilayer and $f = 16$ GHz for the Pt/Fe bilayer as a function of $1/d_{FM}$ in Fig. 4(e). The measured values of $1/\xi_{FMR}$ is linear to $1/d_{FM}$ in all the devices, consistent with Eq. (3). The linear dependence of $1/\xi_{FMR}$ on $1/d_{FM}$ supports that the additional contributions, including the spin pumping and thermal effects, are negligible in ξ_{FMR} . The reason for this is that in the presence of the additional contributions, $1/\xi_{FMR}$ deviates from the linear dependence on $1/d_{FM}$ [57].

Figure 4(e) shows that the sign of the intercept of the linear relation is positive in all the devices, showing that $\xi_{DL}^E > 0$ in the Pt/Ni and Pt/Fe bilayers because the intercept corresponds to $1/\xi_{DL}^E$ [see 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 slope of the linear relation corresponds to ξ_{FL}^E/ξ_{DL}^E , indicating that the sign of the fieldlike torque is opposite between the Pt/Ni and Pt/Fe bilayers: $\xi_{FL}^E > 0$ in the Pt/Ni film and $\xi_{FL}^E < 0$ in the Pt/Fe film. The values of ξ_{DL}^E and ξ_{FL}^E , obtained by fitting the data with Eq. (3), are listed in Table I.

The result in Table I shows that the dampinglike torque efficiency ξ_{DL}^E for the Pt(d_{Pt})/Ni and Pt(d_{Pt})/Fe bilayers is enhanced by increasing d_{Pt} . This result also shows that ξ_{DL}^E

TABLE I. Parameters for the Pt/Ni and Pt/Fe bilayers, determined by the STFMR measurement: ξ_{DL}^E and ξ_{FL}^E are the dampinglike and fieldlike torque efficiencies per 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. (5); and $\text{Re}[G_{\text{eff,tot}}^{\uparrow\downarrow}]$ is the total effective spin-mixing conductance, determined by fitting the FM-thickness dependence of the effective Gilbert magnetic damping α_{eff} using Eq. (6). The errors are the standard deviation determined by the fitting.

Bilayer	ξ_{DL}^E ($10^3 \Omega^{-1} \text{cm}^{-1}$)	ξ_{FL}^E ($10^3 \Omega^{-1} \text{cm}^{-1}$)	K_s (mJ/m ²)	$\mu_0 M_s$ (T)	$\text{Re}[G_{\text{eff,tot}}^{\uparrow\downarrow}]$ ($10^{15} \Omega^{-1} \text{m}^{-2}$)
Pt(1.5)/Ni	1.81 ± 0.36	0.42 ± 0.02	0.05 ± 0.02	0.47 ± 0.02	1.30 ± 0.25
Pt(7.4)/Ni	2.84 ± 0.12	0.53 ± 0.05	0.14 ± 0.01	0.49 ± 0.01	1.73 ± 0.08
Pt(1.5)/Fe	1.75 ± 0.15	-0.77 ± 0.03	1.41 ± 0.04	2.07 ± 0.01	1.27 ± 0.03
Pt(7.4)/Fe	2.99 ± 0.11	-2.18 ± 0.11	1.24 ± 0.18	1.93 ± 0.06	1.26 ± 0.05

is almost identical in the Pt(d_{Pt})/Ni and Pt(d_{Pt})/Fe bilayers. In contrast, the choice of the FM layer strongly affects the fieldlike torque; even the sign of ξ_{FL}^E is reversed by changing the FM layer from Ni to Fe.

C. Magnetic anisotropy and effective spin-mixing conductance

Before discussing the spin-torque efficiencies, we first characterize the spin-orbit coupling at the Pt/FM interface by quantifying the magnetic anisotropy and effective spin-mixing conductance, both affected by the interfacial spin-orbit coupling. The interface magnetic anisotropy can be estimated from the $1/d_{\text{FM}}$ dependence of $\mu_0 M_{\text{eff}}$ using [58]

$$\mu_0 M_{\text{eff}} = \mu_0 M_s - \frac{2K_s}{M_s} \frac{1}{d_{\text{FM}}}, \quad (5)$$

where K_s and M_s are the interface perpendicular magnetic anisotropy energy density and the saturation magnetization, respectively. We determined $\mu_0 M_{\text{eff}}$ by fitting the measured f dependence of H_{FMR} using the Kittel formula. In Fig. 5(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. Here K_s is the sum of the magnetic anisotropy energy density at the Pt/FM and FM/SiO₂ interfaces: $K_s = K_s^{\text{Pt/FM}} + K_s^{\text{FM/SiO}_2}$. Since a previous study shows that $K_s^{\text{Fe/SiO}_2} = 0.6 \text{ mJ/m}^2$ [59], the result shown in Table I indicates that $K_s^{\text{Pt/Fe}}$ is several times larger than $K_s^{\text{Pt/Ni}}$. The larger $K_s^{\text{Pt/Fe}}$ suggests that the interfacial spin-orbit coupling

at the Pt/Fe interface is stronger than that at the Pt/Ni interface [60].

The magnetic damping, affected by the interfacial spin-orbit coupling, also supports the stronger interfacial spin-orbit coupling at the Pt/Fe interface. In Fig. 5(b) we show the $1/d_{\text{FM}}$ dependence of the effective Gilbert damping α_{eff} for the Pt/Ni and Pt/Fe bilayers. The effective Gilbert damping α_{eff} was determined by fitting the measured f dependence of the STFMR linewidth W using $W = W_0 + (2\pi\alpha_{\text{eff}}/\gamma)f$, where W_0 is the inhomogeneous linewidth. The effective Gilbert magnetic damping α_{eff} in the presence of the spin pumping is expressed as [61]

$$\alpha_{\text{eff}} = \alpha_{\text{int}} + \text{Re}[G_{\text{eff,tot}}^{\uparrow\downarrow}] \frac{g\mu_B h}{4\pi e^2 M_s d_{\text{FM}}} + \frac{\beta_{\text{TMS}}}{d_{\text{FM}}^2}, \quad (6)$$

where α_{int} is the intrinsic magnetic damping of the FM layer, $\text{Re}[G_{\text{eff,tot}}^{\uparrow\downarrow}]$ is the real part of the total effective spin-mixing conductance, g is the g factor, μ_B is the Bohr magneton, and h is the Planck constant. In addition, $\text{Re}[G_{\text{eff,tot}}^{\uparrow\downarrow}]$ consists of two components $\text{Re}[G_{\text{eff,tot}}^{\uparrow\downarrow}] = \text{Re}[G_{\text{eff}}^{\uparrow\downarrow}] + G_{\text{SML}}$, where $G_{\text{eff}}^{\uparrow\downarrow}$ is the effective spin-mixing conductance, which characterizes the spin relaxation in the bulk of the Pt layer, and G_{SML} characterizes the strength of the spin memory loss at the Pt/FM interface. In Eq. (6) the third term is the contribution from two-magnon scattering, where the coefficient β_{TMS} depends on both $(K_s/M_s)^2$ and the density of magnetic defects at the FM surfaces [61–63]. Since the two-magnon scattering at FM/oxide interfaces is known to be relatively weak, the primary source of the two-magnon scattering in the devices used in the present study is the Pt/FM interface. For the Pt/Fe bilayers, α_{int} obtained by neglecting the d_{FM}^{-2} term is unphysically small or even negative, showing that the contribution from the two-magnon scattering cannot be neglected. In contrast, reasonable values of α_{int} were obtained without taking into account the two-magnon scattering for the Pt/Ni bilayers. This difference is consistent with the fact that the strength of the two-magnon scattering depends on $(K_s/M_s)^2$, which is clearly different in the Pt/Fe and Pt/Ni films, as shown in Table I. In Table I we show $\text{Re}[G_{\text{eff,tot}}^{\uparrow\downarrow}]$ for the Pt/FM bilayers, extracted by fitting the $1/d_{\text{FM}}$ dependence of α_{eff} in Fig. 5(b) using Eq. (6). From the fitting, we obtained $\beta_{\text{TMS}} = 0.1 \text{ nm}^2$ for the Pt/Fe bilayers, while we neglected the two-magnon scattering for the Pt/Ni bilayers for the above reason.

Table I shows that the effective spin-mixing conductance $\text{Re}[G_{\text{eff,tot}}^{\uparrow\downarrow}]$ in the Pt/Ni bilayer depends on the Pt thickness d_{Pt} , while $\text{Re}[G_{\text{eff,tot}}^{\uparrow\downarrow}]$ in the Pt/Fe bilayer is independent

FIG. 5. (a) The $1/d_{\text{FM}}$ dependence of the effective demagnetization field $\mu_0 M_{\text{eff}}$, where d_{FM} is the thickness of the FM layer. The dotted lines are the linear fitting result. (b) Effective magnetic damping α_{eff} as a function of $1/d_{\text{FM}}$. The dotted lines are the fitting result.

of d_{Pt} . Since the effective spin-mixing conductance $\text{Re}[G_{\text{eff}}^{\uparrow\downarrow}]$ depends on the thickness of the Pt layer d_{Pt} , while G_{SML} is independent of d_{Pt} , this difference shows that the spin memory loss at the Pt/Fe interface is stronger than that at the Pt/Ni interface, supporting the stronger spin-orbit coupling at the Pt/Fe interface. This result is consistent with the stronger two-magnon scattering at the Pt/Fe interface because the two-magnon scattering increases with the strength of the interfacial spin-orbit coupling [64].

D. Dampinglike torque

Next we discuss the dampinglike torque efficiency. The measured dampinglike torque efficiency ξ_{DL}^E can be decomposed into d_{Pt} -dependent $\xi_{\text{DL,dep}}^E(d_{\text{Pt}})$ and d_{Pt} -independent $\xi_{\text{DL,indep}}^E(d_{\text{Pt}})$ components: $\xi_{\text{DL}}^E(d_{\text{Pt}}) = \xi_{\text{DL,dep}}^E(d_{\text{Pt}}) + \xi_{\text{DL,indep}}^E$. One of the sources of $\xi_{\text{DL,dep}}^E(d_{\text{Pt}})$ is the bulk spin Hall effect in the Pt layer. Although the dampinglike torque due to the interfacial spin current originating from interfacial spin-orbit scattering also increases with d_{Pt} [41,65], we first neglect the contribution from this mechanism for simplicity.

The dampinglike torque efficiency due to the bulk spin Hall effect in the simplest drift-diffusion model is expressed as $\xi_{\text{DL,SHE}}^E(d_{\text{Pt}}) = [1 - \text{sech}(d_{\text{Pt}}/\lambda_s)]\sigma_{\text{SHE}}^{\text{eff}}$, where $\sigma_{\text{SHE}}^{\text{eff}} = \sigma_{\text{SHE}}\varepsilon$ is the effective spin Hall conductivity of the Pt layer, where σ_{SHE} is the spin Hall conductivity and ε represents the strength of the spin memory loss at the interface ($\varepsilon \leq 1$). The reason for using this simple model is that this study aims to clarify the role of the bulk and interface in the generation of the spin-orbit torques in the Pt/FM structures with the different FM layers, rather than precisely quantify the bulk and interfacial spin-orbit torque efficiencies.

Since the spin diffusion length λ_s and the resistivity ρ_{Pt} of Pt films are dependent on the Pt thickness d_{Pt} , we estimate λ_s for each Pt/FM devices with different d_{Pt} , assuming the Elliot-Yafet spin-relaxation mechanism $\lambda_s \propto 1/\rho_{\text{Pt}}$: $\lambda_s = 0.98$ nm for $d_{\text{Pt}} = 1.5$ nm and $\lambda_s = 2.65$ nm for $d_{\text{Pt}} = 7.4$ nm, obtained from $\rho_{\text{Pt}}\lambda_s = 0.61 \times 10^{15} \Omega \text{ m}^2$ [66]. For the Pt/FM films, we also assume that the spin Hall conductivity σ_{SHE} is independent of d_{Pt} because the Pt resistivity in the devices is in the moderately dirty regime [66]. Using the drift-diffusion model with the above assumptions, we obtain the change of the dampinglike torque efficiency due to the spin Hall effect as $\xi_{\text{DL,SHE}}^E(d_{\text{Pt}} = 7.4 \text{ nm})/\xi_{\text{DL,SHE}}^E(d_{\text{Pt}} = 1.5 \text{ nm}) = 1.42$.

From the values shown in Table I, we obtain $\xi_{\text{DL}}^E(d_{\text{Pt}} = 7.4 \text{ nm})/\xi_{\text{DL}}^E(d_{\text{Pt}} = 1.5 \text{ nm}) = 1.57 \pm 0.13$ for the Pt/Ni bilayer and $\xi_{\text{DL}}^E(d_{\text{Pt}} = 7.4 \text{ nm})/\xi_{\text{DL}}^E(d_{\text{Pt}} = 1.5 \text{ nm}) = 1.71 \pm 0.05$ for the Pt/Fe bilayer. The experimental value of $\xi_{\text{DL}}^E(d_{\text{Pt}} = 7.4 \text{ nm})/\xi_{\text{DL}}^E(d_{\text{Pt}} = 1.5 \text{ nm})$ for the Pt/Ni bilayer is close to the prediction of the above simple model of the spin Hall effect, suggesting that the dampinglike torque in the Pt/Ni bilayer is dominated by the spin Hall effect. The experimental value of $\xi_{\text{DL}}^E(d_{\text{Pt}} = 7.4 \text{ nm})/\xi_{\text{DL}}^E(d_{\text{Pt}} = 1.5 \text{ nm})$ for the Pt/Fe bilayer is also comparable to the prediction of the spin Hall effect. However, it is reasonable to consider that a sizable dampinglike torque is generated not only by the bulk spin Hall effect in the Pt layer but also by different mechanisms other than the spin Hall effect in the Pt/Fe bilayer. The reason for this is that the magnitude of ξ_{DL}^E of the Pt/Fe bilayer is comparable to that of the Pt/Ni bilayer despite the

fact that the stronger spin memory loss at the Pt/Fe interface suppresses the dampinglike torque due to the spin Hall effect. This suggests that the dampinglike torque originating at the Pt/Fe interface contributes to ξ_{DL}^E in the Pt/Fe bilayer, which is consistent with the interfacial spin-orbit coupling in the Pt/Fe bilayer being stronger than that in the Pt/Ni bilayer.

E. Fieldlike torque

The fieldlike torque efficiency ξ_{FL}^E can also be decomposed into d_{Pt} -dependent $\xi_{\text{FL,dep}}^E(d_{\text{Pt}})$ and d_{Pt} -independent $\xi_{\text{FL,indep}}^E$ components: $\xi_{\text{FL}}^E(d_{\text{Pt}}) = \xi_{\text{FL,dep}}^E(d_{\text{Pt}}) + \xi_{\text{FL,indep}}^E$. We note that $\xi_{\text{FL,dep}}^E(d_{\text{Pt}})$ and $\xi_{\text{FL,indep}}^E$ mainly originate from the bulk spin Hall effect and interfacial spin-orbit coupling, respectively; the fieldlike torque originating from the spin current due to the interfacial spin-orbit scattering, as well as the spin accumulation due to the Rashba-Edelstein effect, is insensitive to d_{Pt} [41,65]. The separation of the bulk and interface contributions from the result shown in Table I based on an established model requires us to assume various parameters, such as the real and imaginary parts of the spin-mixing conductance, as well as the spin Hall conductivity [29,67], making the analysis less reliable. Thus, we use an alternative approach to roughly estimate the bulk and interface contributions to the fieldlike torque. We assume that the fieldlike torque efficiency due to the spin Hall effect $\xi_{\text{FL,SHE}}^E(d_{\text{Pt}})$ follows the same d_{Pt} dependence as with the dampinglike torque efficiency $\xi_{\text{DL,SHE}}^E(d_{\text{Pt}})$: $\xi_{\text{FL,SHE}}^E(d_{\text{Pt}}) = [1 - \text{sech}(d_{\text{Pt}}/\lambda_s)]\xi_{\text{FL,SHE}}^{E,0}$ or $\xi_{\text{FL,SHE}}^E(d_{\text{Pt}} = 7.4 \text{ nm})/\xi_{\text{FL,SHE}}^E(d_{\text{Pt}} = 1.5 \text{ nm}) = 1.42$.

From the values shown in Table I, we obtain $\xi_{\text{FL}}^E(d_{\text{Pt}} = 7.4 \text{ nm})/\xi_{\text{FL}}^E(d_{\text{Pt}} = 1.5 \text{ nm}) = 1.26 \pm 0.08$ for the Pt/Ni bilayer and $\xi_{\text{FL}}^E(d_{\text{Pt}} = 7.4 \text{ nm})/\xi_{\text{FL}}^E(d_{\text{Pt}} = 1.5 \text{ nm}) = 2.83 \pm 0.02$ for the Pt/Fe bilayer. This result shows that $\xi_{\text{FL}}^E(d_{\text{Pt}} = 7.4 \text{ nm})/\xi_{\text{FL}}^E(d_{\text{Pt}} = 1.5 \text{ nm})$ for the Pt/Fe film is clearly different from the expectation from the fieldlike torque efficiency $\xi_{\text{FL,SHE}}^E(d_{\text{Pt}})$ due to the bulk spin Hall effect. This shows that a sizable fieldlike torque is generated by the Pt/Fe interface, which is consistent with the strong spin-orbit coupling at the Pt/Fe interface.

In the Pt/Fe bilayer, the clear change of ξ_{FL}^E induced by changing d_{Pt} indicates that a sizable fieldlike torque is also generated by the bulk spin Hall effect. To test the role of the bulk spin Hall effect in the fieldlike torque efficiency ξ_{FL}^E , we define the change of the fieldlike torque efficiency $\Delta\xi_{\text{FL}}^E$ as $\Delta\xi_{\text{FL}}^E = \xi_{\text{FL}}^E(7.4 \text{ nm}) - \xi_{\text{FL}}^E(1.5 \text{ nm}) = \xi_{\text{FL,dep}}^E(7.4 \text{ nm}) - \xi_{\text{FL,dep}}^E(1.5 \text{ nm})$. From the result shown in Table I, we obtain $\Delta\xi_{\text{FL}}^E > 0$ for the Pt/Ni bilayer, while $\Delta\xi_{\text{FL}}^E < 0$ for the Pt/Fe bilayer. Since the nonzero value of $\Delta\xi_{\text{FL}}^E$ arises from the d_{Pt} -dependent component of the fieldlike torque, the opposite sign of $\Delta\xi_{\text{FL}}^E$ shows that the sign of the fieldlike torque due to the bulk spin Hall effect in the Pt layer is opposite in the Pt/Ni and Pt/Fe bilayers. We also note that the fieldlike torque efficiency ξ_{FL}^E in Table I shows that the magnitude of the fieldlike torque in the Pt/Fe bilayer is clearly larger than that in the Pt/Ni bilayer. Since the above result is a rough estimation, we only focus on the sign and relative magnitude of the fieldlike torque below.

The interfacial spin-orbit coupling plays an important role in the generation of the fieldlike torque due to the bulk spin

Hall effect, as well as that arising from the interface. In the model of the spin-orbit torques due to the bulk spin Hall effect, the real part of the spin-mixing conductance $\text{Re}[G_{\text{Pt/FM}}^{\uparrow\downarrow}]$ contributes to the dampinglike torque, whereas the imaginary part $\text{Im}[G_{\text{Pt/FM}}^{\uparrow\downarrow}]$ contributes to the fieldlike torque [29]. The reason for this is that the fieldlike torque due to the spin Hall effect arises from the reflection of the spin current at the interface, while the dampinglike torque arises from the injection of the spin current. Although $\text{Im}[G_{\text{Pt/FM}}^{\uparrow\downarrow}]$ has been believed to be negligible compared to $\text{Re}[G_{\text{Pt/FM}}^{\uparrow\downarrow}]$ in metallic films, recent studies have shown non-negligible $\text{Im}[G_{\text{Pt/FM}}^{\uparrow\downarrow}]$ in such systems [43,68–70]. Since sizable $\text{Im}[G_{\text{Pt/FM}}^{\uparrow\downarrow}]$ appears when a spin current reflected at the interface experiences a

large angle rotation of its spin direction due to interfacial spin-orbit coupling [68], the stronger fieldlike torque in the Pt/Fe film, compared with that in the Pt/Ni film, is consistent with the stronger spin-orbit coupling at the Pt/Fe interface.

The opposite sign of the fieldlike torque in the Pt/Ni and Pt/Fe bilayers indicates that the sign of $\text{Im}[G_{\text{Pt/FM}}^{\uparrow\downarrow}]$ is opposite in these devices. Here the sign of the imaginary part of the spin-mixing conductance can be different depending on the choice of the FM layer. For a model where all of the Fermi surfaces are spherical and the same size, the real and imaginary parts of the spin-mixing conductance due to spin-dependent reflection arising from a spin-dependent potential at the interface are expressed as [29,67]

$$\text{Re}[G_{\text{Pt/FM}}^{\uparrow\downarrow}] = \frac{e^2 k_F^2}{2\pi h} \left\{ \frac{1}{2} + \frac{u^\uparrow u^\downarrow}{2(u^\uparrow + u^\downarrow)} \left[u^\downarrow \ln \left(\frac{u^{\downarrow 2}}{1 + u^{\downarrow 2}} \right) + u^\uparrow \ln \left(\frac{u^{\uparrow 2}}{1 + u^{\uparrow 2}} \right) \right] \right\}, \quad (7)$$

$$\text{Im}[G_{\text{Pt/FM}}^{\uparrow\downarrow}] = \frac{e^2 k_F^2}{2\pi h} \left(\frac{u^\uparrow u^\downarrow}{2(u^\uparrow + u^\downarrow)} (u^\downarrow [\pi - 2 \tan^{-1} u^\downarrow] - u^\uparrow [\pi - 2 \tan^{-1} u^\uparrow]) \right). \quad (8)$$

Here $u^\uparrow$ and $u^\downarrow$ represent the strength of the spin-dependent potential at the interface, where $\uparrow$ and $\downarrow$ refer to majority and minority electrons, respectively. Equations (7) and (8) show that the sign of $\text{Re}[G_{\text{Pt/FM}}^{\uparrow\downarrow}]$ is always positive. In contrast, the sign of $\text{Im}[G_{\text{Pt/FM}}^{\uparrow\downarrow}]$ depends on the relative strength between the spin-dependent potentials $u^\uparrow$ and $u^\downarrow$. This indicates that the sign of the fieldlike torque due to the spin Hall effect depends on the electronic structure of the FM layer.

IV. CONCLUSION

In summary, we have investigated the dampinglike and fieldlike 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. We found that the dampinglike torque efficiency ξ_{DL}^E is enhanced by increasing d_{Pt} in both Pt/Ni and Pt/Fe bilayers. The result also shows that the magnitude of ξ_{DL}^E is almost identical in the Pt/Ni and Pt/Fe bilayers despite the stronger spin memory loss at the Pt/Fe interface. These results suggest that although the d_{Pt} dependence of ξ_{DL}^E is consistent with the dampinglike torque due to the bulk spin Hall effect in the Pt layer, the Pt/Fe interface also contributes to the dampinglike torque in the Pt/Fe bilayer. The non-negligible contribution from the interface to the dampinglike torque is consistent with the spin-orbit coupling at the Pt/Fe interface being stronger than that at the Pt/Ni interface. Although a part of the dampinglike torque in the Pt/Fe bilayer originates from the interface, the origin is unclear from the result; the intrinsic spin-orbit torque and/or the interfacial spin-orbit scattering may play an important role in the interface generation of the dampinglike torque.

In contrast to the dampinglike torque, whose magnitude and sign are almost identical in the Pt/Ni and Pt/Fe bilayers, the fieldlike torque strongly depends on the choice of the FM layer. In particular, the sign of the d_{Pt} -dependent component of the fieldlike torque efficiency ξ_{FL}^E is opposite between the

Pt/Ni and Pt/Fe bilayers. This indicates that the direction of the fieldlike torque due to the bulk spin Hall effect in the Pt layer is opposite between the Pt/Ni and Pt/Fe bilayers, which is attributed to the opposite sign of the imaginary part of the spin-mixing conductance. The magnitude, as well as the sign, of the fieldlike torque is also clearly different in the Pt/Fe and Pt/Ni bilayers. The stronger fieldlike torque in the Pt/Fe bilayer indicates that the imaginary part of the spin-mixing conductance in the Pt/Fe bilayer is larger than that in the Pt/Ni bilayer, which is also consistent with the stronger interfacial spin-orbit coupling in the Pt/Fe bilayer.

Previous studies have demonstrated that the interfacial spin-orbit coupling is also strong in Pt/Co bilayers. However, the role of the bulk and interfacial spin-orbit coupling in the generation of the spin-orbit torques is clearly different between the Pt/Co and Pt/Fe bilayers. The dominant source of the dampinglike torque in the Pt/Co bilayer is the bulk spin Hall effect in the Pt layer, which is the same as that in the Pt/Ni and Pt/Fe bilayers [64,71,72]. In contrast, the fieldlike torque in the Pt/Co bilayer is mainly generated by the Pt/Co interface; the contribution from the bulk spin Hall effect to the fieldlike torque is negligible in the Pt/Co bilayer. This is different from the fieldlike torque in the Pt/Fe bilayer, where the bulk spin Hall effect plays an important role, even though both films show the strong interfacial spin-orbit coupling. The different mechanisms responsible for the spin-orbit torques in the Pt/FM bilayers show that the electronic structure of the FM layer, as well as the interfacial spin-orbit coupling, plays an important role in the generation of the spin-orbit torques.

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