Isotropic non-local Gilbert damping driven by spin pumping in epitaxial Pd/Fe films on MgO(001) substrates

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Abstract

Although both theoretical predictions and experimental observations have demonstrated that the Gilbert damping is anisotropic at ferromagnet/semiconductor interface possessing robust interfacial spin–orbit coupling, it is not well understood whether non-local Gilbert damping driven by spin pumping in heavy metal/ferromagnetic metallic bilayers is anisotropic or not. Here, we investigated the angular and frequency dependence of magnetic relaxation in epitaxial Pd/Fe films on MgO(001) substrates. After disentangling parasitic contributions, we unambiguously observe that the non-local Gilbert damping is isotropic in the Fe(001) plane, suggesting that the spin transport across the Pd/Fe interface is independent of the Fe magnetization orientation. First principles calculations reveal that the effective spin mixing conductance of the Pd/Fe interface is nearly invariant for different magnetization directions, in good agreement with the experimental observations. These results offer valuable insight into spin transport in metallic bilayers, and facilitate the development of next-generation spintronic devices.

1. Introduction

The rapid development of spintronic devices necessitates a deeper understanding of the magnetization relaxation mechanism [1–3]. Gilbert damping, one of the key parameters in spin dynamics, characterizes the energy transfer from the spin subsystem to the lattice and governs the magnetization switching time and the critical current density in spin transfer torque devices [4–6]. An anisotropic Gilbert damping is expected in single crystal ultrathin films if the Fermi surface or the spin–orbit coupling can change with magnetization orientation [7–10]. Chen et al discovered the anisotropic damping in ultrathin Fe films on GaAs(001) substrates due to the presence of robust interfacial spin–orbit coupling. The magnitude of anisotropic damping, however, decreases with increasing Fe thickness, and disappears when the Fe thickness is larger than 1.9 nm [11–13].

Apart from the intrinsic Gilbert damping in ferromagnetic materials (FM), spin currents driven by spin pumping sink into heavy metals (HM) or other magnetic layers, importing non-local Gilbert damping in heavy metal/ferromagnetic bilayers or spin valve structures [14–16]. Although the anisotropic behavior of magnetization relaxation was observed, it is still debated whether the spin transport, related to non-local Gilbert damping and parameterized by the spin mixing conductance, is anisotropic or isotropic in ferromagnetic multilayers [17–19]. For instance, Li et al found nearly isotropic absorption of pure spin currents in the Py17/Cu50/Cu(111) trilayers, while Baker et al found the anisotropic absorption of pure spin currents for the...
Co$_{50}$Fe$_{50}$/Cr$_x$/Ni$_{81}$Fe$_{19}$ spin valves [18, 19]. Besides, Tokac et al have corroborated the interfacial structure dependent non-local Gilbert damping in Co/Ir multilayers with fcc(111) or hcp(0001) interfacial textures [20]. However, the dependence of non-local damping on magnetization orientation has attracted continuous attention, but is still disputed [21–24]. For the purpose of exploring the question of whether spin transport is anisotropic or not, we investigated spin pumping and clarified the dependence of diverse magnetic relaxations on Fe magnetic orientation in epitaxial Pd/Fe bilayers using ferromagnetic resonance (FMR). By excluding misleading magnetic dragging effects and other parasitic contributions, we observed that non-local Gilbert damping is isotropic in Fe(001) plane. The isotropic non-local Gilbert damping suggests that the spin transport across Pd/Fe interface is independent of Fe magnetization orientation, which is supported by first principles calculations.

2. Experiments

Samples were prepared via molecular beam epitaxy with a chamber base pressure of $\sim$2 $\times$ 10$^{-10}$ mbar [25]. Prior to deposition, MgO(001) substrates were annealed at 700 °C for 2 h. 6 nm Fe films were then deposited using an electron-beam gun, followed by the deposition of Pd films, labeled as Pd($t_{pd}$)/Fe(6 nm), where $t_{pd}$ indicates the Pd thickness in nanometers. The crystalline quality and epitaxial relationships were confirmed by high-resolution transmission electron microscopy, as shown in figures 1(a) and (b). The selected area electron diffraction spots shown in figure 1(b) are split into three lattices, corresponding to MgO, Fe and Pd, because of the small lattice mismatch between the different layers. It has been revealed that the films were grown with the epitaxial relationship Pd(001)/[110]||Fe(001)/[100]||MgO(001)/[110] (see the inset of figure 1(b)). For comparison, the reference sample, a 6 nm Fe film, was also prepared on MgO(001) substrate with Fe(001)/[100]||MgO(001)/[110] [25]. 3.5 nm Cu was deposited nonepitaxially on the Fe film to prevent the oxidation of Fe atoms [26–28]. In-plane Vector Network Analyzer ferromagnetic resonance (VNA-FMR) measurements were performed by placing the sample face-down on a co-planar waveguide (CPW) and recording the transmission coefficient $S_{21}$ [29–31]. Meanwhile, out-of-plane FMR measurements were also performed using the NanOsc PhaseFMR instrument with the magnetic field perpendicular to the Fe(100) plane. All depositions and measurements were performed at room temperature.

3. Results and discussion

3.1. Magnetic anisotropy and magnetic dragging effect

Figure 2(a) shows schematically the stacked samples and the in-plane FMR configuration. The representative VNA-FMR spectra for various magnetic field angles $\varphi_f$ at fixed frequency 13.4 GHz are illustrated in figure 2(b). The VNA-FMR signal (the transmission parameter $S_{21}$) is a superposition of symmetric and antisymmetric Lorentzian functions, and is used to extract the resonance field $H_r$ and the resonance linewidth $\Delta H$ using the following expression:

![Figure 1.](image1.jpg)
H_{\text{eff}} = H_{r}(\cos(\varphi_{M} - \varphi_{H}) + H_d + H_A(3 + \cos 4\varphi_{M})/4 - H_2\sin^2(\varphi_{M} - 45^\circ)),

H_2 = H_r\cos(\varphi_{M} - \varphi_{H}) + H_4\cos 4\varphi_{M} + H_2\sin 2\varphi_{M}\text{ and } H_D = 4\pi M_{s} - \frac{2K_{\text{out}}}{M_{s}}.\text{ Here, } \gamma \text{ is the gyromagnetic ratio, } H_2, H_4, \text{ and } M_{s} \text{ are the uniaxial magnetic anisotropy field, the four-fold magnetocrystalline anisotropy field and saturation magnetization, respectively. } K_{\text{out}} \text{ is the out-of-plane uniaxial magnetic anisotropy constant. The equilibrium azimuthal angle of magnetization } \varphi_{M} \text{ is determined by the following equation } [32]:

H_r\sin(\varphi_{M} - \varphi_{H}) + (H_4/4)\sin 4\varphi_{M} + (H_2/2)\cos 2\varphi_{M} = 0.\text{ (3)}

The angular dependent FMR measurements were performed by rotating the samples in the Fe(001) plane while sweeping the applied magnetic field at a fixed microwave frequency of 13.4 GHz. The angular dependence of \(H_{r}\) can be derived from equation (2) and plotted in figures 2(c) and (d) for Cu/Fe(6 nm) and Pd(5 nm)/Fe(6 nm) films, respectively. It can clearly be seen that the angular dependent \(H_{r}\) possesses a four-fold symmetry, and we find that the values of \(H_2 = (0 \pm 2)\text{ Oe, } H_4 = (625 \pm 4)\text{ Oe and } H_D = (20.1 \pm 0.2)\text{ KOE for Pd(5 nm)/Fe (6 nm) and } H_2 = (0 \pm 3)\text{ Oe, } H_4 = (625 \pm 7)\text{ Oe and } H_D = (19.0 \pm 0.4)\text{ KOE for Cu/Fe(6 nm). Compared to the reference sample Cu/Fe(6 nm), the Pd(5 nm)/Fe(6 nm) film shows an enhancement of } H_D \text{ perhaps because the values of } K_{\text{out}} \text{ should be slightly different for Pd/Fe and Cu/Fe considering the same } M_{s} \text{ for the Fe(6 nm) films. Otherwise, the other magnetic anisotropic parameters of Pd(5 nm)/Fe(6 nm) are consistent with those of Cu/Fe(6 nm).}

For epitaxial Fe films with a strong magnetocrystalline anisotropy field, the magnetization will not always align in the direction of the applied magnetic field, and the precession trajectory is distorted elliptically. This so-called magnetic dragging effect will broaden the linewidth [12, 13, 33]. Here, we evaluated the magnetic dragging during the in-plane angular or frequency dependent FMR measurements based on numerical calculations using equation (3) and the magnetic anisotropy parameters of Pd(5 nm)/Fe(6 nm). Figure 3(a) shows the dependence of } \varphi_{M} \text{ on } \varphi_{H} \text{ at 13.4 GHz. The angle deviation } \left| \varphi_{H} - \varphi_{M} \right| \text{ reveals a conspicuous magnetic dragging effect with a}
four-fold symmetry. At $\varphi_H = 25^\circ$, $|\varphi_M - \varphi_H|$ is as high as $12^\circ$. Meanwhile, $\varphi_M$ dependence on $f$ at various $\varphi_H$ is shown in figure 3(b). With the magnetic field along the easy axis Fe(100) or hard axis Fe(110), the magnetization is always aligned along the applied magnetic field. For the field along intermediate axis, such as $\varphi_H = 10^\circ$, 20$^\circ$, 30$^\circ$, 40$^\circ$, the magnetization is not parallel to the magnetic field directions. For instance, the angle deviation $|\varphi_M - \varphi_H|$ is $5^\circ$ at $\varphi_H = 20^\circ$ even though the resonance frequency is up to 18 GHz. In addition, the magnetic dragging effect for the case of a perpendicular geometry (i.e. the magnetic field is perpendicular to the plane Fe(100)) was also evaluated in the supplementary materials. It can be seen that the magnetic dragging effect vanishes when the applied magnetic field is larger than $\sim 20$ KOe.

3.2. Spin pumping in Pd/Fe bilayers

To preclude the degenerate magnon modes, we performed the out-of-plane FMR [34]. Figure 4(a) shows the frequency dependence of $\Delta H$ with the magnetic field perpendicular to the plane Fe(100). The Gilbert damping $\alpha_{\text{eff}}$ can be obtained using the linear relationship [28]:

$$\Delta H = \frac{4\pi\alpha_{\text{eff}} f}{\gamma} + \Delta H_0$$

Here, $\gamma$ and $\Delta H_0$ are the gyromagnetic ratio and the inhomogeneous non-Gilbert linewidth at zero-frequency, respectively [29–31]. $\Delta H$ versus $f$ can be fitted linearly with $\alpha_{\text{eff}} = (6.0 \pm 0.1) \times 10^{-3}$ and $(4.2 \pm 0.1) \times 10^{-3}$ for Pd(5 nm)/Fe(6 nm) and Cu/Fe(6 nm) samples, respectively. We also present the Pd thickness $t_{\text{Pd}}$ dependence of Gilbert damping with a fixed thickness of 6 nm Fe in figure 4(b). According to the spin pumping model [14], precessional magnetization in the FM layer will pump spins into adjacent nonmagnetic metals across the interface. Since Cu only contains an s conduction band with a small spin-flip probability and a larger spin diffusion length than 500 nm, the Gilbert damping of the Fe film will not increase with thin Cu capping layers [35]. Therefore, we can use Cu/Fe as a reference sample to extract the local Gilbert damping, where the thickness of Cu (3.5 nm) is thick enough to prevent oxidation of the Fe layer. In contrast, Pd has a larger spin-flip probability due to its strong spin–orbit coupling and the injected spin currents are thus dissipated in the Pd layer.
introducing a non-local Gilbert damping. The experimental results of figure 4(b) can be described by [36]:

\[
\alpha_{\text{eff}} = \alpha_0 + \frac{\mu_B}{4\pi M_s t_{\text{Fe}}} g^{\text{eff}} [1 - \exp(-2t_{\text{Pd}}/\lambda_{\text{Pd}})].
\]  

(5)

Here, \( g, \mu_B, t_{\text{Fe}} \) and \( \alpha_0 \) are the Lande g-factor, the Bohr magneton, Fe thickness and the local damping of Fe, respectively. The fitting gives the spin diffusion length \( 6.2 \pm 1.4 \) \( \text{nm} \) and the spin mixing conductance \( 1.37 \pm 0.12 \times 10^{-2} \) \( \text{across the Pd/Fe interface} \), which are both comparable to literature values [36–38]. In order to confirm the spin pumping effect, we also carried out inverse spin Hall effect measurements (see figure S3 of supplementary materials is available online at stacks.iop.org/NJP/21/103040/mmedia). The enhancement of Gilbert damping in Pd/Fe films allows us to comprehend the dependence of the non-local relaxation on magnetization orientation.

### 3.3. Disentanglement of magnetic relaxation channels

The in-plane angular dependence of \( \Delta H \) is used to distinguish the diverse magnetization relaxation paths. As shown in figures 5(a) and (b), \( \Delta H \) indicates a four-fold symmetry with multiple extrema. Taking both intrinsic and extrinsic contributions into account, \( \Delta H \) is followed by the expression to understand the anisotropic linewidth \( \Delta H \) in figure 4 [39–43]:

\[
\Delta H = \Delta H_{\text{TMS}} + \Delta H_{\text{mosaicy}} + \Delta H_{\text{Gilbert\_dragging}}.
\]  

(6)

The first term denotes two-magnon scattering (TMS), representing that a uniform precession magnon \( (k = 0) \) is scattered into a degenerate magnon \( (k \neq 0) \) due to imperfect crystal structure. Therefore, the TMS linewidth relies on the symmetrical distribution of defects and manifests anisotropic features. In the case of Fe epitaxial films on MgO(001), the TMS linewidth is composed of numerous four-fold TMS channels [40–43]

\[
\Delta H_{\text{TMS}} = \sum_j \Gamma_{j,\text{max}}^{\text{fourfold}} \cos^2(\varphi_j - \varphi_{j,\text{max}}^{\text{fourfold}}).
\]  

(7)

Here, \( \Gamma_{j,\text{max}}^{\text{fourfold}} \) and \( \varphi_{j,\text{max}}^{\text{fourfold}} \) represent the TMS strength and the angle of the maximum scattering rate in four-fold scatterings along the direction \( j \), respectively. The second term of equation (6) describes the mosaicity contribution in the film’s plane, which is caused by the fluctuation of magnetic parameters on a very large scale. The angular dependence of mosaicity contribution can be described as [41, 43]

\[
\Delta H_{\text{mosaicy}} = \left| \frac{\partial H_\varphi}{\partial \varphi_H} \right| \Delta \varphi_H,
\]  

(8)

where \( \Delta \varphi_H \) represents the in-plane variation of mosaicity. The last term \( \Delta H_{\text{Gilbert\_dragging}} \) is the Gilbert damping contribution stemming from magnetic dragging. Owing to magnetic dragging (see figure 3(a)), \( \Delta H \) corresponding to Gilbert contribution should be disclosed according to the following equations [12, 13]

\[
\Delta H_{\text{Gilbert\_dragging}} = \Delta [\text{Im}(\chi)].
\]  

(9)
and

\[ \text{Im}(\chi) = \frac{4\pi M_s \alpha_{\text{eff}} \sqrt{H_a^R H_b^R} [H_a H_a + H_a^R H_b^R]}{(H_a H_b - H_a^R H_b^R)^2 + \alpha_{\text{eff}}^2 H_a^R H_b^R (H_a + H_b)^2}, \]  

where \( H_a \) and \( H_b \) are \( H_a^R \) and \( H_b^R \) in non-resonance condition. \( \text{Im}(\chi) \) represents the imaginary part of the dynamic magnetic susceptibility \( \chi \), and \( \Delta \text{Im}(\chi) \) corresponds to the linewidth of \( \text{Im}(\chi) \). The effective parameter \( \alpha_{\text{eff}} \) consists of the local Gilbert damping and the non-local one driven by spin pumping. The Gilbert damping contribution to linewidth along various directions is evaluated by assuming that Gilbert damping is isotropic and equal to the values extracted in the perpendicular FMR (figure 4).

As shown in figures 5(a) and (b), the contributions of TMS, mosaicity, and Gilbert damping with magnetic dragging are separated from the angular dependence of \( \Delta H \) for Cu/Fe(6 nm) and Pd(5 nm)/Fe(6 nm) samples. Table 1 summarizes the fitted parameters in the samples. It is worth mentioning that the contribution of Gilbert damping with magnetic dragging results in giant anisotropic linewidth. Furthermore, the TMS contribution with \( \gamma \Gamma_{<100>} = (5.8 \pm 0.3) \times 10^8 \text{ Hz} \) along Fe(100) causes a four-fold linewidth broadening in the reference sample Cu/Fe(6 nm). In contrast, we observe a significant reduction of mosaicity broadening and a negligible TMS term in Pd(5 nm)/Fe(6 nm) bilayers. Consequently, a fully epitaxial structure could significantly decrease the extrinsic contributions, and thereby offers a great advantage in accurately determining Gilbert damping along various directions.

**Table 1.** The fitted magnetic anisotropy parameters and magnetic relaxation parameters in Pd(5 nm)/Fe (6 nm) and Cu/Fe(6 nm) films in figures 2 and 5.

| Sample   | \( H_4 \) (Oe) | \( H_2 \) (Oe) | \( H_d \) (KOe) | \( \alpha_{\text{eff}} \) | \( \gamma \Gamma_{<100>} \) (10^7 Hz) | \( \Delta \varphi \) (deg.) |
|----------|----------------|----------------|----------------|----------------|-----------------|----------------|
| Pd/Fe    | 625(4)         | 0(2)           | 20.1(2)        | 0.0060(1)      | 0(2)            | 0.23(5)        |
| Cu/Fe    | 625(7)         | 0(3)           | 19.0(4)        | 0.0042(1)      | 58(3)           | 1.26(8)        |

Figure 5. The measured linewidth \( \Delta H \) as a function of \( \varphi_{\parallel} \) at 13.4 GHz for Pd(5 nm)/Fe(6 nm) (a) and Cu/Fe(6 nm) (b). The linewidth \( \Delta H \) is superimposed by several terms, such as TMS, mosaicity and Gilbert contribution with magnetic dragging.
3.4. Determination of isotropic non-local Gilbert damping both experimentally and theoretically

Although the magnetization relaxation paths have been identified as mentioned above, the values of Gilbert damping along different directions still need to be accurately determined using the frequency dependent FMR measurements. The frequency dependence of $H_i$ at various directions can be fitted well by equation (2) using the magnetic anisotropy parameters in table 1, as shown in figures 6(a)–(e). Figures 6(f)–(j) show the frequency dependence of $\Delta H$ at various directions. The $\Delta H$ versus $f$ curves show the simple linear relations at $\varphi_H = 0^\circ$ (the magnetic field along the Fe(100)) and $\varphi_H = 45^\circ$ (the magnetic field along the Fe(110)). For other directions, nonlinear relations between $\Delta H$ and $f$ are evident and illustrated in figures 6(g)–(i). At $\varphi_H = 20^\circ$ (figures 6(g)), the $\Delta H$ versus $f$ curve exhibits a slight bump compared to the linear ones along hard or easy axes. At $\varphi_H = 27^\circ$ (figure 6(b)), $\Delta H$ rises rapidly and then goes through a maximum before decaying at higher frequency. At $\varphi_H = 33^\circ$ (figure 6(i)), $\Delta H$ decreases more sharply after 11 GHz. Considering the huge magnetic dragging effect based on the calculation in figure 4(b), the experimental data $\Delta H$ versus $f$ should be fitted using the equation (6) in association with the original formulas (9) to obtain Gilbert damping at various directions [13]. The frequency dependence of $\Delta H$ at various directions can be well reproduced, as shown in figures 6(f)–(j).

The Gilbert damping $\alpha_{\text{eff}}$ along various directions is shown in figure 7(a). It can be seen that the Gilbert damping is insensitive to the magnetization orientation for samples Cu/Fe(6 nm), Pd(1 nm)/Fe(6 nm) and Pd(5 nm)/Fe(6 nm). Their effective Gilbert damping parameters are around $4.2 \times 10^{-3}$, $4.6 \times 10^{-3}$ and $6.0 \times 10^{-3}$, respectively. Kambersky’s theory can account for the isotropic Gilbert damping of the reference sample Cu/Fe(6 nm) (21, 33) [4]. In the microscopic picture, the Gilbert damping in metallic ferromagnets hinges on the intraband transitions $(\alpha \propto \xi n(E^f_H)\tau_m)$ and the interband transitions $(\alpha \propto \xi n(E^f_H)\tau_{\text{ax}}$). Here, $\tau_{\text{ax}}$, $\zeta$ and $n(E^f_H)$ are the momentum relaxation time, spin–orbit coupling constant and density of electronic states at the Fermi surface, respectively. The interband transitions dominate damping and favor isotropic local damping at room temperature for the reference sample Cu/Fe(6 nm) [9, 44]. In contrast, the total Gilbert damping of Pd/Fe $\varphi_{\text{PD}}$, including the local damping of Fe and the non-local loss channel of angular momentum due to Pd layer, is also dependent of Fe magnetization orientation, shown in figure 6(a). Therefore, the non-local relaxation driven by spin pumping shows an isotropic behavior when comparing the damping parameters between Pd/Fe and Cu/Fe. According to the Elliott–Yafet mechanism in a nonmagnetic cubic metal, spins will indiscriminately and isotropically relax energy and momentum along all orientations in the Pd layer since a cubic Pd metal is expected to possess a weak anisotropy of the Elliott–Yafet parameter [45]. As a consequence, the isotropic non-local relaxation reveals that the spin transport across interface Pd(100) [110]/Fe(001) [100] is independent of the Fe magnetization orientation.

To describe the spin transport across the Pd/Fe interface, the non-local Gilbert damping $\Delta \alpha$ is parameterized by the effective spin mixing conductance $g_{\text{eff}}^{11}$ [36]:

$$\Delta \alpha = \alpha_{\text{PD}} - \alpha_{\text{Cu}} = \frac{\mathcal{S}_{\text{PD}}}{4\pi M_{\text{eff}}} g_{\text{eff}}^{11}$$

(11)

Figure 7(b) presents that the experimental values $g_{\text{eff}}^{11}=1.23 \pm 0.07 \times 10^{19}$ m$^{-2}$ are insensitive to the magnetization orientation for Pd(5 nm)/Fe(6 nm) film.

In order to theoretically investigate the dependence of spin transport on the magnetization orientation, the first principles calculation was performed to calculate the total Gilbert damping of the Pd(5 nm)/Fe/Pd(5 nm) multilayer on the basis of the scattering theory [46–48]. The electronic structure of the Pd/Fe interface was calculated self-consistently using the surface Green’s function technique implemented with the tight-binding linearized muffin-tin orbitals method. Within the atomic sphere approximation, the charge and spin densities and the effective Kohn–Sham potentials were evaluated inside atomic spheres [49]. The total Gilbert damping was then calculated using the scattering theory of magnetization dissipation [48]. We simulated the room temperature via introducing frozen thermal lattice disorder into a 5 $\times$ 5 lateral supercell [46]. The root-mean-squared displacement of the atoms is determined by the Debye model with the Debye temperature 470 K. A $28 \times 28$ k-mesh is used to sample the two-dimensional Brillouin zone and five different configurations of disorder have been calculated for each Fe thickness. The total Gilbert damping exhibits a linear dependence on the length of Fe and the intercept of the linear function can be extracted corresponding to the contribution of the spin pumping at the Pd/Fe interface [47]. The interfacial contribution is converted to the effective spin mixing conductance, plotted in figure 7(b) as a function of the magnetization orientation. It can be seen that the effective spin mixing conductance across Pd/Fe interface $g_{\text{eff}}^{11} = (1.29 \pm 0.02) \times 10^{19}$ m$^{-2}$ is independent of the magnetization direction, and is in very good agreement with the experimental value $(1.23 \pm 0.07) \times 10^{19}$ m$^{-2}$. Besides, the first principles calculation was also performed to calculate the out-of-plane spin mixing conductance, which is also independent of magnetization orientation (see figure S5 of supplementary materials).
Figure 6. Frequency dependence of the resonance field $H_r$ (a)–(e) and frequency dependence of the resonance linewidth $\Delta H$ (f)–(j) for Pd(5 nm)/Fe(6 nm) at various $\phi_H$. The green solid squares and curves in (f) and (i) corresponding to frequency dependence of $\Delta H$ at $\phi_H = 0^\circ$ and $\phi_H = 45^\circ$ for Cu/Pd(6 nm).
4. Conclusions

In summary, we have investigated the non-local Gilbert damping driven by spin pumping in epitaxial Pd/Fe films. The Gilbert contribution can result in the anisotropic $H_D$ and the nonlinear $H_D$ versus $f$ relations (except for when the magnetic field aligns along hard or easy axes) due to the magnetic dragging effect. Extrinsic relaxation, such as TMS and mosaicity, also relies on magnetization orientation. It is noteworthy that an isotropic non-local Gilbert damping is clarified adequately after ruling out the misleading magnetic dragging and extrinsic contributions. Magnetization orientation has a negligible contribution to the non-local Gilbert damping based on both theoretical and experimental results, revealing that the spin transport across the interface Pd(100)[110]/Fe(001)[100] is independent of the Fe magnetization orientation.

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