Deterministic field-free switching of a perpendicularly magnetized ferromagnetic layer via the joint effects of the Dzyaloshinskii–Moriya interaction and damping- and field-like spin–orbit torques: an appraisal

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Abstract
Field-free switching of a perpendicularly magnetized ferromagnetic layer by spin–orbit torque (SOT) from the spin Hall effect is of great interest in the applications of magnetic memory devices. In this paper we investigate by micromagnetic simulations the possibility of deterministic field-free switching by combining SOT with the Dzyaloshinskii–Moriya interaction (DMI). We confirmed that within a certain range of DMI values and charge current densities, it is possible to deterministically switch the magnetization without the assistance of an external magnetic field. SOT terms including Slonczewski-like (damping-like) torque and field-like torque (FLT) are considered when analyzing the SOT switching and domain wall dynamics. We show that the FLT could play an adverse role in blocking and slowing down the magnetization switching under certain cases of DMI and charge current-driven field-free switching. However, in other cases, FLT assists DMI in the deterministic field-free SOT switching. In addition, it is found that FLT can effectively expand the current density window for deterministic field-free SOT switching in the presence of DMI.

Keywords: spin–orbit torque, Dzyaloshinskii–Moriya interaction, field-like torque, field-free switching, spin Hall effect

(Some figures may appear in colour only in the online journal)

1. Introduction

Recently, there have been extensive experiments on the demonstration of deterministic switching of perpendicularly magnetized layers in heavy metal/ferromagnet (HM/FM) structures with large spin–orbit coupling, offering a new route towards high-speed and low-power-storage applications [1–9]. Specifically, in this HM/FM structure, an in-plane charge current is applied to the HM layer to generate an out-of-plane spin-polarized current due to the strong spin–orbit interactions. The spin torque from the spinpolarized current is transferred to the FM layer and induces magnetization switching. This switching mechanism has led to spin–orbit torque magnetic random access memory
Figure 1. (a) Sketch of field-free SOT switching in a HM/FM structure. The FM circular dot with perpendicular magnetic anisotropy is on top of an HM stripe. An FM circular dot with a diameter of 100 nm is assumed. Charge current pulses are injected along the HM channel (x-axis). The directions of the spin polarization $\sigma$ of the injected electrons, the unit magnetization vector $m$, and the torques $\tau_{SL}$ and $\tau_{FL}$ relative to the coordinate axes are labeled on the right. (b) Temporal evolutions of the perpendicular magnetization component, $m_z$, under various DMI conditions ($DMI = 0$ and 0.5 mJ m$^{-2}$) without the assistance of FLT $\tau_{FL}(R = 0)$. (c) Temporal evolutions of the perpendicular magnetization component, $m_z$, under various field-like torque conditions ($R = 0$ and $R = 0.05$) with DMI = 0.8 mJ m$^{-2}$. The charge current pulse $J_e$ is applied during a time window of 5 ns (the shaded region). Note: $m_z$ is the averaged perpendicular magnetization component of the FM layer.

Table 1. Simulation parameters.

| Parameter                          | Description                               | Values                     | Ref.     |
|------------------------------------|-------------------------------------------|----------------------------|----------|
| FM layer dimensions                | Diameter $\times$ thickness               | 100 nm $\times$ 1 nm       | This paper|
| Cell size                          | Length $\times$ width $\times$ thickness  | 2 nm $\times$ 2 nm $\times$ 1 nm | This paper|
| $\gamma$                           | Gyromagnetic ratio                        | $2.21 \times 10^5$ m A$^{-1}$ s | Constant|
| $\mu_0$                            | Vacuum permeability                       | $4\pi \times 10^{-7}$ H m$^{-1}$ | Constant|
| $\alpha$                           | Gilbert damping factor                    | 0.1                        | [33, 51, 52]|
| $A_{ex}$                           | Exchange constant                         | $2 \times 10^{-11}$ J m$^{-1}$ | [20, 33, 53, 54]|
| $M_s$                              | Saturation magnetization                  | $1.1 \times 10^6$ A m$^{-1}$ | [20, 33]|
| $\theta_{SHA}$                     | Spin Hall angle                           | 0.3                        | [33, 55, 56]|
| $K_x$                              | Intrinsic perpendicular anisotropy of FM layer | $8 \times 10^5$ J m$^{-3}$ | [20, 33]|
| $H_K$                              | Perpendicular anisotropy field            | 1.45 T                     | $H_K = 2K_x/M_s$|
| DMI                                | Dzyaloshinskii–Moriya interaction factor  | 0–1.0 mJ m$^{-2}$          | [48–50]|
| $R(=\frac{\tau_{FL}}{\tau_{SL}} = \frac{\epsilon'}{\epsilon})$ | Ratio of FLT to SLT                        | 0, 0.01, 0.03, 0.05, 0.1, 0.3 | [57, 58]|
| $J_e$                              | Charge current density                    | 0.5–$1.5 \times 10^{12}$ A m$^{-2}$ | This paper|
Figure 2. Field-free SOT switching of the perpendicularly magnetized FM circular dot without the effect of FLT $\tau_{FL}$. Temporal evolutions of the perpendicular magnetization component $m_z$ under various DMI and $J_e$ conditions. Blue lines indicate successful magnetization switching, green lines indicate that the magnetization is switched to the $x$–$y$ plane, and red lines indicate a failure in magnetization switching where the magnetization returns to its previous state (+$z$ direction) after the removal of the current pulse. The charge current pulse $J_e$ is applied during a time window of 5 ns (the shaded region).

(MRAM) [10–14]. The spin torque contributes to the magnetic dynamics in the FM layer and it is described by the Landau–Lifshitz–Gilbert–Slonczewski (LLGS) equation. However, the injected spin-polarized current simply drives the magnetization from out-of-plane to in-plane, so conventional spin–orbit torque (SOT) switching requires an external in-plane magnetic field that is collinear with the charge current for stable bidirectional magnetization switching, which is a major challenge for practical realization of devices [15].

Recently, the ability to perform SOT switching without an external field is of great interest for applications. To realize field-free SOT switching of a perpendicular magnetization, many works have been reported, such as adding a bias layer [16–19]. However, this complicates the fabrication process and potentially reduces the memory density [20]. Other methods such as using the assistance of an antiferromagnetic (AFM) layer, a tilted anisotropy, and broken lateral inversion asymmetry have also been reported [21–25].

On the other hand, it has been shown that the Dzyaloshinskii–Moriya interaction (DMI) plays an important role in SOT switching as well as domain wall motion [26–31]. The chiral effective field arising from DMI at the FM and HM interfaces along with the spin-polarized current may contribute to the deterministic field-free switching of a perpendicularly magnetized FM layer [27, 32–35]. Perez et al reported that in a perpendicularly magnetized HM/FM system, a large DMI could lead to stable helical magnetization strips in the switching region, giving rise to intermediate states in the magnetization and proving the essential role of DMI in switching processes [27]. Later in 2015, Mikuszeit et al confirmed that in such an HM/FM system, the SOT-induced magnetization switching in the presence of DMI is governed by the domain nucleation on one edge and followed by the domain wall propagation to the opposite edge [36]. The switching is completed by the current-driven domain wall propagation, where the switching current amplitude decreases with increasing amplitude of the DMI and the switching current direction determines the direction of the wall movement [34, 36]. Chen et al pointed out the possibility of field-free SOT switching with DMI, where a parametric
window enabling field-free SOT switching in a perpendicular ferromagnet is established [33]. Lee et al reported the experimental demonstration of field-free SOT switching by exploiting the domain wall motion in an anti-notched microwire with perpendicular anisotropy. The combination of SOT, DMI, and domain wall surface-tension-induced geometrical pinning allows a deterministic control of the domain wall and achieves field-free SOT switching [37].

Furthermore, Slonczewski-like (damping-like) torque (SLT or DLT) has been mainly used to analyze SOT switching and domain wall dynamics [38–41]. However, the role of field-like torque (FLT) has not been paid much attention in most SOT switching works. Until now, the role of FLT in SOT switching has remained vague. Recent works have pointed out that the FLT can be much larger than SLT in some material combinations and it is possible to use FLT to switch the magnetization [42, 43]. In this regard, we investigate the role of DMI and FLT in deterministic field-free SOT switching. This paper focuses on the dynamic switching in a perpendicularly magnetized multilayer FM layer (circular dot with diameter of 100 nm) via the joint effects of DMI and FLT. Our results show that for FLT within a certain value range, it can assist in DMI-induced deterministic field-free SOT switching; however, for other cases, FLT impedes deterministic switching.

2. Theoretical approach

The LLGS equation including DMI and SOT terms is expressed as:

\[ \frac{\partial \mathbf{m}}{\partial t} = - \gamma |\mathbf{M}| \mathbf{m} \times \mathbf{H}_{\text{eff}} + \alpha m \times \frac{\partial \mathbf{m}}{\partial t} + \tau_{\text{SL}} + \tau_{\text{FL}} \]

where \( m = \frac{\mathbf{M}}{|\mathbf{M}|} \) is the unit magnetization vector, \( \mathbf{H}_{\text{eff}} \) is the effective field, \( \alpha \) is the Gilbert damping parameter, and \( \gamma \) is the gyromagnetic ratio.

The SOT can be described as the sum of longitudinal SLT (DLT) \( \tau_{\text{SL}} \) and the transverse field-like torque \( \tau_{\text{FL}} \):

\[ \tau_{\text{SL}} = |\gamma| \beta (\sigma \times m) \times \sigma \]

\[ \tau_{\text{FL}} = |\gamma| \beta' (\sigma \times m) \]

where \( \beta = \frac{\hbar J_p}{|\mathbf{e}| M_s \gamma F} \)

\[ \beta' = \frac{\hbar J_e}{|\mathbf{e}| M_s \gamma F} \]

\[ \tau_{\text{DMI}} = \frac{\hbar}{2} \beta' \epsilon (\sigma \times m) \]

\[ \tau_{\text{DLT}} = \frac{\hbar}{2} \beta (\sigma \times m) \]

\[ \tau_{\text{DMT}} = \frac{\hbar}{2} \beta' \epsilon (\sigma \times m) \]

where \( \epsilon \) is the elementary charge, \( J_p \) is the thickness of the FM layer, and \( J_e \) is the charge current density flowing in the HM (we assume \( J_e \) flows along the \( x \)-axis in this paper). We describe the magnitudes of \( \tau_{\text{SL}} \) and \( \tau_{\text{FL}} \) by their efficiencies \( \epsilon \) and \( \epsilon' \). In an HM/FM structure:

\[ \epsilon = \frac{\theta_{\text{SHA}}}{2} \]

Figure 3. Deterministic field-free spin–orbit torque switching window for varying DMI values, charge current densities \( J_e \), and FLT \( \tau_{\text{FL}} \) for the FM circular dot. (a) Without the FLT \( \tau_{\text{FL}} \). (b) With the FLT \( \tau_{\text{FL}}, R = \tau_{\text{SL}}/\tau_{\text{FL}} = 0.05 \). The blue and black regions indicate successful magnetization switching, and the green region indicates that the magnetization is switched to the \( x-y \) plane, and the red and grey regions indicate a failure in magnetization switching where the magnetization returns to its previous state (+z direction) after the removal of the current pulse.
Figure 4. Field-free SOT switching of the FM circular dot in the presence of FLT $\tau_{FL}$. $R = \tau_{FL}/\tau_{SL} = 0.05$. Temporal evolutions of the perpendicular magnetization component $m_z$ under various DMI and $J_e$ conditions. Blue lines indicate successful magnetization switching, green lines indicate that the magnetization is switched to the $x$–$y$ plane, and red lines indicate a failure in magnetization switching where the magnetization returns to its previous state ($+z$ direction) after the removal of current pulse. The charge current pulse $J_e$ is applied during a time window of 5 ns (the shaded region).

where $\theta_{SHA}$ is the spin Hall angle of the HM layer.

The directions of the SOTs $\tau_{SL}$ and $\tau_{FL}$ are determined by the spin polarization $\sigma$ of the injected electrons, which, from the spin Hall effect, is perpendicular to the spin current and the charge current directions (as shown in figure 1(a), it is either along the $+y$ or $-y$ direction).

In this work, we explore the joint effects of DMI and FLT $\tau_{FL}$ on the deterministic field-free switching of a perpendicularly magnetized ferromagnetic layer. The typical values of DMI vary from that reported in different works [48–50]. Herein, we assume the DMI value varies from 0 to 1 mJ m$^{-2}$.

The contribution of FLT $\tau_{FL}$ is characterized by a dimensionless ratio $R$ as listed in table 1.

Herein, we perform simulation using the Object-Oriented Micro-Magnetic Framework (OOMMF) public code by numerically solving the LLGS equation [59, 60]. The OOMMF package ‘Oxs_DMExchange6Ngbr’ is used to introduce the DMI term. The parameters used in this OOMMF simulation are listed in table 1. The FM layer is assumed to be circular with a diameter of 100 nm and thickness of 1 nm, and is discretized into 2 nm $\times$ 2 nm $\times$ 1 nm cells for calculations. For all the simulations in this paper, the initial magnetization configuration of the FM layer is set as $[m_x, m_y, m_z] = [0.001, 0, 1]$ and relaxed for 3 ns before a current with a pulse width of 5 ns is applied, followed by another 5 ns of relaxation. Thus, the magnetic dynamics in the FM layer are recorded in a 13 ns time window.

It has been reported that the DMI assists in the deterministic field-free SOT switching of a perpendicular ferromagnet [33]. Figure 1(b) shows the simulated temporal evolution of the perpendicular magnetization component $m_z$ with and without the assistance of the DMI term. For the case with DMI = 0.5 mJ m$^{-2}$, $m_z$ becomes negative ($-z$ direction) within 1 ns from the onset of charge current, resulting in deterministic magnetization switching in the FM layer. However, under the same condition but without the presence of the DMI term, $m_z$ approaches 0 (magnetization switches to the $x$–$y$ plane), which leads to a non-deterministic state when
Figure 5. Adverse effect of FLT on the field-free SOT switching in the FM circular dot in the presence of DMI (the current pulse is applied within the shaded region). DMI = 0.5 mJ m$^{-2}$ and $J_e = 0.8 \times 10^{12} \text{A/m}^2$. (a) Temporal evolutions of the perpendicular magnetization component $m_z$ under various $R$ conditions. Note: $m_z$ is the averaged perpendicular magnetization component of the FM layer. (b) Snapshots of magnetization profiles before ($t = 2.5$ ns), during ($t = 3.5, 4.5, \text{and} 7.5$ ns), and after ($t = 8.1 \text{and} 13$ ns) the application of charge current pulses. The red and blue regions represent $m_z$ along the $+1 \text{ and} -1$ directions, respectively. The white region represents magnetization in the $x$–$y$ plane. (c)–(e) Temporal evolutions of the $m_x$, $m_y$, and $m_z$ components during one magnetization switching period. (c) DMI = 0.5 mJ m$^{-2}$, $R = 0$, and $J_e = 0.8 \times 10^{12} \text{A/m}^2$. (d) DMI = 0.5 mJ m$^{-2}$, $R = 0.05$, and $J_e = 0.8 \times 10^{12} \text{A/m}^2$. (e) DMI = 0.5 mJ m$^{-2}$, $R = 0.3$, and $J_e = 0.8 \times 10^{12} \text{A/m}^2$. (f) Relative directions of magnetization, spin polarization, SLT (DLT) $\tau_{SL}$ and FLT $\tau_{FL}$ acting on the domain wall where magnetization is in-plane (white region in (b)).

the current is removed. It is also reported that the FLT $\tau_{FL}$ assists in the deterministic field-free SOT switching for single-domain devices (macrospin mode) with a uniform magnetization [61]. In some scenarios where the DMI alone is unable to achieve deterministic field-free SOT switching (black curve in figure 1(c)), a small FLT $\tau_{FL}$, $R = \tfrac{2\pi}{\tau_{SL}} = 0.05$ is able to assist in successful magnetization switching (red curve in figure 1(c)).

3. Results

3.1. Deterministic field-free switching via DMI

The deterministic field-free SOT switching of a perpendicular ferromagnet with DMI has been reported in another paper published in 2019 [33]. Herein, we reproduced the previous work by investigating the magnetization switching behaviors of the perpendicular magnetized FM layer without considering the effect of FLT $\tau_{FL}$ ($R = 0$). Figure 2 shows the temporal evolutions of out-of-plane magnetization component $m_z$ under different combinations of charge current densities and DMI values. At low charge current density $j_e = 0.5 = 0.5 \times 10^{12} \text{A/m}^2$, below the critical switching current, magnetization switching fails for both DMI and non-DMI cases (bottom row in figure 2). This is because the SOT only leads to a slight tilting of the magnetization during a current pulse, while the magnetization relaxes towards its initial equilibrium state after the removal of the current pulse. On the other hand, with high charge current density $j_e = 1.5 = 1.5 \times 10^{12} \text{A/m}^2$, the magnetization is trapped in the $x$–$y$ plane for both DMI and non-DMI cases (top row in figure 2). This is due to the fact that the propagation of the domain wall becomes oscillatory under higher currents, and the coherence of the switching is destroyed [36]. As is expected, deterministic field-free SOT switching of a perpendicularly magnetized FM layer is unachievable without the DMI term ($DMI = 0 \text{ mJ m}^{-2}$, the first column on the left in figure 2). With intermediate charge current densities and DMI values, successful magnetization switching is achieved at different combinations of DMI and $J_e$ values (blue lines in figure 2).

We also carried out OOMMF simulations with other DMI and $J_e$ values to investigate deterministic field-free switching
without the FLT term $\tau_{FL}$. The charge current density $J_e$ is varied from $0.5 \times 10^{12}$ to $1.5 \times 10^{12}$ A m$^{-2}$ with a step value of $0.1 \times 10^{12}$ A m$^{-2}$, and the DMI value is varied from 0 to 1.0 mJ m$^{-2}$ with a step value of 0.1 mJ m$^{-2}$. Figure 3(a) summarizes the deterministic field-free SOT switching results for different combinations of DMI and $J_e$ values for a circular device of 100 nm diameter. The out-of-plane magnetization components $m_z$ at the 13th ns are summarized in figure 3 to investigate the magnetization switching results, where $m_z = -1$ indicates successful magnetization switching (blue regions), $m_z = -1$ indicates a failure in magnetization switching (red regions), and $m_z = 0$ indicates that the magnetization is switched to the x-y plane (green regions). Thus, the blue/black area in figure 3 represents the deterministic field-free SOT switching window.

3.2. Deterministic field-free switching via the joint effects of DMI and field-like torque

Furthermore, we added the FLT term $\tau_{FL}$ with magnitude $R = \tau_{FL}/\tau_{SL} = 0.05$ to the OOMMF simulations, and the deterministic field-free SOT switching results under different combinations of DMI and $J_e$ values are summarized in figure 3(b). By adding a small FLT term $\tau_{FL}$, the deterministic field-free SOT switching window expands compared to that from figure 3(a). We also noticed that for successful magnetization switching, as the DMI value increases, the critical charge current density $J_e$ increases (the stepped shape of the region in figure 3(b)). By adding an FLT term, the temporal evolutions of $m_z$ under different combinations of charge current densities and DMI values are plotted in figure 4.

3.3. Effect of field-like torque on deterministic field-free switching

In this section, we explore the effect of the FLT term $\tau_{FL}$ on deterministic SOT field-free switching. The strength of FLT $\tau_{FL}$ is characterized by the ratio of $R = \tau_{FL}/\tau_{SL}$ and, herein, we varied $R$ from 0 to 0.3 under different combinations of DMI and $J_e$ values. Figure 5 shows the adverse effect of FLT $\tau_{FL}$ on deterministic SOT field-free switching. When the charge current density and DMI are set as constants (DMI = 0.5 mJ/m$^2$ and $J_e = 0.8 \times 10^{12}$ A/m$^2$), successful magnetization switching is achieved without the

Figure 6. Adverse effect of FLT on the field-free SOT switching in the presence of DMI (the current pulse is applied within the shaded region). DMI = 1.0 mJ/m$^2$ and $J_e = 0.8 \times 10^{12}$ A/m$^2$. (a) Temporal evolutions of the perpendicular magnetization component, $m_z$, under various R conditions. Note: $m_z$ is the averaged perpendicular magnetization component of the FM layer. (b) Snapshots of magnetization profiles before ($t = 2.5$ ns), during ($t = 3.5, 4.5, 7.5$ ns), and after ($t = 8.1$ and $13$ ns) the application of charge current pulses. The red and blue regions represent magnetization switching (red regions), and the blue/black area in figure 6 indicates that the magnetization is switched to the out-of-plane magnetization components $m_z$.

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Figure 7. Supportive effect of FLT on the field-free SOT switching in the presence of DMI (the current pulse is applied within the shaded region). DMI = 0.5 mJ m$^{-2}$ and $J_e = 0.9 \times 10^{12}$ A/m$^2$. (a) Temporal evolutions of the perpendicular magnetization component $m_z$ under various $R$ conditions. Note: $m_z$ is the averaged perpendicular magnetization component of the FM layer. (b) Snapshots of magnetization profiles before ($t = 2.5$ ns), during ($t = 3.5, 4.5$, and $7.5$ ns), and after ($t = 8.1$ and $13$ ns) the application of charge current pulses. The red and blue regions represent $m_x$ and $m_y$, respectively. The white region represents magnetization in the $x$–$y$ plane. (c)–(e) Temporal evolutions of the $m_x$, $m_y$, and $m_z$ components during one magnetization switching period. (c) DMI = 0.5 mJ m$^{-2}$, $R = 0$, and $J_e = 0.9 \times 10^{12}$ A/m$^2$. (d) DMI = 0.5 mJ m$^{-2}$, $R = 0.03$, and $J_e = 0.9 \times 10^{12}$ A/m$^2$. (e) DMI = 0.5 mJ m$^{-2}$, $R = 0.3$, and $J_e = 0.9 \times 10^{12}$ A m$^{-2}$.

assistance of FLT ($R = 0$, black curve in figure 5(a)). DMI induces significant magnetization tilting at the edges of magnetic structures, resulting in asymmetric field-induced domain nucleation [36]. Figure 5(b) shows that the SOT-induced magnetization switching in the presence of DMI is governed by domain nucleation on one edge followed by propagation to the opposite edge. It has been reported that DMI plays an important role in forming a Néel-type domain wall in thin films, which can be driven efficiently by the SOT terms [62, 63]. The domain wall (white region in figure 5(b)), with in-plane magnetization, experiences an out-of-plane FLT $\tau_{FL}$ (see figure 5(f)) that tries to switch the magnetization to the perpendicular direction. Consequently, once a domain is nucleated by DMI, the FLT $\tau_{FL}$ drives the domain wall and leads to switching via domain expansion. The switching time $t_0$, defined by $m_z|_{t_0} = 0$, increases as $R$ increases, and the slope of $m_z(t)$ in figure 5(a) indicates that the switching time is related to a slower domain wall propagation. This is also confirmed by the magnetization profiles in figure 5(b) where the domain wall propagates at a slower rate in the second row ($R = 0.05$) compared to the bottom row ($R = 0$). As a result, as we increase the magnitude of FLT by increasing $R$, $m_z$ flips with a slower pace, and the magnetization fails to flip to the $-z$ direction when $R$ reaches 0.1. Herein, the FLT $\tau_{FL}$ impedes the field-free, deterministic switching in the presence of DMI. The temporal evolutions of the $m_x$, $m_y$, and $m_z$ components at $R = 0, 0.05$, and 0.3 are plotted in figures 5(c)–(e).

The adverse effect of FLT $\tau_{FL}$ on deterministic SOT field-free switching is very commonly seen. In addition, we also noticed that successful magnetization switching with the assistance of larger DMI values is more susceptible to the adverse effect of FLT $\tau_{FL}$. In figure 6, we show another case where DMI = 1.0 mJ m$^{-2}$ and $J_e = 0.8 \times 10^{12}$ A/m$^2$ can successfully switch the magnetization in the FM layer without the assistance of FLT. Compared to the case in figure 5, the DMI value is doubled and the charge current density is identical; however, the DMI-based field-free switching is blocked by the adverse effect of FLT $\tau_{FL}$ to $R = 0.03$. Similarly, the FLT slows down the speed of domain wall propagation as shown in the magnetization profiles in figure 6(b).

On the other hand, in some cases, we found a supportive effect of FLT $\tau_{FL}$ on the deterministic SOT field-free switching. As shown in figure 7, DMI = 0.5 mJ m$^{-2}$ and
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Figure 8. (a) Temporal evolutions of two consecutive charge current pulses applied to an HM/FM system. (b) Corresponding perpendicular magnetization component \( m_z \) at (b) DMI = 0.5 mJ m\(^{-2}\) and \( R = 0.05 \); (c) DMI = 0.5 mJ m\(^{-2}\) and \( R = 0.3 \).

\( J_e = 0.9 \times 10^{12} \) A/m is unable to switch the magnetization without the assistance of FLT \( (R = 0, \) black curve in figure 7(a)). However, within a certain range of magnitudes, the FLT assists in the deterministic field-free switching \( (R = 0.01, 0.03, 0.05, \) and 0.1 cases, corresponding to the red, green, blue, and cyan curves in figure 7(a)), while a larger FLT \( (R = 0.3, \) corresponding to the magenta curve in figure 7(a)) fails to reach deterministic switching.

This field-free SOT switching based on an HM/FM system allows for unipolar switching of magnetizations in a perpendicularly magnetized FM layer. By applying consecutive charge current pulses, it is possible to switch the magnetization back and forth. As shown in figure 8(a), two consecutive charge current pulses \( J_e = 0.8 \times 10^{12} \) A m\(^{-2}\) are applied to this system. For an HM/FM system with DMI = 0.5 mJ m\(^{-2}\) and \( R = 0.05 \), as shown in figure 8(b), the first current pulse is able to switch the magnetization from the +\( z \) to −\( z \) direction (proved in figure 5(b)); then the magnetization is relaxed for 3 ns followed by a second charge current pulse, which flips the magnetization from the −\( z \) to +\( z \) direction. In addition, for an HM/FM system with DMI = 0.5 mJ m\(^{-2}\) and \( R = 0.3 \), as shown in figure 8(c), it is impossible to flip the magnetization (proved in figure 5(b)); although two consecutive charge current pulses are applied, the magnetization relaxes back to the +\( z \) direction. These results prove that the field-free SOT switching in an HM/FM system is completely deterministic and allows for unipolar switching with unipolar charge current pulses.

4. Conclusions

In this paper, we carried out micromagnetic simulations on an HM/FM system to investigate the magnetization dynamics of deterministic field-free SOT switching in a perpendicularly magnetized FM circular dot. Different switching processes and results are recorded under different charge current densities, DMI values, and FLT values. The effects of DMI and current density on deterministic field-free switching performance are presented. We have mapped the current density window for deterministic switching via DMI only and via the joint effects of DMI and FLT for a FM circular dot of 100 nm diameter in figure 3. In section 3.1, we reproduced a previous 2019 paper by investigating the magnetization switching behaviors of a perpendicular ferromagnet via DMI, in the absence of FLT [33]. We got a similar deterministic field-free SOT switching window for varying DMI constants and current densities as shown in figure 3(a). In addition, we moved one step
Further by investigating the roles of DMI and FLT in deterministic field-free SOT switching. It is found that the FLT can effectively expand the current density window for deterministic field-free SOT switching, as shown in figure 3(b). We have also shown that the FLT can play an adverse role in blocking and slowing down the deterministic field-free switching via DMI. However, FLT is able to assist DMI in achieving successful deterministic field-free switching.

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Conflict of interest

The authors declare no conflict of interest.

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