Magnetization Dynamics Modulated by Dzyaloshinskii-Moriya Interaction in the Double-Interface Spin-Transfer Torque Magnetic Tunnel Junction

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Abstract
Currently double-interface magnetic tunnel junctions (MTJs) have been developed for enhancing the thermal stability barrier at the nanoscale technology node. Dzyaloshinskii–Moriya interaction (DMI) inevitably exists in such devices due to the use of the heavy-metal/ferromagnet structures. Previous studies have demonstrated the detrimental effect of DMI on the conventional single-interface spin-transfer torque (STT) MTJs. Here, in this work, we will prove that the detrimental effect of DMI could be almost eliminated in the double-interface STT-MTJ. This conclusion is attributed to the suppressing effect of Ruderman–Kittel–Kasuya–Yosida (RKKY) interaction on the DMI. Detailed mechanisms are analyzed based on the theoretical models and micromagnetic simulation results. Our work highlights the importance of appropriately controlling the DMI in the composite free layer of the double-interface STT-MTJ.

Keywords: Magnetic tunnel junction, Spin-transfer torque, Dzyaloshinskii–Moriya interaction, Ruderman–Kittel–Kasuya–Yosida interaction

Introduction
Magnetic random access memory (MRAM) is one of the most promising candidates for the next-generation non-volatile memory thanks to its low power consumption, high density, fast access speed, almost infinite endurance, and good compatibility with CMOS technology [1, 2]. The elementary device of the MRAM is the magnetic tunnel junction (MTJ), which is composed of a tunnel barrier sandwiched between two ferromagnetic layers (named pinned layer and free layer). Benefiting from the progress in the perpendicular anisotropy, the feature size of the MTJ has been scaled below 40 nm or even 1× nm [3–5]. However, a challenge for the sub-40 nm MTJ is to keep the adequate thermal stability barrier $E = \mu_0 M_s H_k V / 2$. (with $\mu_0$ the vacuum magnetic permeability, $M_s$ the saturation magnetization, $H_k$ the anisotropy field, $V$ the volume of the free layer). As indicated by this equation, $E$ decreases with the scaling of the MTJ, resulting in a reduction of data retention time. To overcome this challenge, double-interface MTJs were proposed for achieving sufficiently high $E$ at the sub-40 nm technology node [6–10]. By using two coupled ferromagnetic layers as the composite free layer, the equivalent volume ($V$) in the double-interface MTJ is increased in order to enhance the thermal stability barrier. Meanwhile, the damping constant is decreased for keeping a low switching current.

In the double-interface MTJs, ferromagnet/heavy-metal (FM/HM) structure plays an important role in optimizing the performance. On the one hand, FM/HM structure increases the spin-orbit coupling (SOC) to induce the perpendicular anisotropy. On the other hand, the heavy metal works as a spacer between two ferromagnetic layers of the composite free layer to provide the Ruderman–Kittel–Kasuya–Yosida (RKKY) interaction [11], which ferromagnetically couples the magnetizations of the two ferromagnetic layers in order that they behave like an identical layer. Besides, recent works...
demonstrate that the strong SOC of the heavy metal combining with the atomic spins of the ferromagnet could form an antisymmetric exchange coupling called Dzyaloshinskii–Moriya interaction (DMI) [12, 13]. Therefore, the DMI is naturally induced in the double-interface MTJ with FM/HM structures. DMI favors the chiral magnetic textures (e.g., spin spirals, skyrmions, and Neel-type domain walls) and dramatically affects the magnetization dynamics, as validated by the recent studies [14–25]. It is important to mention that the role of DMI will become more complicated in the double-interface MTJ, since two FM/HM interfaces need to be considered together with an additional RKKY interaction. Therefore, it is of significance to reveal the effect of DMI on the double-interface MTJ.

In this letter, for the first time, we study the switching process of the double-interface MTJs under the actions of DMI and RKKY interaction. The double-interface MTJ is switched by the spin-transfer torque (STT), which is a mainstream approach for the data writing of the MRAM. It was recently reported that the DMI has a detrimental effect on the STT switching [21, 22]. Here, our results demonstrate that in double-interface MTJs, the detrimental effect of DMI could be suppressed by RKKY interaction, resulting in a fast switching and more uniform dynamics. Our work proves the robustness of the double-interface STT-MTJ against the negative interfacial effect.

Methods
The device studied in this work is illustrated in Fig. 1a, with a FM/HM/FM structure as the composite free layer. The HM layer thickness is adjusted to an appropriate value in order that the induced RKKY interaction ferromagnetically couples two FM layers. One of the FM layers is magnetically softer, which is denoted as FL1 (free layer 1), while the other is magnetically harder and denoted as FL2 (free layer 2). To switch the magnetization of the composite free layer, a current is applied to the double-interface MTJ and generates the STT. In this work, we only consider the transmitted STT from reference layer to FL1, whereas the other torques between FL1 and FL2 are neglected. This simplified model is consistent with the previously reported works [26–28]. The DMIs are induced in both FM/HM and HM/FM interfaces and have the opposite signs due to the different chirality [29].

The magnetization dynamics of the FL1 and FL2 in the double-interface MTJ is studied by micromagnetic simulation. The time evolution of the unit magnetization vector is governed by the following Landau-Lifshitz-Gilbert (LLG) equation. We choose OOMMF package, an open-source micromagnetic simulation tool [30], to model the device structure and solve the LLG equation for analyzing the magnetization dynamics.

$$\frac{\partial \mathbf{m}}{\partial t} = -\gamma \mathbf{m} \times \mathbf{H}_{\text{eff}} + \alpha \mathbf{m} \times \frac{\partial \mathbf{m}}{\partial t} + \gamma \frac{\hbar}{2eM_{s,F}} f \mathbf{m} \times (\mathbf{m} \times \mathbf{z})$$

where $\gamma$ is the gyromagnetic ratio, $\mathbf{m}$ is the unit vector along the magnetization, $\mathbf{z}$ is the unit vector along the thickness direction, $\mathbf{H}_{\text{eff}}$ is the effective field including uniaxial perpendicular anisotropy, 6-neighbor exchange energy, DMI field, RKKY interaction, demagnetization field, dipolar interaction, and STT.
Other parameters and their default values are listed in Table 1, unless stated otherwise. These parameter values are in accordance with the state-of-the-art technologies. As for the DMI magnitude, we consider a $\pm 2 \text{ mJ/m}^2$ for a general study.

The RKKY energy between a pair of magnetic moments $\mathbf{m}_i$ and $\mathbf{m}_j$ is defined as $E_{ij} = \sigma [1 - \mathbf{m}_i \cdot \mathbf{m}_j] / \Delta_{ij}$, where $\mathbf{m}_i$ and $\mathbf{m}_j$ are magnetic moments of FL1 and FL2, respectively. $\sigma$ is the bilinear surface exchange coefficient between two surfaces. $\Delta_{ij}$ is the discretion cell size in the direction from cell $i$ toward cell $j$. In this work FL1 and FL2 are ferromagnetically coupled, then $\sigma > 0$ which means that the RKKY interaction tends to make $\mathbf{m}_i$ parallel to $\mathbf{m}_j$. The DMI acts on the neighboring atomic spins $S_1$ and $S_2$ through a third atom with large SOC. Corresponding DMI Hamiltonian is expressed as $H_{DM} = -D_{12} \cdot (S_1 \times S_2)$, where $D_{12}$ is the DMI vector. Therefore, the DMI degrades the uniformity between $S_1$ and $S_2$, which competes with the RKKY interaction.

Results and Discussion

First of all, typical simulation results of the time-dependent $m_z$ (perpendicular component of the unit magnetization) are shown in Fig. 1b. If the RKKY interaction is sufficiently strong (e.g., $\sigma = 1 \times 10^{-3} \text{ J/m}^2$ in case A and case B), FL1 and FL2 are coupled together and thus their magnetization dynamics are almost identical, no matter whether the DMI is considered or not. It is also seen that the introduction of DMI distorts the process of the magnetization switching (see case B), which is in agreement with the reported results [21–23] and can be attributed to the antisymmetric exchange of DMI. Once the RKKY

![Image](image_url)

**Fig. 2** Switching time as a function of RKKY strength, with $\sigma$ shown in the logarithm scale. $D_1$ and $D_2$ are set to the same values, but with the opposite signs.

| Parameters | Description | Value |
|------------|-------------|-------|
| $M_s$      | Saturation magnetization | 1 MA/m |
| $d$        | MTJ diameter | 40 nm |
| $\alpha$   | Gilbert damping constant | 0.01 |
| $P$        | Spin polarization | 0.5 |
| $J$        | Applied current density | 4 MA/cm$^2$ |
| $A$        | Exchange stiffness | 20 pJ/m |
| $K_{u1}$   | Anisotropy constant of FL1 | 0.8 mJ/m$^3$ |
| $K_{u2}$   | Anisotropy constant of FL2 | 0.7 mJ/m$^3$ |
| $t_1$      | Thickness of FL1 | 1 nm |
| $t_2$      | Thickness of FL2 | 1.5 nm |
| $D_1$      | DMI magnitude of FL1 | $-2$ to $2 \text{ mJ/m}^2$ |
| $D_2$      | DMI magnitude of FL2 | $-2$ to $2 \text{ mJ/m}^2$ |
| $\sigma$   | Bilinear surface exchange energy for RKKY interaction | $3 \times 10^{-4} \text{ J/m}^2$ to $10^{-2} \text{ J/m}^2$ |
interaction is not strong enough, the magnetization
dynamics of FL1 and FL2 cannot be ideally coupled
so that significant difference between them is ob-
served (see case C). Below, the simulation results are
obtained under a sufficiently strong RKKY interaction,
unless stated otherwise.

Afterwards, we study the switching speed under the
various RKKY interaction. The switching speed is
reflected by a time when \( m_z \) reaches 0 (defined as the
switching time). The \( D_1 \) and \( D_2 \) are set to positive
and negative values, respectively [29]. The corre-
sponding results are shown in Fig. 2. In the absence
of DMI, the switching time increases with the
enhanced RKKY interaction, in agreement with the
other reported results [26–28, 38]. The reason is that
the stronger RKKY interaction makes the
magnetization dynamics of FL1 and FL2 more coher-
ently, which equivalently increases the anisotropy of
the composite free layer. However, the dependence of
the switching time on the RKKY strength becomes
more chaotic in the presence of DMI. This chaos is
mainly attributed to the inconsistency of the
anisotropy between FL1 and FL2. More explanation
will be shown later. These results evidence the non-
negligible effect of DMI on the switching behavior of
the double-interface MTJ.

Next, we study the effect of DMI in more details.
Figure 3 shows the switching time as a function of
DMI strength. It is important to mention that \( D_1 \)
and \( D_2 \) are intentionally set to the same positive
values in Fig. 3a, although they have the opposite
signs in reality. In other words, Fig. 3a cor-
responds to a virtual case, which we study for verifying
the simulation model. From the viewpoint of physical
theory, the detrimental effects of two positive DMIs
are cumulated under the action of ferromagnetically
coupled RKKY interaction. Therefore, the switching
time is expected to rise with the increasing \( D_1 \)
and \( D_2 \), as reported in the previous works [21, 22].
This analysis is in good agreement with the results shown
in Fig. 3a. Thus, the rationality of the simulation
model is validated. In contrast to Fig. 3a, the detri-
mental effects of DMI could be mitigated if \( D_1 \)
and \( D_2 \) have the opposite signs, as shown in Fig. 3b,
where the variation of switching time is much smaller compared with Fig. 3a. Note that in Fig. 3b, the curve is not exactly monotonous; the local fluctuation will be explained later. Remarkably, the effects of DMIs at two interfaces could be canceled out by appropriately tuning the magnitudes of $D_1$ and $D_2$, as shown in Fig. 3c. These results can be explained in terms of chirality theories as follows.

The DMI energy is expressed as $E_{DM} = \int \int D [m_x (\partial m_z/\partial x) - m_z (\partial m_x/\partial x) + m_y (\partial m_z/\partial y) - m_z (\partial m_y/\partial y)] d^2r = t D \varepsilon_{DM}$ [39], where $D$ is the continuous DMI constant, $t$ is the thickness of ferromagnetic layer. As mentioned above, the magnetization dynamics of FL1 and FL2 are almost identical under a sufficiently strong RKKY interaction. In this case, the same $\varepsilon_{DM}$ is obtained in FL1 and FL2. Then the total DMI energy of FL1 and FL2 could be calculated by $E_{tot} = (t_1 D_1 + t_2 D_2) \varepsilon_{DM}$. Therefore, by setting $D_1/D_2 = -t_2/t_1$, the DMI effects of FL1 and FL2 could be completely offset in the case of a large enough $\sigma$, in agreement with Fig. 3c. This conclusion is further verified by the additional results shown in Fig. 3d, where the other parameters are intentionally varied while keeping $D_1/D_2 = -t_2/t_1$.

The equivalent DMI magnitude ($D_{eq}$) of the composite free layer can be expressed as $D_{eq} = (t_1 D_1 + t_2 D_2)/(t_1 + t_2)$, which could be used for quantitatively analyzing the effect of DMI on the double-interface MTJ. To validate the effectiveness of this equation, we show two groups of simulation results in Fig. 4a, where two curves were obtained under the same $D_{eq}$ but with two pairs of different $\{D_1, D_2\}$ values, respectively. Although there is a little difference between the two curves, their overall trends are similar and validate the detrimental effect of DMI on the STT switching. Here, the difference between two curves could be explained as follows. FL1 and FL2 have different anisotropy constants, leading to the local uncertain oscillation of the magnetization dynamics, as shown in Fig. 4c. The same phenomenon is also observed in Fig. 2 and Fig. 3b. Instead, an ideal case is shown in Fig. 4b, d, where the anisotropy constants of FL1 and FL2 are set to the same values. Clearly, a good coincidence between the two curves is seen, indicating that the above expression of $D_{eq}$ could well describe the equivalent DMI effect of the double-interface MTJ.
Finally, we analyze the time evolution of magnetization dynamics in more details. Figure 5 shows the time-dependent energy during magnetization switching. The DMI energies of the FL1 and FL2 are accumulated or canceled, depending on the signs and magnitudes of $D_1$ and $D_2$. This trend is in good agreement with the above theoretical models. In addition, the RKKY energies are kept at low values, which validates that the magnetic moments of FL1 and FL2 are synchronously driven. The distributions of RKKY and DMI fields are shown in Fig. 6, where RKKY field plays different roles in various cases. First, in the case of non-zero DMI (see case 2 and case 3), the RKKY field is much stronger compared with the case of zero DMI (see case 1). It could be understood that the RKKY field has to overcome the additional non-uniformity of the magnetic textures in the presence of DMI. Second, if $D_1$ and $D_2$ are of the opposite signs, the RKKY field resists the DMI fields in both FL1 and FL2 (see case 2). As a result, the DMI is weakened so that the magnetization dynamics become more uniform. In contrast, once $D_1$ and $D_2$ have the same sign, the RKKY field resists the DMI field in one ferromagnetic layer but assists it in the other ferromagnetic layer (see case 3). Thus the overall DMI field still has a certain effect on the magnetization dynamics, which validates that the DMI cannot be canceled out if $D_1$ and $D_2$ are of the same sign.

Figure 7 shows the micromagnetic configurations of the FL1 and FL2 during the magnetization switching. Although the domain wall appears in all the cases, different features could be observed at some time moments. It is well known that the DMI favors the non-uniform magnetic textures. Nevertheless, in Fig. 7, uniform magnetization is still formed even in the presence of DMI (see the time when $m_z = -0.5$ in case 2), as long as the DMI effect is canceled out. Again, this result validates the above theoretical model. In addition, it is also seen that the magnetization dynamics is more non-uniform if $D_1$ and $D_2$ are of the same sign (see case 3 where the domain wall always appears), consistent with the above analysis. We also show some results simulated with smaller MTJ (see the last two rows in Fig. 7). The difference of micromagnetic configurations between case 2 (DMI is canceled out) and case 3 (DMI is not canceled out) is more notable.
Conclusion
We have comprehensively studied the effect of DMI on the double-interface STT-MTJ. As is well known, the double-interface MTJ was developed for enhancing the thermal stability barrier. In this work, our results prove another advantage of double-interface MTJ, that is, suppressing the detrimental effect of DMI. The DMIs in two ferromagnetic layers could be suppressed or even canceled out if they are configured with appropriate values and opposite signs, which is naturally satisfied by the double-interface STT-MTJ structure. Theoretical models were proposed to explain the conclusion. Micromagnetic simulation results were discussed for revealing the roles of DMI played in the magnetization dynamics. Our work provides a feasible approach to minimizing the DMI in the double-interface STT-MTJ.

![Fig. 6](image)

**Fig. 6** Spatial distributions of the DMI and RKKY fields. Here a typical result at one time moment is shown for each case. The conclusion remains unchanged at the other time moments. Case 1: $D_1 = D_2 = 0$. Case 2: $D_1 = 1.5 \text{ mJ/m}^2$, $D_2 = -1 \text{ mJ/m}^2$, i.e., DMI effect is canceled out. Case 3: $D_1 = D_2 = 1 \text{ mJ/m}^2$, i.e., DMI effect is accumulated.

![Fig. 7](image)

**Fig. 7** Micromagnetic configurations during the magnetization switching. Here, cases 1~3 are configured with the same parameters as Fig. 6.
Abbreviations
DML: Dzyaloshinskii–Moriya interaction; FL: Free layer; FM/MHM: Ferromagnet/heavy-metal; MRAM: Magnetic random-access memory; MTJ: Magnetic tunnel junction; RKKY: Ruderman–Kittel–Kasuya–Yosida; SOC: Spin-orbit coupling; STT: Spin-transfer torque

Acknowledgements
The authors would like to thank Xianjie Tang and Haoyang Zhang for their technical help.

Authors’ Contributions
WZH and ZWS conceived and supervised the project. LSM and WYJ performed the simulation. LSM, WZH, and WMX wrote the paper and analyzed the results. All the authors have read and approved the final manuscript.

Funding
The work was partly supported by the National Natural Science Foundation of China under grant 61704005.

Availability of Data and Materials
All data are fully available without restriction.

Competing Interests
The authors declare that they have no competing interests.

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Received: 6 July 2019 Accepted: 6 September 2019

Published online: 14 September 2019

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