Spin–orbit torque driven skyrmion motion under unconventional spin Hall effect

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Abstract
The effective control of skyrmion motion is a critical aspect for realizing skyrmion-based devices. Among the potential directions, the use of current induced spin–orbit torque (SOT) is energetically efficient. However, the conventional heavy metals with high crystal symmetry limit the charge-to-spin conversion to the orthogonal configuration, which causes the skyrmions to deflect from the electrical current direction with a finite skyrmion Hall angle. Here, we investigate the SOT driven skyrmion motion under unconventional spin Hall effect. We systematically study the effect of a noncollinear low-symmetry spin source layer with spin moments mixed by Rashba-like $S_y$, Dresselhaus-like $S_x$ and out-of-plane like $S_z$ on skyrmion features (velocity, diameter and Hall angle) stabilized in a ferromagnet/WTe$_2$ heterostructure. Our results may provide a new degree of freedom for controlling the skyrmion Hall angle, and can open the way for the discovery of new ferromagnetic multilayer where the skyrmion Hall angle is suppressed by the proper design of different SOT driven forces.

1. Introduction

Magnetic skyrmions are topologically protected magnetic configurations that can be stable even at nanometer sizes and can be manipulated electrically [1–8]. In this respect, skyrmions offer a platform for realizing next-generation spin-based information processing devices with proposals in storage [9–14] and computing [15–21]. Recently, current-induced magnetization dynamics through spin–orbit torques (SOTs) [22–24] have shown an effective and efficient technique in the fast-developing field of spin-orbitronics [25], as well as in driving skyrmion motion [26–30]. However, in ferromagnets, the skyrmion motion is characterized by a deflection angle with respect to the electrical current direction, i.e., the skyrmion Hall angle [27, 28, 31]. The control of the skyrmion Hall angle is crucial for skyrmion applications where skyrmions, coding the information, are unavoidably driven toward the sample edges with a subsequent annihilation. This aspect also limits the maximum applicable current and hence the maximum velocity achievable for the skyrmion. Several strategies have been considered in recent years to solve this issue, such as the use of coupled skyrmions with opposite skyrmion numbers in compensated ferrimagnets [32], synthetic antiferromagnets [33–37], antiferromagnets [38–43], and the use of tracks with engineered anisotropy [44–46]. Here, we propose to exploit an ‘unconventional’ SOT [47, 48] driving source, by
considering the noncollinear low-symmetry spin source layer with spin moments mixed by Rashba-like $S_z$, Dresselhaus-like $S_x$, and out-of-plane like $S_y$.

In a heavy metal/ferromagnet (HM/FM) conventional system, the HM high crystal symmetry limits the charge-to-spin conversion to the orthogonal configuration. The corresponding SOT is then related to the spin moments of Rashba-like $S_y$ in the generated spin current only, and the current-driven skyrmion motion exhibits a nonzero skyrmion Hall angle. Figure 1(a) shows the charge-to-spin mechanism diagram of a conventional HM. The charge current $J$ flows in the HM along the $x$-direction, and generates a spin current $J_S$ flowing along the $z$-direction with a spin moment $S_z$ along the $y$-direction. Due to the requirement by symmetry in a conventional HM, for example Pt [49], the charge current can only be converted into a spin current with Rashba-like spin moment $S_y$, and there is no spin moment along the $x$ or $z$-direction. Therefore, the spin-Hall conductivities $\sigma^{y}_{xz} (i, j, k$ are spin current, charge current, and spin moment directions, respectively) follow the conditions of $\sigma^{y}_{xz} = 0$ but $\sigma^{y}_{zx} \neq 0$. The nonzero $S_z$ gives rise to damping-like (DL) $\tau_y$,DL and field-like (FL) $\tau_y$,FL torques on the magnetization $m$ in the adjacent FM layer [50], with $\tau_y$,FL $\propto m \times S_y$ and $\tau_y$,DL $\propto m \times (m \times S_y)$, as shown in figure 1(b). Their corresponding effective magnetic fields are indicated by $B_y$,DL and $B_y$,FL, respectively.

On the other hand, materials with low-symmetry crystals support unusual spin-to-charge conversion, leading to the unconventional spin Hall effect, which has been reported experimentally in Weyl semimetal MoTe$_2$ [51, 52] and WTe$_2$ [53, 54]. It was found that the charge current can induce spin current with the spin moment along both the $z$-direction ($S_z$) and $y$-direction ($S_y$), as shown in figure 1(c), where $\sigma^{y}_{zx} \neq 0$ and $\sigma^{y}_{zx} \neq 0$ are achieved by the unique broken in-plane symmetry [51]. The corresponding generated unconventional SOTs linked to $S_z$ on the adjacent FM layer are shown in figure 1(d). Since $\tau_z$,FL $\propto m \times S_z$ and $\tau_z$,DL $\propto m \times (m \times S_z)$, $\tau_z$,DL can efficiently manipulate the out-of-plane magnetization component $m_z$. In the case of a skyrmion, this allows for the control of the skyrmion size. In addition, with the further lowering of the symmetry, the generated spin current can also include the Dresselhaus-like $S_x$ [48, 55] spin moment, as shown in figure 1(e). The corresponding generated unconventional spin torques on the adjacent FM layer are shown in figure 1(f). Therefore, we expect the magnetization dynamics driven by the previous unconventional SOT to be unique and different from the conventional HM/FM bilayer systems [47]. A potential application of these torques is skyrmion velocity enhancement by controlling the skyrmion Hall angle [56].

With this in mind, here, we explore, by means of a systematic study carried out with micromagnetic simulations, the effect of different unconventional SOTs on the current-driven skyrmion motion with noncollinear spin moments mixed by Rashba-like $S_y$, Dresselhaus-like $S_z$, and out-of-plane like $S_x$. We analyze their effects on skyrmion features such as the diameter, velocity, and Hall angle. We observe that the unconventional SOT can effectively reduce the skyrmion Hall angle and, for a particular combination of spin moments, it can be completely suppressed. Our results provide a direction for controlling skyrmion motion by a noncollinear spin source with the potential to realize skyrmion long-distance motion along ferromagnetic track as well as for stimulating the exploration of new ferromagnetic systems where the skyrmion Hall angle is zero thanks to the unconventional SOT.
2. Micromagnetic modeling

We perform micromagnetic simulations by using the Mumax3 program [57], which numerically integrates the following Landau–Lifshitz–Gilbert equation:

$$\frac{\partial \mathbf{m}}{\partial t} = \gamma \frac{1}{1 + \alpha^2} \left( \mathbf{m} \times \mathbf{B}_{\text{eff}} + \alpha \mathbf{m} \times (\mathbf{m} \times \mathbf{B}_{\text{eff}}) \right) + \mathbf{\tau}_{\text{SOT}},$$

(1)

where $\gamma$ is the gyromagnetic ratio and $\alpha$ is the Gilbert damping coefficient. $\mathbf{B}_{\text{eff}}$ is the effective magnetic field which, and includes the magnetostatic $\mathbf{B}_{\text{demag}}$, magnetic anisotropy $\mathbf{B}_{\text{ani}}$, exchange $\mathbf{B}_{\text{exch}}$ and Dzyaloshinskii–Moriya interaction (DMI) effective field $\mathbf{B}_{\text{DMI}}$ [57]. We consider zero temperature and an external field.

The spin torque term of $\mathbf{\tau}_{\text{SOT}}$ is expressed as equation (2).

$$\mathbf{\tau}_{\text{SOT}} = \frac{\beta \theta_{\text{SH}}}{2(1 + \alpha^2)}(\mathbf{m} \times (\mathbf{s} \times \mathbf{m}) - \alpha (\mathbf{s} \times \mathbf{m})),

(2)

where $\theta_{\text{SH}}$ is the spin–Hall angle and $\beta = \frac{\hbar}{m_{\text{sat}}^* \tau_{\text{rel}}} I$ is the charge current density, $t_{\text{FM}}$ is the FM thickness, $\hbar$ is the reduced Planck constant, and $e$ is the electron charge. The FM material CoPt is used with the following parameters: saturation magnetization $m_{\text{sat}} = 0.58$ MA m$^{-1}$, DMI parameter $D = 3$ mJ m$^{-2}$, exchange stiffness $A = 15$ pJ m$^{-1}$, perpendicular anisotropy constant $K_u = 0.9$ MJ m$^{-3}$, and $\alpha = 0.3$ [56]. We consider a racetrack geometry with length 200 nm, width 80 nm, and thickness 0.8 nm. The cell size was 1 nm $\times$ 1 nm $\times$ 0.1 nm. While in the paper we present the results for this set of parameters, we wish to highlight that qualitatively similar results can be achieved with other combinations of parameters that stabilize the skyrmion. For unconventional SOT, the spin Hall angle is defined as $\theta_{\text{SH}}^i$, where $i, j, k$ are the directions $\mathbf{J}_i$, $\mathbf{J}_j$ and $\mathbf{S}_k$, respectively. In our simulations, the current is applied along the $x$-direction, and the generated spin current is along the $z$-direction [as shown in figures 1(a)–(c)]. Therefore, the spin hall angle is expressed as

$$\theta_{\text{SH}}^x = \frac{\hbar J_{\text{Sx}}}{2e^* I},

(3)

where $J_{\text{Sx}}$ is the spin current density with the spin moment along the $k$ axis ($k = x, y, \text{or} z$). We consider an absolute value of spin Hall angle $\theta_{\text{SH}} = \sqrt{\theta_{\text{Sx}}^2 + \theta_{\text{Sx}}^2 + \theta_{\text{Sx}}^2} = 0.3$ [58] in the first set of simulations.

3. Results and discussions

We start our discussion by examining the effect of the SOT on the velocity $v$, skyrmion Hall angle $\phi$, and skyrmion diameter $d$ [see figure 2(a)], when $S_x$, $S_y$, and $S_z$ act separately. The presence of only $S_x$ [see figure 2(b)] does not provide any motion, but only a change in $d$ [59] which is defined as the diameter of the circular region enclosed by $M_z = 0$ indicated by the dashed line in the inset of figure 2(b) [see also supplemental note 1 (https://stacks.iop.org/NJP/24/053053/mmedia)]. $S_x$ promotes a well-known [11] skyrmion motion with velocity of approximately 90 m s$^{-1}$ [see figure 2(c), red curve], $\phi = 165^\circ$ [see figure 2(d), green curve] and $d = 31$ nm [see figure 2(d), orange curve] for $J = 10$ MA cm$^{-2}$ (see also supplemental note 2). The motion provided by only $S_x$ is similar to the previous one ($v \approx 90$ m s$^{-1}$, and $d = 31$ nm) but with $\phi = 77^\circ$ (see also supplemental note 2).

Now, we study the combined effect of $S_x$, $S_y$, and $S_z$. We start from the combination of $S_y$, and $S_z$. When fixing $\theta_{\text{Sx}}^x$ and increasing $\theta_{Sy}^y$, no significant change is observed for the skyrmion velocity [see figure 2(c), red curve], while the skyrmion Hall angle results from the trade-off between the effect $S_y$ and $S_z$. In particular, $\phi$ linearly decreases up to $\theta_{\text{Sx}}^x/\theta_{\text{Sy}}^y = 1.5$. Beyond that value, it starts to saturate approximately 80$^\circ$ [see figure 2(d), green curve], which, as expected, coincides with the skyrmion Hall angle when only $S_x$ acts. The observed reduction in the skyrmion Hall angle due to $S_y$ and $S_z$ seems promising for realizing zero skyrmion Hall angle devices, as we will show later.

Now, we combine $S_x$ and $S_y$, by fixing $\theta_{\text{Sx}}^x$ and increasing $\theta_{Sy}^y$. The velocity linearly increases up to $\theta_{\text{Sx}}^x/\theta_{\text{Sy}}^y = 1.5$. Beyond that value, it starts to saturate approximately 70 m s$^{-1}$ [see figure 2(c), blue curve], which is very close to the velocity obtained when only $S_x$ acts, as expected. We ascribed the velocity saturation to the behavior of the skyrmion diameter, which qualitatively follows the same trend, as shown in figure 2(e), orange curve. Such a behavior is due to the competition between $S_x$ and $S_y$. The former tries to maintain a shorter diameter of approximately 24 nm, while, the latter, tries to increase the skyrmion size to 31 nm. Therefore, we obtain a saturation both in the diameter and in the velocity. However, no significant changes are observed for the skyrmion Hall angle [figure 2(e), green curve]. Similar results are obtained when $S_z$ and $S_y$ are combined, as shown in figure 2(f).
Figure 2. (a) SOT driven skyrmion motion under noncolinear spin Hall angles $\theta_{yz}$. The skyrmion Hall angle is indicated by $\phi$, and the skyrmion size is indicated by diameter $d$. The ferromagnetic film thickness is 2 nm. (b) The relation of stable skyrmion diameters versus current density and space distribution value of $B_z$ in the out-of-plane direction ($B_z$), centered at the skyrmion. The skyrmion is marked by the black dashed circle. (c) The relation of skyrmion motion velocity versus $\theta_{xz}/\theta_{zy}$. (d) The relation of skyrmion Hall angle and diameter versus $\theta^x_{xz}/\theta^y_{xy}$. (e) The relation of skyrmion Hall angle and diameter versus $\theta^x_{xz}/\theta^y_{yz}$. (f) The relation of skyrmion Hall angle and diameter versus $\theta^y_{xy}/\theta^z_{yz}$.

The previous results gave us a fundamental understanding of the effect of the different spin moments, and, of course, confirmed that conventional SOTs drive the skyrmion with a finite Hall angle, which inevitably leads the skyrmion to meet the edge of a confined sample where it will be annihilated (see supplemental note 3). Therefore, in the following, we wish to analyze a realistic scenario where the skyrmion Hall angle can be strongly reduced thanks to the unconventional SOT. Recently, skyrmion motion in an FM/WTe$_2$ heterostructure has been experimentally observed [60], and unconventional SOTs have been found in WTe$_2$ [53, 54, 61], which satisfies $\sigma_{xz}^z \neq 0$ or/and $\sigma_{yz}^x \neq 0$ by the unique broken in-plane symmetry. Hence, the FM/WTe$_2$ heterostructure seems to be a promising system to achieve our aim. With this in mind, we investigate the skyrmion motion in an FM/WTe$_2$ by exploring SOTs generated from the spin source layer of WTe$_2$ by the spin moment along $S_z$ and $S_y$ with $\theta^x_{xz}/\theta^y_{xy} \sim 0.5$ [53]. Figures 3(a)–(e) show the results of the skyrmion motion after simulations 10 ns at different current densities $J$ from $5 \times 10^{10}$ A m$^{-2}$ to $2.5 \times 10^{11}$ A m$^{-2}$. The white lines indicate the skyrmion motion trajectory. It is clear that the skyrmion Hall angle is not completely suppressed and motion occurs along the sample edges, where the skyrmion diameter decreases due to the simultaneous action of the unconventional SOT and repulsive force from the boundary. When the current reaches $3 \times 10^{11}$ A m$^{-2}$, the skyrmion is expelled. The skyrmion velocity increases from 6 m s$^{-1}$ to 31 m s$^{-1}$ [figure 3(f)].

Eventually, we wish to propose a scenario where the skyrmion Hall angle can be completely suppressed thanks to a proper combination of the unconventional SOTs. Usually, the motion of the skyrmion can be understood within the picture of the Thiele equation as used to describe the skyrmion Hall effect in rigid
Figure 3. (a)–(e) The unconventional SOT driven skyrmion motion by the spin moment along the $z$-direction ($S_z$) and $y$-direction ($S_y$) with an $\theta_{yx}/\theta_{zx} \sim 0.5$. The white dashed lines indicate the skyrmion motion trajectory, under different current densities $J$ from $5 \times 10^{10}$ A m$^{-2}$ to $2.5 \times 10^{11}$ A m$^{-2}$. (f) The relation of skyrmion motion velocity versus current density.

skyrmion systems [11, 27, 62],

$$G \times \mathbf{v} - \alpha \mathbf{D} \cdot \mathbf{v} - 4\pi \mathbf{B} \cdot \mathbf{J} = 0,$$

(4)

where $G = (0, 0, -4\pi Q)$ is the gyromagnetic coupling vector. The topological charge $Q$ can be written as

$$Q = \frac{1}{4\pi} \int \mathbf{m} \cdot \left( \frac{\partial \mathbf{m}}{\partial x} \times \frac{\partial \mathbf{m}}{\partial y} \right) \, dx \, dy,$$

(5)

where $\mathbf{m}$ is the normalized magnetization. $\mathbf{v} = (v_x, v_y)$ is the drift velocity of the skyrmion along the $x$ and $y$-axes, respectively. The dissipative force tensor $\mathbf{D}$ is determined by the spin configuration in the skyrmion. The tensor $\mathbf{B}$ represents the efficiency of the spin Hall torque over the skyrmion. $\mathbf{J}$ is the electrical current density flowing in the heavy metal (WTe$_2$ in this letter). The Thiele equation of the Bloch skyrmion driven by unconventional SOT yields (see supplemental note 4)

$$v_x = -\frac{4\pi JB(4\pi Q\theta_{zx} + \alpha D\theta^y_{zx})}{\theta_{zx}(4\pi Q)^2 + (\alpha D)^2},$$

(6)

$$v_y = \frac{4\pi JB(4\pi Q\theta^y_{zx} - \alpha D\theta^x_{zx})}{\theta_{zx}(4\pi Q)^2 + (\alpha D)^2}.$$

(7)

Therefore, the skyrmion Hall angle can be calculated by

$$\phi = \arctan \left( -\frac{4\pi Q\theta^y_{zx}/\theta^x_{zx} + \alpha D}{4\pi Q + \alpha D\theta^y_{zx}/\theta^x_{zx}} \right).$$

(8)

When $\theta^y_{zx}/\theta^x_{zx} = \frac{\theta^y_{zx}}{4\pi Q}$, the skyrmion Hall angle is zero, that is, the skyrmion Hall effect can be completely suppressed. Figures 4(a)–(e) show a zero skyrmion Hall angle motion when $\theta^y_{zx}/\theta^x_{zx} = -0.46$ ($\theta^y_{zx}$ is zero because it controls the skyrmion size only), and figure 4(f) shows the relationship between skyrmion Hall angle and $\theta^y_{zx}/\theta^x_{zx}$ where the theoretical calculation results are consistent with the simulation results. The slight deviation mainly comes from the neglect of the boundary force which can depress the skyrmion Hall angle for simplicity in the theoretical calculation. Figure 4(g) depicts the achievement of a very high velocity up to 216 m s$^{-1}$. These results suggest that ferromagnetic systems with such a combination of unconventional SOTs should be designed.

4. Summary

By exploring the unconventional SOT with noncollinear spin moments mixed by Rashba-like $S_y$, Dresselhaus-like $S_x$, and out-of-plane like $S_z$ of the low-symmetry spin source layer, we demonstrated, via micromagnetic simulations, an additional degree of freedom to control the skyrmion Hall angle in ferromagnetic systems.

We found that the combination of $S_y$, $S_x$, and $S_z$ can effectively reduce the skyrmion Hall angle, and we proved it in a realistic FM/WTe$_2$ scenario. We also proposed a proper combination of the unconventional SOTs to completely suppress the skyrmion Hall angle. Our results may provide a deeper understanding of
Figure 4. (a)–(e) The unconventional SOT driven skyrmion motion by the spin moment along the $x$-direction ($S_x$) and $y$-direction ($S_y$) with an $\theta_x \sim 0.46$. The white dashed lines indicate the skyrmion motion trajectory, under different current densities $J$ from $5 \times 10^{10}$ A m$^{-2}$ to $2.5 \times 10^{11}$ A m$^{-2}$. (f) The relationship between skyrmion Hall angle and $\theta_x / \theta_y$, where the theoretical calculation results are consistent with the simulation results. (g) The relation of skyrmion motion velocity versus current density.

the current-induced SOT-driven skyrmion motion by a noncollinear spin source for the potential application of spintronics devices, and pave the way for exploring new material combinations to achieve a zero skyrmion Hall angle in ferromagnets.

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Conflict of interest

The authors declare no conflicts of interest.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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