

TOPICAL REVIEW

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Topical Review

Frontiers in all electrical control of magnetization by spin orbit torque

Shuai Hu¹, Xuepeng Qiu^{2,*} , Chang Pan², Wei Zhu², Yandong Guo², Ding-Fu Shao³, Yumeng Yang^{4,5}, Delin Zhang¹ and Yong Jiang^{1,*}

¹ Institute of Quantum Materials and Devices, School of Electronic and Information Engineering; State Key Laboratory of Separation Membrane and Membrane Processes, Tiangong University, Tianjin 300387, People's Republic of China

² Shanghai Key Laboratory of Special Artificial Microstructure Materials and Technology and School of Physics Science and Engineering, Tongji University, Shanghai 200092, People's Republic of China

³ Key Laboratory of Materials Physics, Institute of Solid State Physics, HFIPS, Chinese Academy of Sciences, Hefei 230031, People's Republic of China

⁴ School of Information Science and Technology, ShanghaiTech University, Shanghai 201210, People's Republic of China

⁵ Shanghai Engineering Research Center of Energy Efficient and Custom AI IC, ShanghaiTech University, Shanghai 201210, People's Republic of China

E-mail: xpqiutongji.edu.cn and yjiangtiangong.edu.cn

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Abstract

Achieving all electrical control of magnetism without assistance of an external magnetic field has been highly pursued for spintronic applications. In recent years, the manipulation of magnetic states through spin-orbit torque (SOT) has emerged as a promising avenue for realizing energy-efficient spintronic memory and logic devices. Here, we provide a review of the rapidly evolving research frontiers in all electrical control of magnetization by SOT. The first part introduces the SOT mechanisms and SOT devices with different configurations. In the second part, the developments in all electrical SOT control of magnetization enabled by spin current engineering are introduced, which include the approaches of lateral symmetry breaking, crystalline structure engineering of spin source material, antiferromagnetic order and interface-generated spin current. The third part introduces all electrical SOT switching enabled by magnetization engineering of the ferromagnet, such as the interface/interlayer exchange coupling and tuning of anisotropy or magnetization. At last, we provide a summary and future perspectives for all electrical control of magnetization by SOT.

Keywords: spintronics, spin orbit torque, magnetism

1. Introduction

As CMOS technology approaches its fundamental physical limit, spintronics stands out for its great potential for advancing the information technology in the post-Moore era [1, 2].

A primary goal of spintronics is to achieve efficient electrical control of the magnetic state, which is particularly important for magnetic random-access memory (MRAM) [3–5]. The first generation of MRAM is Toggle-MRAM which utilizes the current-induced Oersted field to control magnetic states. However, Toggle-MRAM faces restriction in the scalability due to the divergence of Oersted field and the inverse scaling of write energy consumption with the volume of

* Authors to whom any correspondence should be addressed.

the MRAM unit cell-magnetic tunnel junction (MTJ). The second and third generation of MRAM have been consecutively proposed which employ spin transfer torque (STT) and spin orbit torque (SOT) to write information [6, 7]. The STT-MRAM employs a spin-polarized current which is generated by passing a neutral current through a ferromagnet (FM), to deliver angular momentum to another FM layer and switch magnetization [8–10]. Nevertheless, STT-MRAM has severe concern in the reliability as the MgO tunnel barrier experiences large electric strain when flowing substantial STT writing current which potentially leads to fatal electrical breaks down [11, 12]. Another strong concern is the incubation time of STT, where the initial parallel alignment of magnetic moments in the free and pinned layers results in a zero cross-product torque, preventing the switching process [13, 14]. Therefore, thermal agitation is needed to introduce a slight tilt of the magnetic moment in the free layer, to initiate magnetization flipping. This, however, increases the switching time and affects the STT-MRAM writing speed [6, 15]. More recently, SOT emerges as a pivotal development, offering a novel approach to electrically manipulate magnetization [16, 17]. It brings advantages such as sub-nanosecond switching times, enhanced efficiency through the using of novel charge-to-spin conversion materials, and the ‘Read–Write Separation’ operating mode [18]. These aspects collectively address and surpass the limitations of STT. The SOT devices are mainly consisted by heavy metal (HM)/FM heterostructures with perpendicular magnetic anisotropy (PMA), which was firstly demonstrated by Miron *et al* in the Pt/Co/AlO_x heterostructure [16]. In such SOT devices, a transverse (*y*) spin-polarized current J_s is generated when longitudinal (*x*) electron current J_e pass through the heterostructures, via both the bulk spin Hall effect (SHE) of the HM layer and the Rashba–Edelstein effect (REE) occurring at the interface between HM and FM layers [19–21]. The spin polarized current carrying spin angular momentum, diffuse to the adjacent FM layer and exert a torque to manipulate the magnetization ($\mathbf{m}$) of the FM layer [22, 23]. This torque facilitates magnetization switching, domain wall motion and magnetic moment precession [16, 17, 24–29].

Due to its vector nature, SOT can be decomposed into damping-like (τ_{DL}) and field-like (τ_{FL}) components [7]. τ_{DL} , primarily responsible for driving SOT-induced switching, is parallel to the vector direction $\mathbf{m} \times (\mathbf{m} \times \boldsymbol{\sigma})$, while τ_{FL} , which plays a supporting role [30], is along $\mathbf{m} \times \boldsymbol{\sigma}$, where $\boldsymbol{\sigma}$ represents the spin polarization. Both the τ_{DL} and τ_{FL} strongly dependent on $\mathbf{m}$ because $\boldsymbol{\sigma}$ is constrained to be simultaneously orthogonal to both J_e and J_s according to the SHE and REE theories [19–21]. Depending on the easy axis of the $\mathbf{m}$, SOT devices can be operated with three different geometric configurations, which are type *z*, type *y* and type *x*, as illustrated in figures 1(a)–(c) [31]. However, the effectiveness of these configurations in achieving deterministic and all electrical magnetization switching relies on whether $\boldsymbol{\sigma}$ aligns collinearly with the easy-magnetization axis. Notably, type *z* and type *x* in figures 1(a) and (c) do not exhibit such

collinear alignment, while type *y* in figure 1(b) meets the collinear requirement for achieving deterministic and all electrical magnetization switching. In the type *z* configuration, as illustrated in figure 1(a), the *y*-polarized (σ_y) spin current exerts torque on the perpendicular $\mathbf{m}$, ultimately resulting in τ_{DL} pointing to the in-plane *y* direction, resulting an effective SOT field perpendicular to the $\mathbf{m}$. This scenario highlights a particular challenge: the in-plane τ_{DL} leads to an equilibrium state for both the $+\mathbf{m}$ (up) and $-\mathbf{m}$ (down) magnetization and results in degenerated energy levels, as depicted in figure 1(d). Consequently, SOT switching between $+\mathbf{m}$ (up) and $-\mathbf{m}$ (down) magnetization will occur stochastically, with no symmetry breaking for a specific perpendicularly magnetized direction, leading to the absence of deterministic switching [32]. In the case of type *z* and *x* modes, external magnetic fields (denoted as H_x for type *z* and H_z for type *x* modes) are required to break magnetic switching energy equivalence (figure 1(e) for the type *z* mode) to enable deterministic switching. Such inevitable requirement of external magnetic field is one of most paramount challenges for practical SOT applications [33]. In contrast, the ideal paradigm requires a parallel alignment between $\mathbf{m}$ and $\boldsymbol{\sigma}$ as exemplified in figure 1(b), which is fulfilled in the type *y* configuration with the magnetization along the *y* axis. The switching of type *y* configuration closely resembles the STT switching, in which the corresponding spin polarizations counteracts the magnetic damping thus enabling all electrical control over magnetization switching without the assistance of an external magnetic field.

While type *y* configuration can achieve all electrical control over in-plane magnetization, the preference in the context of MRAM technology often leans towards type *z* configurations with PMA heterostructures [34]. According to the mechanism as described above, the *z*-polarized (σ_z) spin current (hereinafter referred to as *z*-spin current) is required for collinear alignment with perpendicular magnetization and to achieve all electrical SOT switching, as shown in figure 1(f) [35]. However, conventional SHE and REE do not facilitate the generation of the *z*-spin current in a SOT heterostructure. Upon revisiting the mechanisms involving external fields, people have explored various innovative strategies to achieve all electrical control of magnetization.

This review comprehensively introduces the developments in all electrical magnetization control via SOT. After considering the symmetry of spin current and SOT switching, we first introduce the developments of all electrical SOT control enabled by spin current engineering, which mainly include the approaches utilize either out-of-plane SOT fields or *z*-spin current in PMA heterostructures. Simultaneously, we introduce the developments based on the engineering of the FM layer, which utilize exchange bias or interlayer exchange coupling to provide an effective magnetic field. We also discuss the developments on the tuning of anisotropy or magnetization of the FM layer. At last, we provide a summary and future perspectives of all electrical SOT switching.

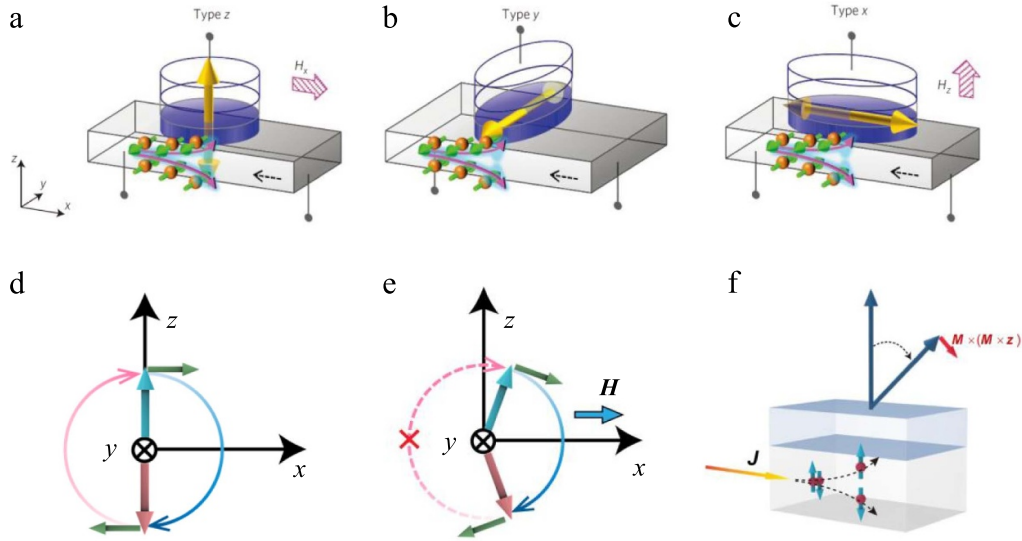


Figure 1. SOT switching configurations. (a)–(c) Schematic diagrams of SOT devices with three different geometries: type z, type y and type x. Reproduced from [31], with permission from Springer Nature. In-plane τ_{DL} driven perpendicular magnetic switching scenario without external magnetic field (d), and with in-plane assisting magnetic field (e). (f) A schematic depiction of a bilayer SOT device facilitating out-of-plane anti-damping torque via in-plane charge current conversion to z-spin current. Reproduced from [35]. CC BY 4.0.

2. All electrical SOT control enabled by spin current engineering

2.1. Lateral symmetry breaking

Lateral symmetry breaking is a phenomenon where a system or structure transits from a symmetry state to asymmetry state along a lateral axis. It can also be described by the symmetry breaking along a horizontal axis, leading to distinct left and right sides. The first groundbreaking work on SOT by harnessing lateral symmetry had been reported in 2014 [33], in which Yu *et al* utilized the non-uniform oxidation of the top TaO_x layer in the $\text{Ta/Co}_{20}\text{Fe}_{60}\text{B}_{20}/\text{TaO}_x$ structure to give rise to a new SOT field that perpendicular to the film plane, as shown in figure 2(a). Its underlying origin has been ascribed to the asymmetry caused by the non-uniform current density across the lateral direction of the device [33, 36]. This asymmetry consequently breaks the symmetry of spin current along the width direction, leading to the generation of out-of-plane effective magnetic field (H_z^{eff}) which cannot be generated by the conventional y-polarized spin current. The existence of H_z^{eff} had been verified by measuring the hysteresis loop shift of the anomalous Hall resistance with both positive and negative electrical currents (I), as demonstrated in figure 2(b) [33]. Later on, all electrical magnetization switching had been also realized in a similar wedge Mo/Co-Fe-B/MgO PMA heterostructure (figure 2(c)) [37], which further broadens the spectrum of material choices and enhances the flexibility of device design [38–40].

Moreover, the insertion of a non-uniform light-metal layer between the HM and FM layers can also induce deterministic switching without external magnetic field, as shown in figure 2(d) [41]. Remarkably, despite the oblique deposition

of the inserted Ti layer to effectively break the lateral symmetry, the authors observed a uniform PMA and switching current density across all devices, which is of stark contrast with the findings of Yu *et al*. Thus, the generation of H_z^{eff} has been attributed to the REE. Moreover, all electrical SOT-driven switching in synthetic antiferromagnets (SAFs) has been demonstrated experimentally by Chen *et al* [42]. They found crystallinity dependent Dzyaloshinskii–Moriya interaction (DMI) at HM/FM interface and its large impact on the domain wall configurations. Through manipulating the domain wall configuration between Bloch type and Néel type, they successfully demonstrated deterministic magnetization switching without an external magnetic field in $[\text{Co/Pd}]/\text{Ru}/[\text{Co/Pd}]$ SAF devices with a wedged structure, as depicted in figures 2(e) and (f) [42]. This study introduces a practical approach for incorporating perpendicular SAF into SOT devices with the advantages in terms of high density, minimal stray field, and low power consumption. Interestingly, the lateral symmetry breaking can be more easily realized through localized annealing using a laser track along the in-plane current direction, as recently demonstrated by Cao *et al* in the Pt/Co/Pt trilayer, shown in figure 2(g) [43]. The polarity of current-induced magnetization switching depends on the annealing track’s location and laser power, with no dependence of the net spin current orientation from the top and bottom Pt layers, as shown in figures 2(h) and (i). These results have been explained by a novel SOT-induced H_z^{eff} , arising from a lateral Pt gradient within the Co layer.

Another approach to induce substantial lateral symmetry breaking involves the use of an electric field [44–49]. Kang *et al* employed two side gates to induce a lateral voltage gradient [44]. This gradient facilitates the generation of H_z^{eff} (figure 3(a)), enabling all electrical control of perpendicular

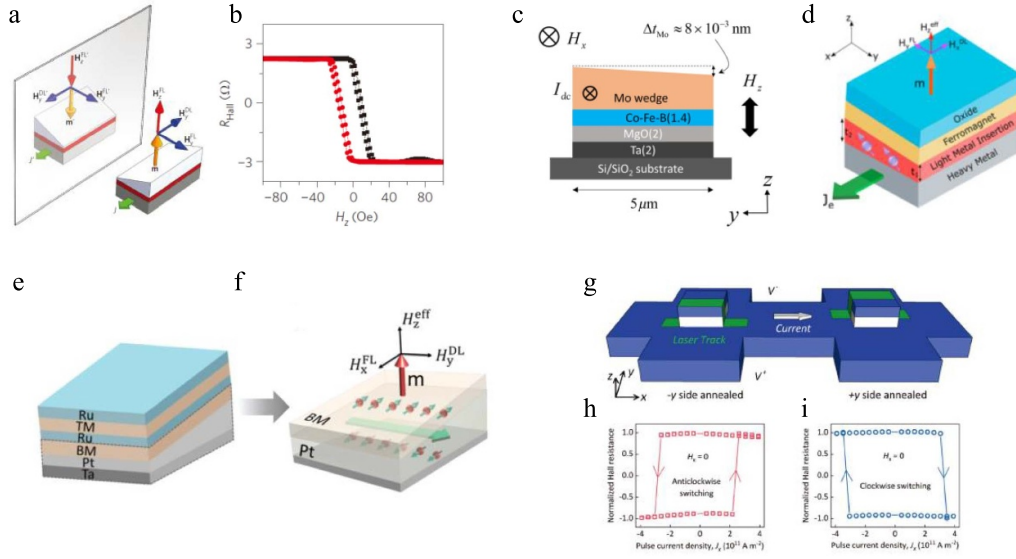


Figure 2. Lateral symmetry breaking induced effective magnetic field. (a) The H_z^{eff} resulting from the laterally asymmetric structure and its mirror image. (b) Hysteresis loop shift of the anomalous Hall resistance with the current of ± 10 mA. Reproduced from [33], with permission from Springer Nature. (c) and (d) Lateral symmetry breaking induced by a top wedge Mo (c) and insertion Ti layer (d). Reprinted (figure) with permission from [37], Copyright (2018) by the American Physical Society. Reprinted with permission from [41]. Copyright (2020) American Chemical Society. (e) Schematic of the Ta/Pt (wedge)/[Co/Pd]₂/Co/Ru/[Co/Pd]₃/Co/Ru stack. Reproduced from [42]. CC BY 4.0. (f) The perpendicular effective field in the SAF structure. Reproduced from [42]. CC BY 4.0. (g)–(i) Schematic of the locally laser-annealed PMA FM pillars (g) and the respective all electrical magnetization switching with the $-y$ side annealed pillar (h) and the $+y$ side annealed pillar (i). [43] John Wiley & Sons. [Copyright © 2020 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim].

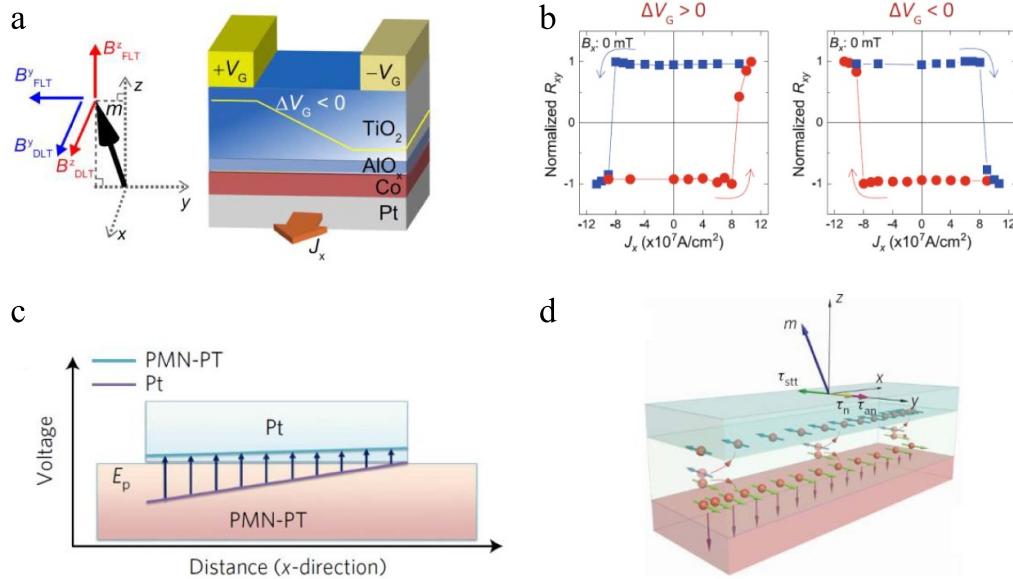


Figure 3. Electrical modulation of the lateral symmetry. (a) Schematic of gate voltage-induced lateral symmetry breaking, which generates H_z^{eff} (red arrows). (b) All electrical SOT switching for $\Delta V_G > 0$ (left) and $\Delta V_G < 0$ (right). Reproduced from [44]. CC BY 4.0. (c) The electric field at the PMN-PT substrate and bottom Pt layer interface during negative current injection ($-I$). (d) The spin current gradient generates an effective torque of τ_n . Reproduced from [45], with permission from Springer Nature.

magnetization and electric field manipulation of the switching polarity (figure 3(b)). Additionally, the reversal of H_z^{eff} sign occurs when the gate oxide is changed, while the electric field-controlled magnetic anisotropy remains consistent, indicating the dominated role of the Rashba effect at the Co/oxide interface in lateral electric-field modulation. The application

of electric field in another work has been reported to generate an in-plane longitudinal effective magnetic field, which is different with the H_z^{eff} . Cai *et al* deposited a Pt/CoNiCo/Pt heterostructure with minimized Rashba effect on PMN-PT substrate [45]. Applying voltage across the substrate in a direction parallel to the current direction produced different electric

potential drop slopes on Pt and PMN-PT along the charge current direction (figure 3(c)). The resulting differences in electrical potential at the Pt-PMN-PT interface generated a perpendicular electric field gradient, the magnitude and sign of which depend on the applied electric field and charge current. Hence, a gradient of spin current along the current direction is generated, effectively producing an additional torque of τ_n (figure 3(d)) and an associated in-plane magnetic field parallel to the current direction, to enable all electrical magnetization switching.

2.2. Spin source with crystal symmetry breaking

Conventional SOT magnetic heterostructures are usually deposited with uniform thickness for each layer, therefore symmetry breaking only occurs in the normal direction of the thin film, this symmetry breaking is essential for the generation of the SOT [16]. However, the quasi-2D nature and in-plane homogeneity of thin film structure, as depicted in figure 1(a), allow for the generation of only y -polarization spin current when the electrical current flows along the x -axis. In below theoretical discussion, we will explore spin currents with alternative polarization directions and the requisite conditions for their generation. The qualitative description of the production of an out-of-plane spin current J_z^p by an in-plane electric field E_x can be described by Ohm's law-like formula:

$$J_z^p = \sigma_{zx}^p E_x, \quad (1)$$

where σ_{zx}^p is the associated spin conductivity, p , z , x denote the directions of the spin polarization, the spin current, and the electric field, respectively. A nonzero σ_{zx}^p can be induced by various mechanism, such as spin-orbit coupling and magnetism. At this stage, we will first disregard the origin of σ_{zx}^p , and focus on the possible directions of p we can have in a spin source. This can be derived from a simple analysis on the symmetry transformations of equation (1). For example, here we consider a system with a mirror symmetry operation $\hat{M}_y$ perpendicular to y axis. Under this symmetry transformation, a polar vector, such as an electric field and a velocity, is invariant (flipped) provided it is parallel (perpendicular) to this mirror plane, while an axial vector, such as a magnetic field, a spin, or a magnetic moment, is flipped (invariant) when being perpendicular (parallel) to the mirror plane. Therefore, applying $\hat{M}_y$ to different parts of equation (1), we get

$$\hat{M}_y E_x = E_x, \quad (2)$$

and

$$\begin{aligned} \hat{M}_y J_z^x &= -J_z^x, \\ \hat{M}_y J_z^y &= J_z^y, \\ \hat{M}_y J_z^z &= -J_z^z. \end{aligned} \quad (3)$$

The latter is due to that the spin current operator is usually written as $\hat{J}_z^p = \frac{1}{2} \{ \hat{v}_z, \hat{s}_p \}$, where $\hat{v}_z$ and $\hat{s}_p$ are the velocity and spin operator. Therefore, in order to preserve the validity

of equation (1) under $\hat{M}_y$ operation, we should have the spin conductivities

$$\begin{aligned} \hat{M}_y \sigma_{zx}^x &= -\sigma_{zx}^x, \\ \hat{M}_y \sigma_{zx}^y &= \sigma_{zx}^y, \\ \hat{M}_y \sigma_{zx}^z &= -\sigma_{zx}^z. \end{aligned} \quad (4)$$

Consequently, in a system with a $\hat{M}_y$, σ_{zx}^x and σ_{zx}^z are enforced to be vanishing, while σ_{zx}^y , also known as y -spin polarization can be finite. Similar analyses on other symmetry operations can be made to derive the complete symmetry constraints of the spin conductivities. Therefore, in order to have a spin current with an unconventional spin polarization direction, one should design material systems with the required symmetry breaking to release these constraints.

Inherent symmetry breaking within the crystal's microstructure offers a significant opportunity for generating novel polarization spin current. Specifically, this occurs through the charge-to-spin conversion in the symmetry-breaking crystal, serving as a spin source. Weyl semimetal WTe_2 is a material that has garnered considerable recent attention due to its distinctive crystal structure with lower symmetry, illustrated in figure 4(a) [50]. Notably, symmetry is broken in the ac plane, while the bc plane maintains mirror symmetry. Accordingly, MacNeill *et al* designed a bilayer consisting of WTe_2 and NiFe , as depicted in figure 4(b), they conducted measurements of SOT utilizing spin-torque ferromagnetic resonance (ST-FMR) and observed the generation of out-of-plane antidamping torque when a current was applied along a low symmetry axis of WTe_2/NiFe bilayers. In contrast, this effect was not observed when the current was applied along a high symmetry axis, as shown in figure 4(c). This discovery opens up a novel avenue for controlling SOTs based on crystal symmetries within the spin source layer and presents a strategy for achieving deterministic, all electrical magnetic switching in PMA heterostructures.

Consequently, the utilization of WTe_2 as a spin source for achieving all electrical switching of magnetic layers with PMA has been successfully demonstrated in $\text{WTe}_2/\text{Fe}_{2.78}\text{GeTe}_2$ (FGT) (figures 4(d) and (e)) [51] and $\text{WTe}_2/\text{SrRuO}_3$ bilayers [53]. However, it is worth noting that this success has been achieved at relatively low temperatures and is not yet suitable for room temperature practical applications. Very recently, Liu *et al* reported room temperature all electrical SOT switching of perpendicular magnetization via z -spin current generated by another Weyl semimetal TaIrTe_4 [54], offering improved efficiency for electrical manipulation adjacent PMA layer due to a larger spin Hall conductivity of TaIrTe_4 than WTe_2 . The aforementioned Weyl semimetals consistently exhibit an asymmetric relative to a 180° rotation about the c axis. In the case of the CuPt/CoPt bilayer, as illustrated in figure 4(f), it possesses a three-fold symmetry [52]. Therefore, the current-induced out-of-plane effective field and associated all electrical switching without an external magnetic field display a distinct angular dependence, representing a unique characteristic compared

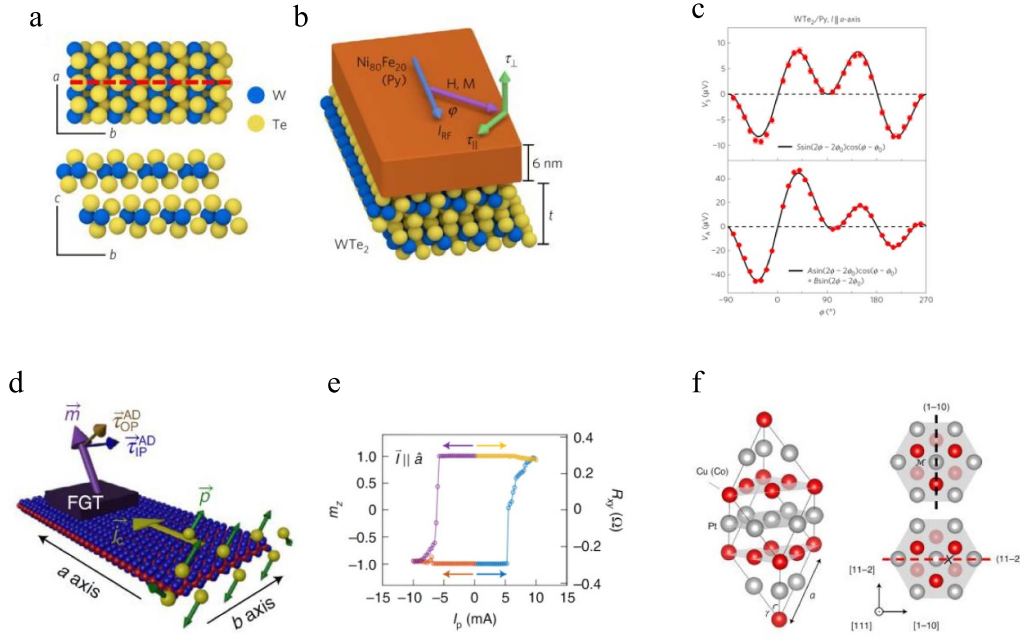


Figure 4. Low crystal symmetry based heterostructure for generating out-of-plane SOTs. (a) Crystal structure near the surface of WTe_2 . (b) Schematic of the bilayer WTe_2/NiFe sample geometry. (c) Symmetric and antisymmetric ST-FMR resonance components with current applied parallel to the a -axis. Reproduced from [50], with permission from Springer Nature. (d) WTe_2/FGT stack and anti-damping torque when current is applied along the a -axis of WTe_2 . (e) Deterministic and all electrical switching of the FGT. Reproduced from [51], with permission from Springer Nature. (f) Left panel: $L1_1$ CuPt crystal structure. Right panel: plane view symmetry of the $L1_1$ hexagon projected along the $[111]$ direction. Reproduced from [52], with permission from Springer Nature.

to previous switching scenarios. More low symmetry crystals such as MnPd_3 also exhibits the capability to generate unconventional SOTs due to the presence of spin polarization along the x , y and z directions, a phenomenon driven by the (114)-oriented crystals [55]. This characteristic provides a versatile approach to manipulate deterministic all electrical SOT switching behavior in both in-plane magnetic anisotropy (IMA) and PMA heterostructures.

2.3. Antiferromagnetic spin source with spin order symmetry breaking

For non-magnetic materials, the corresponding spin current symmetry and current induced SOT are uniquely determined after the material fabrication as the crystal structure is fixed. In contrast to the conventional non-magnetic materials, non-collinear antiferromagnet (AFM) Mn_3X ($\text{X} = \text{Sn, Ga, Ge, Pt, Ir, Rh}$) is regarded as a more advantageous spin source [35, 56–67], offering intriguing spin freedom beyond atomic and crystalline aspects. This unique characteristic enables the manipulation of the relative angle between current and spin while keeping the crystalline structure unchanged. Leveraging this feature, unconventional SOTs can be generated based on their intriguing spin order symmetry. A recent study by Nan *et al* presented an approach for generation of spin current with polarizations along y , x , or z direction by harnessing the unique low symmetry noncollinear spin arrangement of an AFM Mn_3GaN thin film (figures 5(a) and (b)) [60]. The study further validated the disappearance of unconventional spin polarizations in the absence of the noncollinear spin

structure when the temperature surpasses the Néel temperature of Mn_3GaN . This underscores the significant influence of spin order on the unconventional spin polarizations generated by the AFM Mn_3GaN thin film. Another noncollinear AFM Mn_3Sn [35], as shown in figure 5(c), is a hexagonal Ni_3Sn -type crystal with a noncollinear AFM order. The noncollinear antiferromagnetism in Mn_3Sn leads to many interesting physical properties, such as the large anomalous Hall effect (AHE) associated with its intrinsic Berry curvature [68], and the emergence of spin polarized current [56–58]. In particular, the magnetic SHE (MSHE) enables a reversal of spin polarization when its triangularly ordered spins switch orientation by the external magnetic field, which cannot be achieved in the conventional non-magnetic materials. This effect is attributed to the momentum-dependent spin splitting effect produced by noncollinear AFM order of Mn_3Sn [59]. Theoretical calculations indicate that a z -spin current can be generated by flowing an in-plane charge current in Mn_3Sn (0001) thin film, which contributes to a large magnetic spin Hall conductivity (MSHC) [35]. The noncollinear spin arrangements of Mn_3Sn , denoted as AFM1 and AFM2 in figure 5(c), introduce z -spin polarization with opposite directions, as represented by the calculated MSHC in figure 5(d). This property promises Mn_3Sn as a superior spin source for deterministic switching of adjacent perpendicular FM layers, eliminating the need for an external magnetic field. Recently, Hu *et al* have successfully demonstrated the generation of the z -spin current induced by applying an in-plane charge current through Mn_3Sn , which is validated by measuring the hysteresis loop of the anomalous Hall resistance versus the out-of-plane magnetic field H_z in the presence

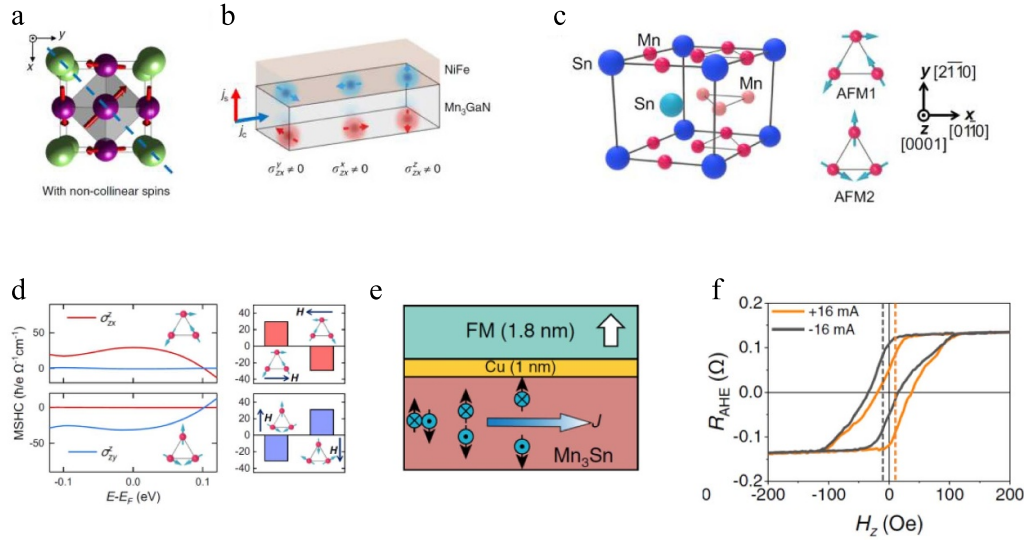


Figure 5. Antiferromagnets based heterostructure for tuning novel spin polarizations. (a) Spin structure of Mn₃GaN projected onto the (001) plane. (b) Schematic illustrations of the NiFe/Mn₃GaN bilayer and the allowed spin polarizations in the low symmetry state. Reproduced from [60]. CC BY 4.0. (c) The structure of the noncollinear AFM Mn₃Sn and the triangular magnetic alignments of Mn moments within each Mn–Sn Kagome plane. (d) The calculated MSHC in Mn₃Sn, right panel shows the MSHC sign change when the magnetic moments in AFM1 and AFM2 are reversed by in-plane magnetic fields. (e) Mn₃Sn (7)/Cu (1)/FM (1.8) stack. (f) R_{AHE} vs. H_z curve at the bias currents of ± 16 mA. Reproduced from [35]. CC BY 4.0.

of a bias d.c. current in the Mn₃Sn/Cu/[Ni/Co]_n multilayer (figures 5(e) and (f)). Remarkably, a deterministic perpendicular magnetization switching of an adjacent [Ni/Co]_n multilayer has been achieved without the need for an external magnetic field. Further, the MSHE of Mn₃Sn enables the reversal of SOT through manipulating its triangle spin order between two different configurations via applying magnetic field. In addition, this z-spin current induced all electrical magnetization manipulating is shown to be more efficient than conventional HM based SHE device [35]. These discoveries underscore the significant promise of utilizing noncollinear AFM as a spin torque source for developing novel, energy-efficient spintronic devices. Other noncollinear AFMs such as Mn₃SnN, Mn₃Ga have been also demonstrated to be capable to generate z-spin current and utilized to switch adjacent Co/Pd and CoPt perpendicular FM layer without an external magnetic field [62, 63]. More recently, noncollinear Mn₃Pt, a cubic crystalline AFM with high crystal symmetry, has been reported to exhibit an intriguing anomalous anisotropy of spin polarization due to the interplay between time reversal-odd and time reversal-even SHE [61]. This has enabled all electrical SOT switching in the perpendicular magnetized Mn₃Pt/Ti/CoFeB/MgO/SiO₂ heterostructure. The switching polarity can be reversed by altering the spin order from ‘all in’ to ‘all out’ and vice versa by an external magnetic field, as shown in figures 6(a) and (b). In addition to above noncollinear AFMs, the collinear AFM Mn₂Au with space-broken symmetry of the spin sublattice has also been reported to generate z-spin current and strongly depends on the spin order of Mn₂Au [64]. All electrical SOT switching has been demonstrated by the antiferromagnetic SHE in the PMA Mn₂Au/(Co/Pd)₃ system (figures 6(c) and

(d)). Moreover, both the electric field and current have been demonstrated to be capable to modulate Mn₂Au antiferromagnetic spin order and the spin torque acting on the adjacent FM layer.

2.4. Interface-generated spin current

Different from previous novel SOTs generated within the bulk of spin source layer, Beak *et al* demonstrated an interface-generated SOTs through engineering of an FM layer with IMA, e.g. CoFeB or NiFe in the FM/Ti/CoFeB/MgO heterostructure (figure 7(a)) [69]. The in-plane FM (CoFeB or NiFe)/Ti acts as a spin source layer to generate conventional in-plane polarized spin current accompanied by additional z-spin current due to the spin–orbit precession at the interface. The z-spin current was verified by measuring the hysteresis loop shift method, and the current dependence of loop shift is shown in figure 7(b). The magnetization direction of the bottom CoFeB layer plays a pivotal role in tuning the polarity of all electrical SOT switching in the top perpendicular CoFeB layer, as illustrated in figures 7(c) and (d). This provides crucial evidence for the presence of interface-generated z-spin current. Another study on antiferromagnetic insulator-based heterostructures demonstrates the generation of z-spin current, which is attributed to the internal electric field at the interface of NiO and HM layer [70]. The efficiency can be further modulated by the canted antiferromagnetic order, as illustrated in figures 7(e) and (f). The observed hysteresis loop shift in figure 7(g) provides the evidence of the existence of z-spin current.

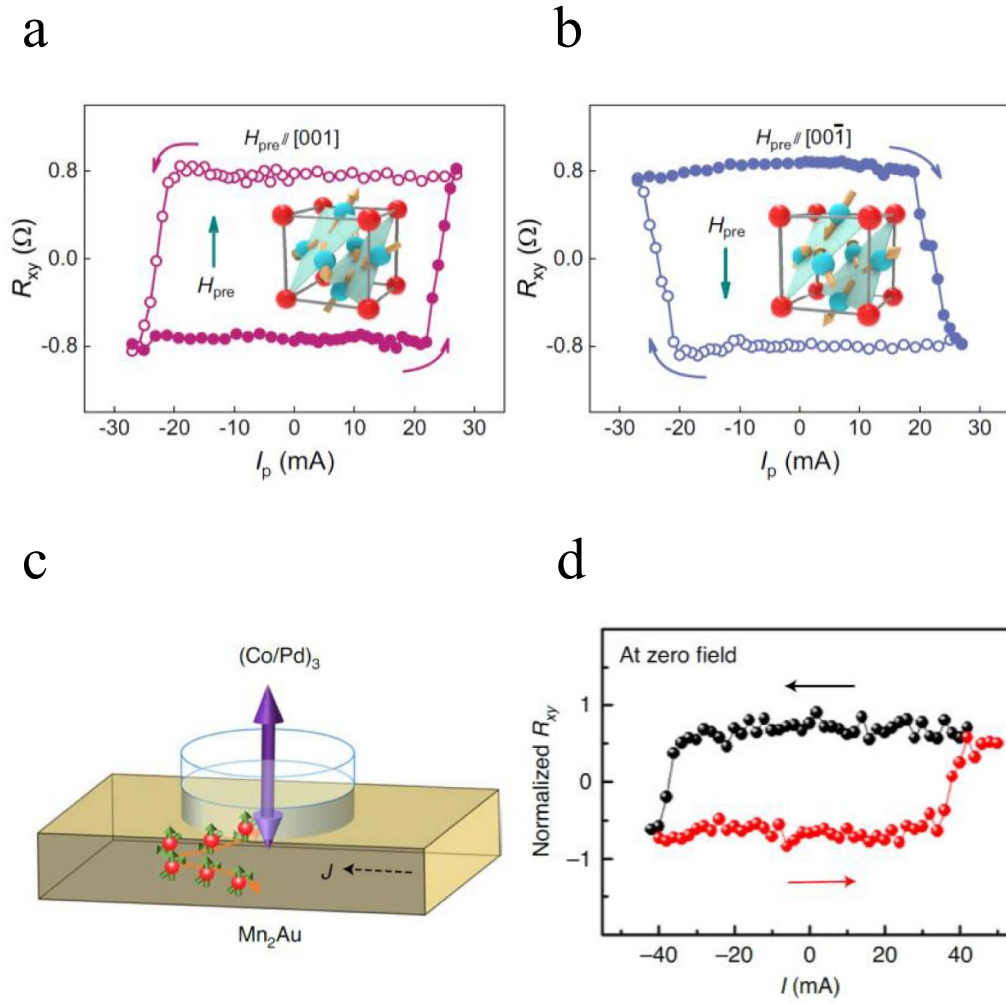


Figure 6. (a) and (b) The switching polarity is reversed with pre-magnetization fields along opposite directions, the insets illustrate the spin configuration. Reproduced from [61]. CC BY 4.0. (c) $Mn_2Au/[CoPd]_3$ PMA heterostructure. (d) All electrical SOT switching in $Mn_2Au/[CoPd]_3$ stack. Reproduced from [64], with permission from Springer Nature.

3. All electrical SOT control enabled by magnetization engineering

Different from the strategy of aligning spin polarization with the perpendicular magnetization of FM to achieve deterministic all electrical SOT switching, another strategy is to break the degenerated symmetry for up and down magnetic state for a FM with PMA. An in-plane external magnetic field along the electrical current direction is effective to break such symmetry. Exchange bias is a phenomenon arising from the exchange coupling at the interface between an AFM and FM layer, characterized as a magnetization hysteresis loop shift of the FM layer [71–78]. This phenomenon closely resembles to the effect of introducing an additional magnetic field within the system. In this case, an effective magnetic field is generated at the exchange coupled interface, thus all electrical SOT switching of the PMA FM layer can be realized [73–78]. Similar to exchange bias in FM/AFM, the pseudo-exchange bias between two FMs is also an effective approach to introduce interface effective magnetic field [79, 80]. Apart from this, structural asymmetry can introduce tilted PMA of the FM,

effectively enabling all electrical deterministic SOT switching [81–84].

3.1. Exchange bias and interlayer coupling

To achieve field-free all electrical SOT switching through exchange bias, one can replace the HM with an AFM in the HM/FM bilayer. Many AFMs like IrMn [85–87] and PtMn [86] can also act as spin sources to generate large SOT. In figure 8(a), the IrMn/CoFeB/MgO heterostructure with PMA is depicted [73]. The magnetic hysteresis loop displays a negative shift when a field is applied in the x direction (figure 8(b)), indicating an in-plane exchange bias introduced by the bottom IrMn layer. This exchange bias facilitates the presence of an equivalent magnetic field parallel to the current, enabling deterministic switching of perpendicular magnetization without requiring any external magnetic field (figure 8(c)). Similar structure using an PtMn and ferromagnetic $[Co/Ni]_n$ multilayer with a perpendicular easy axis (figure 8(d)) [74]. The SHE of the PtMn layer is accountable for the switching phenomenon. Due to the

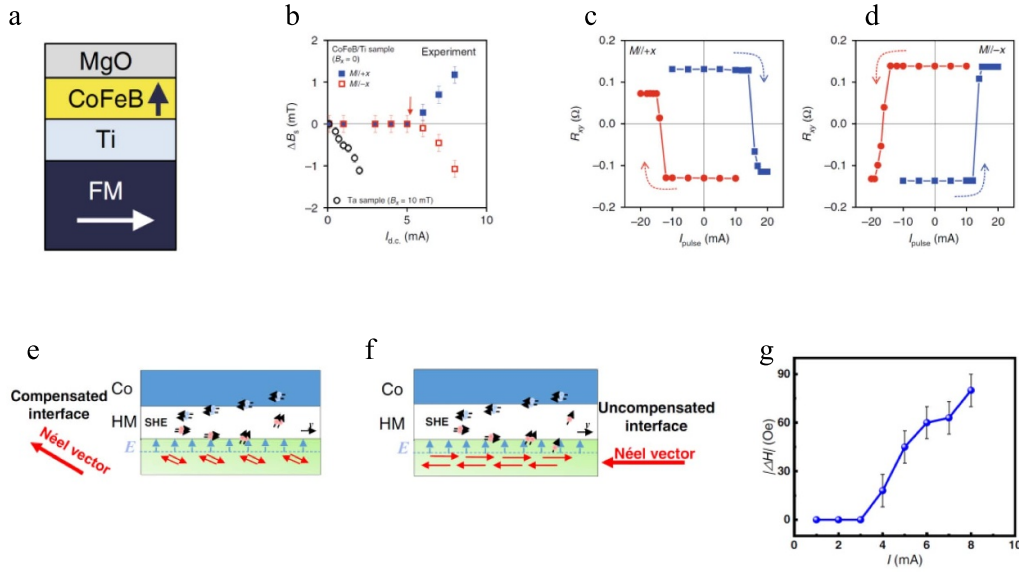


Figure 7. Interfaced generated z-spin current. (a) Structure of a magnetic trilayer of FM/Ti/CoFeB. The arrows in the layers indicate the magnetized direction. (b) Anomalous Hall hysteresis loop shift (ΔB_s) vs. I_{dc} , blue (red) square symbols represent the results for different magnetization of the bottom CoFeB layer. (c), (d) All electrical switching of perpendicular magnetization with different polarity tuned by the direction of magnetization in the bottom CoFeB layer. Reproduced from [69], with permission from Springer Nature. (e) and (f) The generation and transportation of z-spin current at the compensated and uncompensated interfaces between NiO and HM. (g) The hysteresis loop shift value with respect to the magnitude of the applied current in the NiO/HM/FM heterostructure. Reproduced from [70]. CC BY 4.0.

exchange bias provided by PtMn, electrical switching in the absence of an external magnetic field was observed, and led to the emergence of memristive behavior as the exchange bias is increased, as shown in figures 8(e) and (f). This development opens up an intriguing avenue for applications in neuromorphic computing. Interlayer exchange coupling via a nonmagnetic spacer instead of direct interface exchange coupling is another approach, the structure stack is shown in figure 8(g) [79]. The perpendicularly magnetized $\text{Co}_{90}\text{Fe}_{10}$ (CoFe) free layer is exchange-coupled to an in-plane exchange biased CoFe/IrMn pinned layer through a Ru spacer, thus, an effective magnetic field is induced to realize all electrical SOT switching. Figures 8(h) and (i) show the robust all electrical SOT switching behavior. The switching polarity of the free layer is governed by the current direction and the sign of the interlayer exchange coupling, which varies with different Ru thicknesses. Importantly, the stray field generated by the top CoFe layer is minimal, approximately 0.001 mT, so the observed effect can be primarily attributed to the interlayer exchange coupling. The utilizing of exchange bias and interlayer coupling, offers a promising scalable solution to realize all electrical controlled SOT device.

The utilization of exchange bias effect has significantly advanced the research on all electrical switching and promoted the practical application of SOT. However, the exchange bias can be significantly influenced by the device temperature due to the Joule heating produced by the substantial SOT switching current [88]. This temperature sensitivity may lead to the instability of SOT devices. Meanwhile, the in-plane exchange bias can partially reduce the PMA of the FM layer, potentially affecting the stability of SOT device.

3.2. Magnetization engineering

The exchange bias introduces an effective in-plane magnetic field to tilt the magnetization of the FM layer, thereby breaking the symmetry of magnetization switching between upward and downward orientations. Alternatively, an inherent tilted anisotropy in FM can be engineered to allow easy axes slightly tilted away from the film's normal direction. As depicted in figure 9(a) [81], when a current is applied along the -y (+y) axis, the +x (-x) polarized spin current aligns the magnetization to its spin polarization direction. For instance, if we start from an initial +m state at the (-x, +z) quadrant, when the -y current generates polarization along the +x direction, the magnetization will traverse its hard axis and eventually return to the -m state at the (+x, -z) quadrant upon ceasing the current. Likewise, when the current flows along the +y axis, the magnetization in the process of rotating to -x direction, it does not cross over the hard axis. Consequently, when the current is deactivated, it is beneficial for the magnetization to return to the +m state. Therefore, -y current induces a -m state, while +y current maintains a +m state, enabling deterministic all electrical SOT switching without the need for an external magnetic field. In 2015, You *et al* have utilized this magnetization switching mechanism based on tilted anisotropy through the engineering of Ta/CoFeB/MgO/Ta heterostructure [81]. As shown in figures 9(b) and (a) wedge shape was formed through a hard mask and Ar^+ ion milling process, causing the magnetization of CoFeB in the wedge region to tilt to minimize magnetostatic energy. Then the reversible and deterministic switching was achieved without the need for an external magnetic field. While this study employed a sophisticated fabrication method to engineer tilted anisotropy, it opens up the

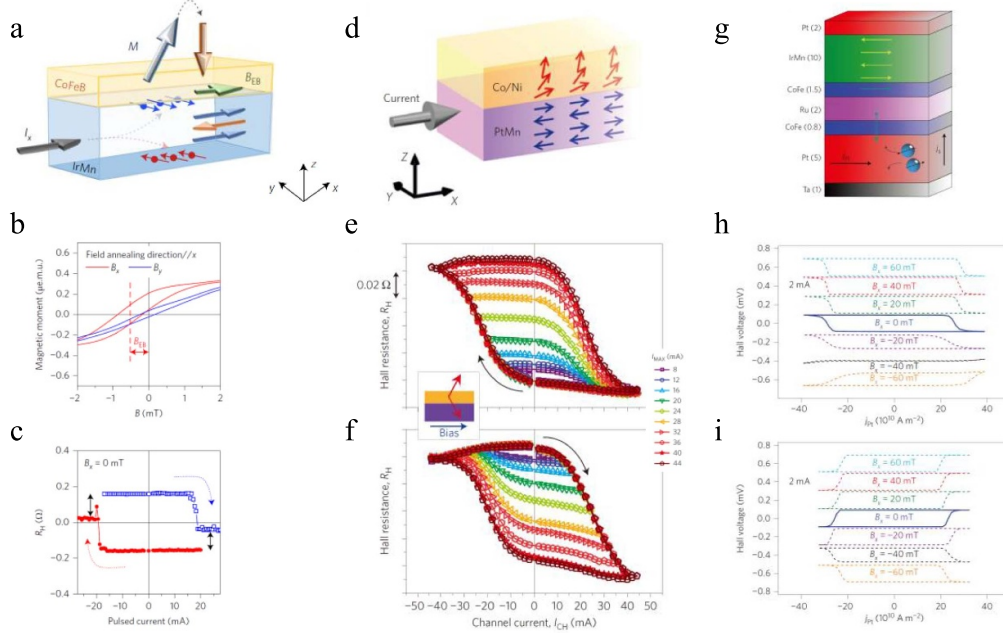


Figure 8. All electrical SOT switching induced by exchange bias and interlayer coupling. (a) Schematics of the IrMn/CoFeB bilayer. (b) In-plane magnetic hysteresis loop of the Ta/IrMn/CoFeB/MgO sample (c) All electrical SOT switching of the Ta/IrMn/CoFeB/MgO sample. Reproduced from [73], with permission from Springer Nature. (d) Schematic of the PtMn/Co/Ni stack. The magnetization near the PtMn interface in the $[\text{Co/Ni}]_n$ multilayer tilts to the x direction affected by the in-plane exchange bias. (e), (f) Anomalous Hall resistance vs. current loops for devices with exchange bias in the $+x$ direction and different current amplitude. Reproduced from [74], with permission from Springer Nature. (g) Stack used for the SOT switching of a PMA CoFeB layer based on interlayer coupling. (h) and (i) Current induced magnetization switching at different external magnetic fields along the current direction, with $t_{\text{Ru}} = 2$ nm (h) and $t_{\text{Ru}} = 2.5$ nm (i). Reproduced from [79], with permission from Springer Nature.

avenue for further exploration of this concept. In other works, such as in $\text{SrIrO}_3/\text{SrRuO}_3$ bilayered structures [82], tilted magneto-crystalline anisotropy was introduced by growing the bilayer on a STO(001) substrate, as depicted in figure 9(c), leading to the realization of all electrical SOT switching. More effective methods for establishing tilted anisotropy include field annealing on CoFeB to create tilted easy axes [89], anisotropy engineering in $[\text{Gd/Co}]_n$ multilayers through the combined contributions of internally and vertically mixed anisotropies [83], use of a miscut substrate to induce a tilted easy axis in $L1_0$ FePt [90], as well as design the orientation of Burgers vectors of dislocations in the Pt/Co heterostructures (figure 9(d)) [91].

In addition to the tilting magnetic anisotropy, Wu *et al* utilize a gradient of magnetization or magnetic anisotropy in $\text{Ta/Gd}_x(\text{FeCo})_{1-x}$ with in-plane gradient of M_s (figure 9(e) upper panel), the Ta/CoFeB (wedged)/MgO with in-plane gradient of magnetic anisotropy (H_k) (figure 9(e) lower panel) and Ta/ $[\text{Gd}_x(\text{FeCo})_{1-x}]_6$, Ta/CoFeB/CoFe/MgO with out-of-plane gradient of M_s (figure 9(f)) [92]. These engineering result in the formation of dynamic noncollinear spin textures under current-driven SOT, breaking the chiral symmetry by DMI. Consequently, all electrical SOT switching of perpendicular magnetization has been achieved.

4. Summary and discussions

The development of SOT has brought great prospects for spintronics. SOT devices hold promise for replacing the prevailing STT based spintronics devices, offering higher efficiency, better reliability, and greater scalability potential. Nonetheless, the road toward practical applications of SOT devices is accompanied by substantial challenges. A most critical one in the operation of SOT devices requires an external magnetic field for achieving perpendicular magnetization switching, which impedes the ultimate goal of making SOT devices practical for achieving all electrical control. Numerous approaches have been explored, including aforementioned exchange bias/interlayer coupling, tilted anisotropy and more recently developed z -spin current to address this challenge. In addition to above explorations, researchers are also actively exploring other innovative approaches. For example, one approach utilizes novel concept of harnessing the interplay of competing spin currents, as exemplified in figure 10(a) [93]. By employing a composite of two HMs, W and Pt, with opposing spin Hall angles, these devices exhibit the capability to induce perpendicular magnetization switching in CoFeB using only in-plane current (figure 10(b)). This phenomenon is ascribed to the generation of competing spin currents by W and Pt, yielding an effective perpendicular field.

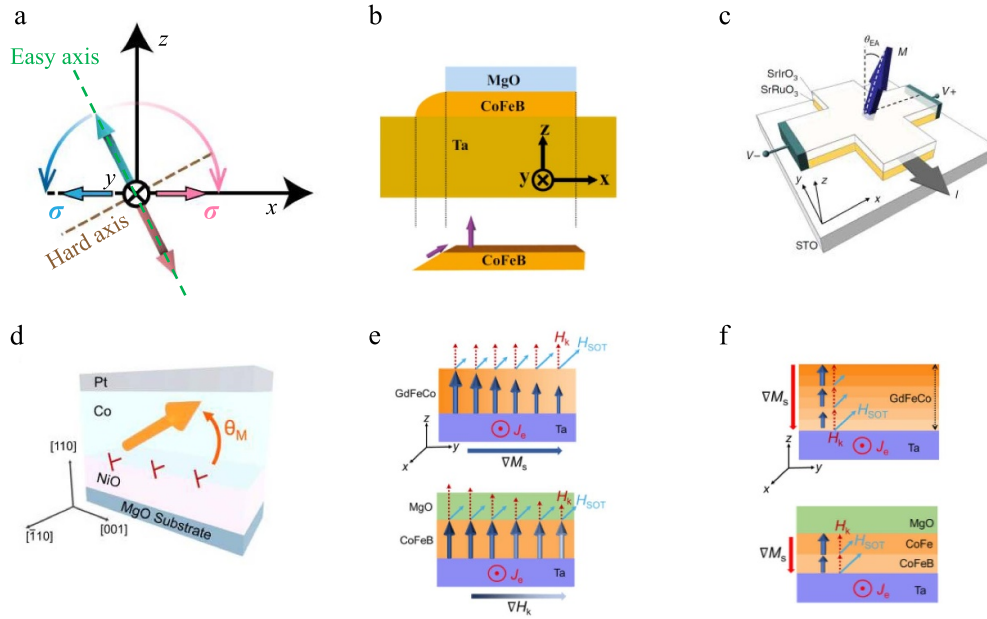


Figure 9. Magnetization engineering based all electrical SOT switching. (a) Schematic description of switching mechanism based on tilted anisotropy. (b) Schematic of the structure and the tilt coming from the spins aligning to the wedge in the Ta/CoFeB/MgO/Ta heterostructure. Reproduced with permission from [81]. (c) SrTiO₃/SrRuO₃ bilayer with tilted anisotropy. Reproduced from [82], with permission from Springer Nature. (d) Tilted magnetic easy axis induced by dislocations in (110)-orientation Pt/Co/NiO/MgO heterostructures. Reproduced from [91]. CC BY 4.0. (e) and (f) Chiral symmetry breaking determined SOT switching with an in-plane gradient of M_s and H_k (e), out-of-plane gradient of M_s (f). Reprinted with permission from [92]. Copyright (2021) American Chemical Society.

This mechanism differs from those solely based on symmetry considerations. Hence, it is of considerable value to conduct more extensive investigations into the field of competing spin currents to gain deeper insight into the associated concepts and mechanisms [94–97].

Leveraging the interplay between SOT and STT represents another noteworthy approach [98–100]. The existence of STT can break the symmetry of SOT, enabling all electrical switching in perpendicular MTJ (p-MTJ) devices. Wang *et al* experimentally demonstrate it in three-terminal p-MTJ devices through the interaction between SOT and STT (figure 10(c)). [98] Tuning the ratio between the SOT and STT current densities results in a substantial decrease in the critical current density for SOT switching, as illustrated in figure 10(d). This approach offers a promising avenue for the development of all electrically controlled, high-density MRAM.

Furthermore, the bending or the non-uniform current effect has been employed to achieve electrical switching in SOT-MTJ devices without external magnetic field [101–104]. As illustrated in figure 10(e), a bending structure is introduced in the SOT channel, generating a bent charge current and subsequently producing a spatially non-uniform spin current (figure 10(f)) [101]. The non-uniformity of the SOT is then applied to the adjacent FM free layer, facilitating deterministic switching without an external magnetic field. The switching mechanism can be understood as the establishment of a fixed nucleation point, determined by the SOT channel's geometry, followed by a complex domain wall propagation process driven by the inhomogeneous SOT. The proposed scheme exhibits scalability, material-agnostic characteristics, and seamless compatibility with wafer-scale manufacturing,

offering a promising avenue for the development of SOT devices.

Nevertheless, the realization of all electrical magnetization control through SOT via the z -spin current holds the most promising direction. This approach offers the potential for enhanced precision and efficiency comparable to the methods [105–109] already appearing in manipulating perpendicular magnetic states for high density SOT device. Its effectiveness stems from its exclusive focus on the engineering of the spin source layer without modifying the magnetic layer, thereby minimizing the influence on the perpendicular magnetized layer which can lead to device instability and decreased operational precision. Also, the introduction of z -spin with its polarization collinear with the direction of PMA will induce an out-of-plane damping-like torque to facilitate a more efficient mechanism, known as anti-damping switching [110, 111]. However, there remains an urgent need for further in-depth research to take the full potential of the z -spin current methodology. As we gain deeper understanding into the intricacies of spin-orbit interactions, the path towards achieving all electrical magnetization control becomes more illuminated. Additionally, the range of material options can be extended from HMs or those with strong SOC to light metals with recently discovered orbital Hall effect (OHE) [112–116] or metal oxides with orbital REE (OREE) [117]. The orbital is another fundamental attribute of electron, and the orbital current does not require strong SOC. The conventional method of employing SHE for achieving all electrical switching can be also generally applied for OHE or OREE. This extension could involve utilizing a wedge-shaped orbital source to induce lateral symmetry, employing light metals alloys with

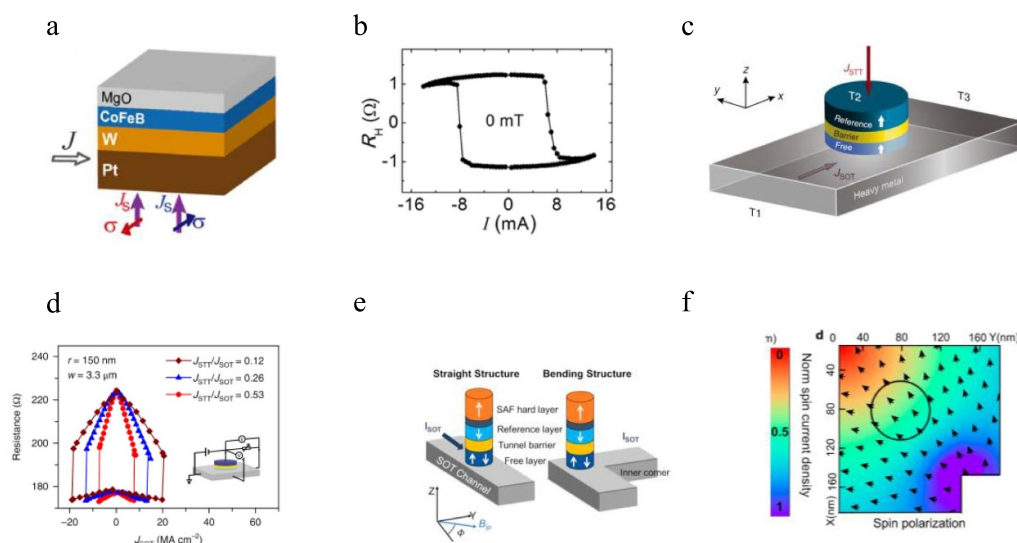


Figure 10. Novel approaches for all electrical SOT switching. (a) Competing SOT effects in Pt/W/CoFeB/MgO stack. (b) All electrical SOT switching in Pt/W/CoFeB/MgO stack. Reprinted (figure) with permission from [93]. Copyright (2018) by the American Physical Society. (c) Principles of the three-terminal devices that combined both SOT and STT. Reproduced from [98], with permission from Springer Nature. (d) Variations in magnetoresistances observed with different current density ratios between SOT and STT. (e) The schematic of a pMTJ on the SOT channel for both straight and bending structural configurations. (f) Spin current gradient of the MTJ in the bending structure. Reproduced from [101]. CC BY 4.0.

crystal asymmetry etc. Combining orbital and spin torque [118] will bring great opportunity to realize a more efficient and effective approach. Lastly, it is important to direct our efforts toward an industrialized strategy. The scalability of SOT devices is of paramount importance, necessitating the ability to fabricate thin films at the wafer level. The maturation of SOT device fabrication techniques will open the door to practical applications and paves the way for the integration of SOT devices into mainstream electronics. By bridging the gap between fundamental research and industrial applications, we embark on a path that may ultimately unlock the full potential of SOT technology and re-define the landscape of spintronics.

Data availability statement

No new data were created or analyzed in this study.

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ORCID iD

Xuepeng Qiu <https://orcid.org/0000-0003-3954-3144>

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