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Spin current and spin-orbit torque induced by ferromagnets

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Spin torque is typically classified based on how the spin current is generated and injected into a magnet for manipulation. Spin-orbit torque arises from the spin-orbit interaction in a nearby normal metal, while spin-transfer torque results from exchange interactions in another ferromagnet. Recent studies have suggested that a ferromagnet itself can also generate a spin current through spin-orbit coupling, leading to the emergence of ferromagnet-induced spin-orbit torque as another class of spin torque. This novel torque mechanism not only inherits the advantages of spin-orbit torque architectures, such as separate reading and writing paths in memory applications but also offers the flexibility to control the generated spin direction by manipulating the orientation of the ferromagnet responsible for generating the spin current. In this article, we review the phenomena related to spin currents generated by ferromagnets, explore their physical descriptions in heterostructures, and discuss several spin torque architectures based on this effect. Ferromagnet-induced spin-orbit torque not only introduces new physical consequences by combining spin-orbit and exchange interactions but also offers a promising building block in spintronics with significant potential for diverse applications.

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INTRODUCTION

Electrical manipulation of magnetization is a key topic in spintronics, bridging the realms of electrical and magnetic degrees of freedom in condensed matter. It opens doors to next-generation devices like magnetic random-access memory and logic applications[1]. When a spin current is injected into a magnetic layer, it transfers its angular momentum to the magnet, generating a spin torque. Figure 1 illustrates two main methods for generating spin torques. In Fig. 1a, a perpendicular electric current becomes spin-polarized due to the exchange interaction between conduction electron spins and magnetic moments in the pinned layer. This spin-polarized electron is then injected into the free layer, exerting a spin-transfer torque (STT)[2–4]. In Fig. 1b, an applied in-plane electric current in a spin-orbit coupled normal metal generates a perpendicular spin current or an interfacial spin accumulation, leading to the so-called spin-orbit torque (SOT)[5,6] on magnetization. The former relies on exchange interaction, while the latter exploits spin-orbit coupling to generate a spin current for injection into the magnetic layer. Both STT and SOT are sufficiently strong to reverse the magnetization direction[7–9].

There are advantages and disadvantages to both methods. STT, requiring perpendicular current injection, shares the same path as tunneling magnetoresistance which is used for reading magnetic information. This can lead to unintended magnetization switching during readout and an endurance issue, making it challenging to optimize device performance. In contrast, SOT, which employs in-plane current injection, separates the reading and writing paths. Moreover, its switching speed can surpass that of STT because the injected spin direction may significantly differ from the initial magnetization direction[10]. However, in most cases, deterministic switching necessitates an external field, unless special treatments like symmetry breaking, exchange bias, or unconventional SOT are employed for field-free switching[11]. This limitation significantly narrows the range of materials and architectures applicable to SOT-based applications.

SOT induced by ferromagnets (FMs) harnesses both exchange and spin-orbit interactions within the FM. This effect arises from the spin-orbit coupling present in a magnetic layer, where an applied electric field can induce a perpendicular spin current. This, in turn, can exert torque on another FM (Fig. 1c)[12,13] or on the magnetic layer itself (Fig. 1d)[14,15]. The FM-induced SOT combines the advantages of both methods: it separates the reading and writing paths, offers controllability of the generated spin current as it depends on the magnetization, and enables field-free switching through additional symmetry breaking by the presence of magnetization. In this article, we review several underlying physics of spin generation in FMs and recent theoretical and experimental advancements in FM-induced SOT. We highlight the potential for innovative architectures in the electrical manipulation of magnetization and its applications.

SPIN CURRENT GENERATION IN FMS

Spin anomalous Hall effect and spin planar Hall effect

The anomalous Hall effect[16] is the most prominent spin-orbit coupling phenomenon in ferromagnetic materials. When an electric field is applied to a FM, the spin-orbit interaction results in a current perpendicular to both the electric field (x) and magnetization (z) directions (Fig. 2a, $j_{\mathrm{AH},\uparrow}+j_{\mathrm{AH},\downarrow}$). The spin anomalous Hall effect[12] represents the spin-polarized version of the anomalous Hall current (Fig. 2a, $j_{\mathrm{AH},\uparrow}-j_{\mathrm{AH},\downarrow}$). Here and in subsequent sections, we refrain from delving into a detailed classification of its origin, such as intrinsic, side jump, and skew scattering, and suggest motivated readers explore other prominent references[16,17]. Since the spin current $j_{\mathrm{AH},\uparrow}-j_{\mathrm{AH},\downarrow}$ includes the spin Hall effect contribution (see next section) as well as the spin anomalous Hall effect contribution, the first-principles calculation of each of the contributions requires careful consideration of their dependencies on the magnetization, as described in ref. [18]. However, such a rigorous distinction does

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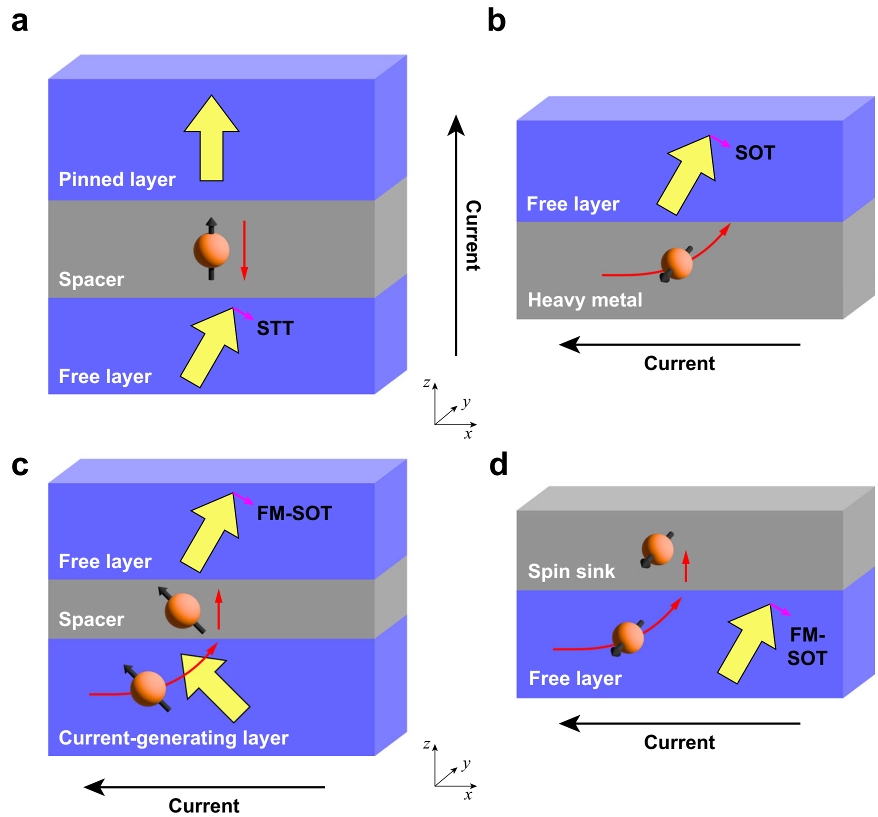

Fig. 1 Illustration of various spin torque mechanisms. **a** Schematics of spin-transfer torque (STT). The current applied along the vertical direction generates a spin-polarized current injected into the free layer and generates STT. **b** Schematics of the conventional spin-orbit torque (SOT). The current applied along the horizontal direction through a heavy metal layer with strong spin-orbit coupling generates a perpendicular spin current injected into the free layer and generates SOT. **c**, **d** Schematics of examples of ferromagnet-induced spin-orbit torque (FM-SOT). The perpendicular spin current generated by spin-orbit coupling in a FM exerts a torque to another FM **c** or the FM itself **d**. The detailed mechanism of **d** is non-trivial so we focus here on phenomenological illustration and defer the illustration of its detailed mechanism to Fig. 4 and related discussions. Throughout this article, blue (gray) layers denote magnetic (non-magnetic) layers, and yellow, red, and magenta arrows denote the directions of magnetization, spin flow, and spin torque, respectively. As the directions of spin torque depends on the details of the system, the directions of the magenta arrows do not have physical meanings but are for schematic purpose only. Orange spheres denote conduction electrons whose spin directions are depicted by black arrows.

not impact its qualitative phenomenology and possible applications, so the entire contribution is often called the spin anomalous current[13]. Due to the microscopic complexity, the spin polarization of the anomalous Hall current is different from its longitudinal counterpart[12].

In addition, the planar Hall effect may generate a similar phenomenon. The planar Hall effect generates a Hall current when both components of magnetization along the input-current (x) and output-current (y) directions are nonzero. The main origin of the planar Hall effect is known to be the anisotropic magnetoresistance which is generally present in FMs. In Fig. 2b, the planar Hall current is given by $j_{\mathrm{PH},\uparrow}+j_{\mathrm{PH},\downarrow}$ where $j_{\mathrm{PH},\uparrow}$ and $j_{\mathrm{PH},\downarrow}$ are generally different due to the spin polarization of the ferromagnet. Therefore, its spin-polarized version generates a spin planar Hall current ($j_{\mathrm{PH},\uparrow}$ - $j_{\mathrm{PH},\downarrow}$) with a different magnetization direction[19,20].

As a side note, it is important to distinguish the terminology "spin anomalous Hall effect" from the "anomalous spin Hall effect"[21]. The latter refers to the spin Hall effect with an unconventional direction of generated spin due to the presence of the magnetization and is discussed in the section named "magnetization-dependent spin Hall effect" below. Similarly, the spin planar Hall effect is a different phenomenon from the planar spin Hall effect in nonmagnets[22]. Note that while the the planar spin Hall effect in nonmagnets requires crystailline asymmetry while the (spin) planar Hall effect in ferromagnets does not.

An advantage of the spin anomalous Hall effect is its ability to conveniently generate a spin current with a desired spin direction, leveraging the controllability of the magnetization direction. However, the field-free switching of a perpendicular magnet is technically difficult since the controllability usually relies on an external magnetic field. Another drawback is that its spin direction is always aligned with the magnetization direction, preventing it from exerting torque on the FM itself and necessitating the use of another FM. The spin torque generated by injecting the spin anomalous Hall current into another FM is discussed later in this article.

Spin Hall effect in FMs

The spin Hall effect[23] is another spin-orbit phenomenon that can convert a charge current into a spin current. When an electric field is applied, spin-orbit interaction results in a spin current flowing perpendicular to the electric field direction, with the spin direction (z) perpendicular to both the input-current (x) and output-current (y) directions (Fig. 2c). A crucial distinction between the spin Hall effect and the spin anomalous Hall effect is that the former does not primarily require magnetism. Therefore, the spin and flow directions of the spin Hall current can be in any direction perpendicular to the applied field, whereas the spin anomalous Hall current flows perpendicular to the magnetization, with the spin direction aligned with the magnetization direction. This

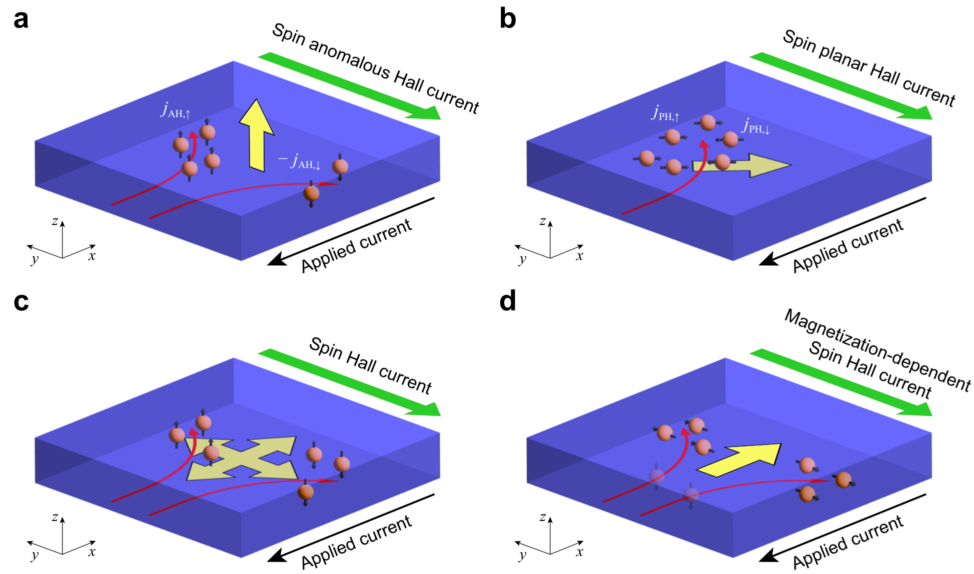

Fig. 2 Illustration of various spin generation mechanisms in FMs. **a** $j_{AH,\uparrow}$ and $j_{AH,\downarrow}$ denote the majority and minority spin current flows induced by the anomalous Hall (AH) effect. The negative sign is introduced for $j_{AH,\downarrow}$ because its direction is opposite to $j_{AH,\downarrow}$. The spin anomalous Hall current is given by $j_{AH,\uparrow} - j_{AH,\downarrow}$. **b** A similar mechanism applied for the planar Hall (PH) effect. The spin planar Hall current is given by $j_{PH,\uparrow} - j_{PH,\downarrow}$. Here the direction of $j_{PH,\downarrow}$ is illustrated as the same direction of $j_{PH,\uparrow}$ because the planar Hall effect mainly originates from anisotropic charge transport. **c** The spin Hall effect generated in a FM. The magnetization direction is illustrated arbitrarily since the spin Hall effect may occur regardless of the direction of the magnetization. **d** Precession of spins of the spin Hall current (translucent orange spheres) around the magnetization direction generates a spin current with another spin component, providing an example of the magnetization-dependent spin Hall effect.

difference in features makes them suitable for different types of architectural applications.

Since spin-orbit coupling energy is typically smaller than the exchange energy in transition-metal ferromagnets (FMs), the spin Hall current with a spin direction transverse to the magnetization had been regarded as negligible[24]. However, several experimental works reported the inverse spin Hall effect in FMs[25,26] and a recent theoretical work[18] has shown that an electric field applied to a FM can quantum-mechanically mix the majority and minority states, resulting in a non-negligible transverse spin Hall current. The calculated spin Hall conductivities for typical 3d transition-metal FMs, such as Fe, Co, and Ni, are found to be $10^3\ \Omega^{-1}\ \mathrm{cm}^{-1}$, which is on the same order of magnitude as that of Pt, and thus the spin Hall effect in FMs should no longer be neglected.

Magnetization-dependent spin Hall effect

A distinct feature of FMs is the presence of magnetism, which can render the response coefficients dependent on the magnetization direction. Of particular interest is the emergence of unconventional components of the spin Hall current that are forbidden in symmetric normal metals. In terms of symmetry, magnetization (*e.g.*, along the z-axis) breaks mirror symmetry with respect to any plane including its vector (*e.g.*, the yz plane and zx plane). The symmetry breaking permits the existence of unconventional spin current components[27,28] as reviewed in ref. [29].

One physical mechanism responsible for the unconventional component allowed by the magnetization is the precession of the spin around it[30]. As shown in Fig. 2d, an electrical current applied along the x direction primarily generates a spin-z current flowing along the y direction, by the conventional spin Hall effect. Due to the exchange interaction between the conduction electron spins and magnetic moments, the generated spins may precess around the magnetization, resulting in an additional spin-y current flowing along the y direction. This generation of a spin Hall current with unconventional spin directions, even in high-symmetry crystals, is a unique feature of magnetic systems. This phenomenon has also been referred to by various terminologies such as the spin Hall effect with spin rotation[31], anomalous spin Hall effect[21], spin-orbit precession[32,33], and the spin swapping effect[34,35].

There are several features of this contribution. First, the additional component arising from the precession is odd with respect to time reversal, indicating that it should originate from an extrinsic mechanism. This can be proven by the relation $j^{\beta}_{s,\alpha} = \sigma^{\beta}_{\alpha\gamma}(\mathbf{m})E_\gamma$ where E_γ is the applied electric field along γ and $j^{\beta}_{s,\alpha}$ is the spin-β current flowing along α. $\sigma^{\beta}_{\alpha\gamma}(\mathbf{m})$ is the corresponding coefficient which satisfies $\sigma^{\beta}_{\alpha\gamma}(-\mathbf{m}) = -\sigma^{\beta}_{\alpha\gamma}(\mathbf{m})$. If $\sigma^{\beta}_{\alpha\gamma}(\mathbf{m})$ purely originates from intrinsic mechanisms, the time-reversal operation implies $j^{\beta}_{s,\alpha} = \sigma^{\beta}_{\alpha\gamma}(\mathbf{m})E_\gamma = -\sigma^{\beta}_{\alpha\gamma}(\mathbf{m})E_\gamma$ and thus its absence. Second, it originates from both the exchange interaction and the spin-orbit interaction. A recent theory suggests that their combination may create momentum-space hot spots of its contributions potentially enhancing its tunability[35]. These features would be helpful for its optimization.

While this illustration intuitively explains an example of the magnetization-dependent spin Hall effect, we emphasize that this is not the whole story. The magnetization-dependent spin Hall conductivity may be represented in the general form of $\sigma^{\beta}_{\alpha\gamma}(\mathbf{m}) = \sigma^{\beta,(0)}_{\alpha\gamma} + \sigma^{\beta,(1)}_{\alpha\gamma,i} m_i + \sigma^{\beta,(2)}_{\alpha\gamma,ij} m_i m_j + \sigma^{\beta,(3)}_{\alpha\gamma,ijk} m_i m_j m_k + \cdots,$ following the Einstein convention. Characterizing each term and identifying other non-negligible contributions would not only be of great physical interest but also open up additional avenues for spintronic applications.

SPIN FLOW IN FMS

Spin-precessing transport

To examine the effects of spin currents generated by a FM, it is necessary to develop a theoretical framework for their transport in heterostructures. A well-known formalism for this purpose is the spin drift-diffusion formalism (combined with the magnetoelectric circuit theory), which is based on the semiclassical Boltzmann approach[36–38]. This semiclassical formalism is effective for describing the transport of eigenstates, such as spins in normal

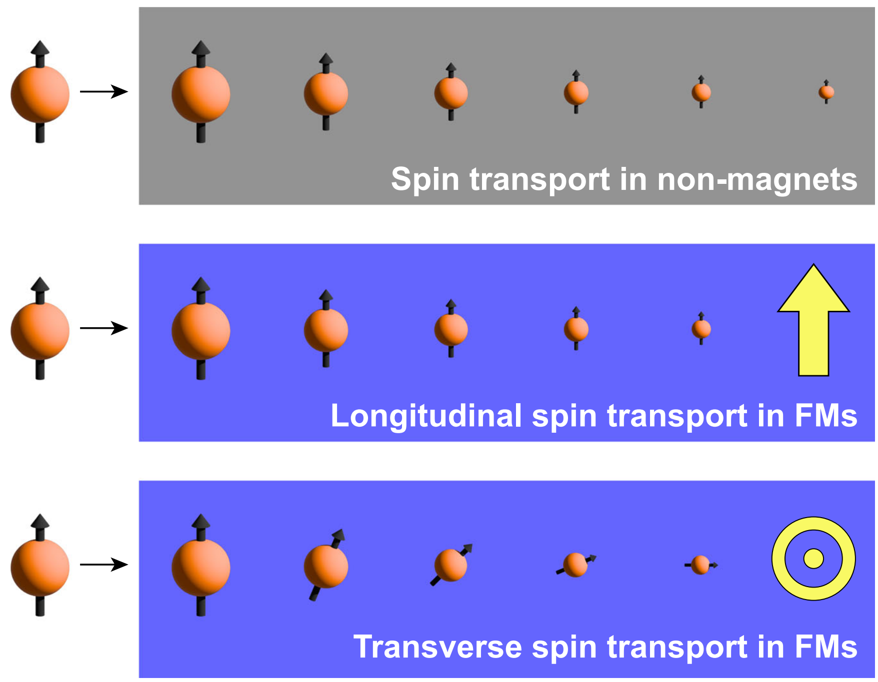

Fig. 3 Transport of injected spins in a non-magnetic metal (top) and a ferromagnet (FM). Although a spin component longitudinal to the magnetization direction undergoes a similar decay mechanism to that in a normal metal (middle), a spin component transverse to the magnetization direction generates another component due to spin-precessing transport (bottom). Here the yellow arrows in the middle and bottom panels are magnetization directions in the FMs and the gradual decreases in the size of electrons represent the decay of the magnitudes of non-equilibrium spins.

metals or the longitudinal spins in ferromagnets. However, when dealing with the spin Hall effects in ferromagnets, it becomes necessary to consider a spin component that is transverse to the magnetization. This component does not solely belong to either the majority state or the minority state but is a quantum superposition of both. Therefore, to analyze spin-orbit effects in FM-based heterostructures, it is essential to go beyond the semiclassical approach and to incorporate the quantum kinetic theory of the Wigner function or, equivalently, the quantum Boltzmann approach.

While quantum transport theory is typically complex and may not yield a tractable analytical formula for experimental fitting, there have been several efforts to simplify it to a level akin to conventional diffusion formalism. Given that the time evolution of a spin-quantum state within a FM can be conceptualized as spin precession, examining the following continuity equation provides an effective means of describing quantum spin transport[34,38–41].

$$\nabla \cdot \mathbb{Q}_s \sim -\frac{(\boldsymbol{\mu}\cdot\mathbf{m}+P\mu_0)\mathbf{m}}{\lambda_{\mathrm{sf}}^2}-\frac{\boldsymbol{\mu}_\perp}{\lambda_{\mathrm{dp}}^2}-\frac{\boldsymbol{\mu}_\perp\times\mathbf{m}}{\lambda_{\mathrm{p}}^2} \tag{1}$$

where $\mathbb{Q}_s$ is the spin-current tensor, $\boldsymbol{\mu}$ and μ_0 are the spin and charge chemical potentials, respectively, $\boldsymbol{\mu}_\perp = -\mathbf{m}\times(\mathbf{m}\times\boldsymbol{\mu})$ is the transverse spin chemical potential, and λ_{sf}, λ_{dp}, λ_{p} are the phenomenological length scales corresponding to the spin flip, spin dephasing, and spin precession, respectively. The first term is the vector representation of the two-current model[42] and its behavior is similar to the spin diffusion in a normal metal (Fig. 3, top and middle). The last two terms in Eq. (1) account for the evolution of the transverse components. The dephasing term behaves similarly to the spin diffusion in normal metal, gradually losing its component, while the precession term alters its component to a perpendicular one ($\boldsymbol{\mu}_\perp\times\mathbf{m}$) during transport (Fig. 3, bottom). This behavior can be intuitively understood through the concept of the spin precession. While the length scale of the longitudinal spin diffusion (λ_{sf}) is on the order of 10 nm[43], those of the transverse spin decay (λ_{dp}, λ_{p}) are an order-of-magnitude smaller for strong ferromagnets[44,45]. Although the roles and physical mechanisms of the spin-precessing transport are similar to those discussed in the magnetization-dependent spin Hall effect above, both should be considered in the equation of motion and treated on equal footing[41]. This is because the magnetization-dependent spin Hall effect reflects spin precession during the generation of the spin current while spin-precessing transport involves precession during the transport of the *generated* current.

Generalized spin drift-diffusion formalism

Considering the modified continuity Eq. (1) extends the drift-diffusion formalism directly. Let us briefly review the core results for spin transport along the z direction, for example. By using $\mathbb{Q}_s \sim \partial_z\boldsymbol{\mu}_\perp +$ (spin Hall currents) for the transverse components, Eq. (1) gives that the transverse spin chemical potential takes the form of $\mu_{\perp,1} + i\mu_{\perp,2} \sim e^{\pm z/\lambda_F}$ where the subscripts 1 and 2 are the two directions transverse to the magnetization and λ_F is the complex diffusion length given by $\left(\lambda_{\mathrm{dp}}^2 + i\lambda_{\mathrm{p}}^2\right)^{-1/2}$. Note that the imaginary part of λ_F^{-1} corresponds to the spin precession as implied by the sinusoidal nature of the complex exponential function. By fitting the oscillation and decay lengths to $\mathrm{Im}\left[\lambda_F^{-1}\right]^{-1}$ and $\mathrm{Re}\left[\lambda_F^{-1}\right]^{-1}$, respectively, one can experimentally determine the phenomenological parameters λ_{dp} and λ_{p}, as attempted in ref. [46].

The boundary condition between a normal metal and a FM also plays a crucial role in the drift-diffusion formalism. In the magnetoelectric circuit theory[24], the concept of spin mixing conductance quantifies the interfacial spin current generated by spin injection from the normal metal side. However, it overlooks the possibility of the existence of a transverse spin component generated within the ferromagnetic side due to strong exchange

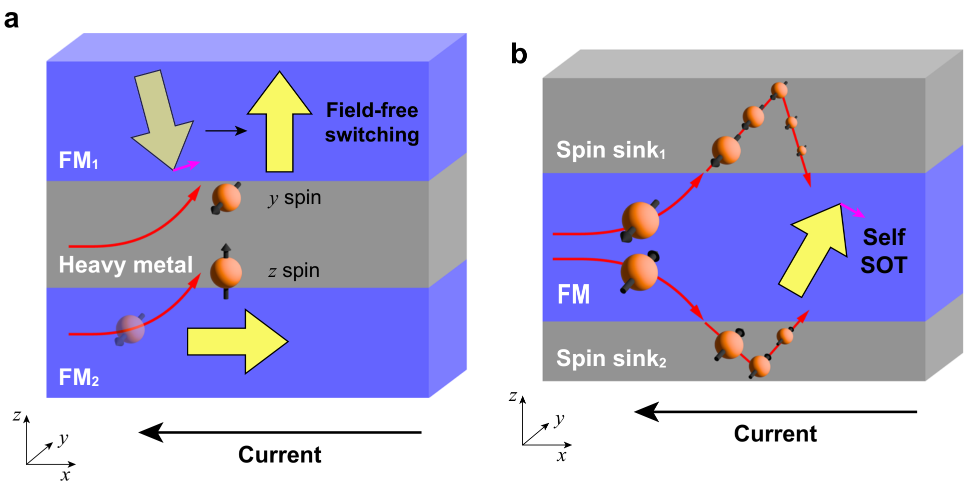

Fig. 4 Examples of architectures for SOT induced by FMs. a Illustration of field-free switching of a FM (FM_1) assisted by another FM (FM_2). When an external current is applied along the *x* direction, the *z* spins generated by the magnetization-dependent spin Hall effect in FM_2 as well as the *y* spins generated by the spin Hall effect in the heavy metal enable deterministic switching without the help of an external magnetic field. The switching process is not deterministic if it relies solely on the spin Hall effect in the heavy metal. **b** Illustration of self-generated SOT driven by the spin Hall effect in a FM. The spin Hall currents outgoing from the FM are reflected at outer boundaries and lead spin torque to the FM itself. The imbalance between the re-entering spin angular momenta from top and bottom interfaces results in a non-zero SOT. Here the gradual decreases in the size of electrons represent the decay of the magnitudes of non-equilibrium spins. Although the spin sink layers are denoted by gray layers, they are not necessary to be non-magnets but can be antiferromagnets, artificial superlattices, or even vacuums.

interactions. As the significance of the spin Hall effect in FMs has been revealed, a recent theory[41] has developed a modified boundary condition that considers the presence of transverse spin accumulation on the ferromagnetic side. It has been revealed that this additional contribution to the boundary condition takes the same form as the conventional spin mixing conductance, although they are calculated from different microscopic parameters.

SOT GENERATION BY FMS

Controllable spin-orbit torque in magnetic trilayers

A spin current generated by spin-orbit coupling in one FM can be injected into another FM to induce a spin torque (Fig. 1c). This can be achieved in a magnetic trilayer consisting of two separate FMs, which we refer to as FM_1 and FM_2. For instance, FM_2 can exert a spin torque on FM_1 through the spin anomalous Hall effect, as proposed by Taniguchi et al. [12] and experimentally demonstrated in refs. [13,47–50]. Another scenario involves spin torque generation via the spin planar Hall effect[19,20]. The ability to manipulate magnetization in FM_2 enhances its functionality and facilitates scientific analysis.

The spin current generated by a FM can be combined with the conventional spin Hall current produced by a normal metal to enable field-free switching of perpendicular magnetization, which is a crucial challenge in the realm of SOT. For example, a theoretical proposal[51] has suggested that the anomalous Hall current generated by FM_2 can assist in the field-free switching of FM_1. Another example is presented in Fig. 4a, where the magnetization-dependent spin Hall effect induced by FM_2 generates a spin current with out-of-plane (*z*) spin polarization, facilitating field-free switching of FM_1. Although the spin planar Hall effect in FM_2 may generate an out-of-plane spin polarization $\sim M_x M_z$, it is difficult to realize a FM with the intermediate direction of magnetization between the *z*-axis and the *x*-axis without an external magnetic field. Several recent works[33,52–54] report field-free switching in structures similar to Fig. 4a. Here, the polarity of the deterministic switching can be controlled by the direction of FM_2, potentially used for logic applications. Furthermore, a recent experiment[55] demonstrated a 30% reduction in the field-free switching current by exploiting all three components of a spin current generated in magnetic trilayers: the spin anomalous Hall current (**m**), the spin Hall current (**y**), and the magnetization-dependent spin Hall current ($\mathbf{m} \times \mathbf{y}$).

Self-generated SOT in a single FM

A transverse spin Hall current generated by a FM may induce torque to the FM itself, a phenomenon referred to as self-generated SOT or the anomalous SOT[14] (Fig. 4b). The lack of necessity for other spin sources, such as another FM or an adjacent heavy metal, is a unique feature of self-generated SOT that has the potential to simplify the architecture. Several theoretical works[41,56] imply that the following two conditions should be met to achieve a non-zero self-generated SOT. First, there must be a symmetry breaking along the perpendicular direction to prevent the contributions at the top and bottom interfaces from canceling out each other. Second, in accordance with the conservation of angular momentum, a spin sink absorbing the spin angular momentum carried by the spin Hall current is required. In terms of symmetry, the self-generated SOT is akin to the SOT generated by the Edelstein effect[57–60], but it offers a more suitable explanation for three-dimensional heterostructures based on typical 3*d* transition-metal FMs. Detailed separation of the two contributions requires further effort.

The illustration in Fig. 4b implies the above constraints evidently. In Fig. 4b, the spin Hall currents leaving from the FM and their reflection at the outer boundaries are depicted. The re-entering spin angular momentum from the top interface is given by $\mathbf{s}_1 - \Delta\mathbf{s}_1$ where $\mathbf{s}_1$ is the outgoing spin angular momentum to Spin sink_1 and $\Delta\mathbf{s}_1$ is its absorption by the Spin sink_1. The same logic is valid for the bottom interface and Spin sink_2. As a result, the total angular momentum incoming to the FM is $\mathbf{s}_1 + \mathbf{s}_2 - \Delta\mathbf{s}_1 - \Delta\mathbf{s}_2$. Since $\mathbf{s}_1 + \mathbf{s}_2 = 0$, the total self-generated SOT is given by $\Delta\mathbf{s}_{\text{self}} \equiv - \Delta\mathbf{s}_1 - \Delta\mathbf{s}_2$. Note that the equation $\Delta\mathbf{s}_{\text{self}} + \Delta\mathbf{s}_1 + \Delta\mathbf{s}_2 = 0$ is a result of the angular momentum conservation. If the spin sinks do not absorb any angular momentum, the self-generated SOT vanishes. In addition, in order to exhibit non-zero $\Delta\mathbf{s}_{\text{self}}$, the symmetry between the two sides should be broken to satisfy $\Delta\mathbf{s}_1 \neq - \Delta\mathbf{s}_2$.

The potential candidates for a spin sink include any materials capable of absorbing spin angular momentum, such as adjacent heavy metals[14,15,61], interfacial spin scattering[15,62–65], magnon dissipation[46], and even another FM. While a non-magnetic material with short spin diffusion length can be a good candidate for the spin sink, that with a long spin diffusion length, like Cu, are not suitable as spin sinks. The source of asymmetry not only includes the structural inversion asymmetry and inequivalent interfaces exploited in the references above but also encompasses a compositional gradient within the FM[66,67]. As a remark, although the magnetization-dependent spin Hall effect can generate a spin component parallel to its flow direction, it cannot contribute to field-free switching because its direction depends on the magnetization direction. Therefore, additional lateral symmetry breaking is required for achieving field-free switching as demonstrated in several recent experimental efforts[68–71].

CONCLUSION AND OUTLOOK

In this article, we review the spin current and SOT generated by FMs. The FM-induced SOT offers both advantages of separate reading/writing paths and the controllability of the generated spin currents. The spin anomalous Hall effect and spin planar Hall effect are able to generate controllable spin-orbit torque in magnetic trilayers and the spin Hall effect enables self-generated SOT in a single FM. Also, the unique transport properties of FMs such as the magnetization-dependent spin Hall effect and the spin-precessing transport enrich its potential. In order to fully exploit the potential of SOT generated by FMs, additional theoretical and experimental efforts are desired. For instance, a challenging task of separating the contribution from FMs from other sources, such as adjacent materials and interfacial spin current[32], needs to be addressed. Furthermore, experimental characterization of transport parameters, such λ_{sf}, λ_{dp}, λ_p, is far from satisfactory at the moment. Lastly, recent experimental reports[72,73] on strong spin-orbit torque not relying on composition gradients and interfaces require further theoretical and experimental investigations into the detailed mechanisms of the self-induced spin-orbit torque.

The FM-induced SOT may provide further functionality of spintronic architectures when combined with previous methods, e.g., the manipulation of the FM that generates a spin current can be controlled by the conventional spin torque. Although our focus is on spin currents generated by FMs, there are numerous similar works conducted with antiferro/ferrimagnets[74–81], altermagnets[82,83], and artificial superlattices[84]. Further theoretical research on spin currents generated by those materials and efforts to integrate these technologies would significantly diversify the architectures for spintronic applications.

Lastly, we discuss the relationship between FM-induced SOT and the field of orbitronics, which is another recently emerging area in spintronics. First, it has been recently reported that orbital transport in FMs may be longer than spin transport[85]. Introducing the orbital degree of freedom in the field of FM-induced SOT could offer new possibilities. Second, analyzing the FM-thickness dependence of SOT[85–89] in the field of orbitronics requires careful elimination of contributions from FM-induced SOTs. Third, the quantum spin transport theory introduced above shares similarities with the orbital transport theory[90,91]. This is because orbital angular momentum results from quantum mechanical superpositions of orbital-quenched eigenstates, which is similar to the transverse spins in FMs[92]. Therefore, further enhancements in theoretical frameworks for FM-induced SOT would be beneficial for orbitronics as well.

DATA AVAILABILITY

No datasets were generated or analyzed during the current study.

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AUTHOR CONTRIBUTIONS

K.-W.K. drafted the outline of the article and designed the original figures with assistance from the other authors. K.-W.K., B.-G. Park, and K.-J. Lee contributed to writing the manuscript.

COMPETING INTERESTS

The authors declare no competing interests.

ADDITIONAL INFORMATION

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