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Perspective

Challenges and opportunities for spintronics based on spin orbit torque

Shuai Ning[a], Haoliang Liu[b], Jingxiong Wu[a], Feng Luo[a,*]

[a] *School of Materials Science and Engineering, Nankai University, Tianjin 300350, China*
[b] *School of Science, Harbin Institute of Technology, Shenzhen 518055, China*

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ABSTRACT

Spintronic devices based on spin orbit torque (SOT) have become the most promising pathway to the next-generation of ultralow-power nonvolatile logic and memory applications. Typical SOT-based spintronic devices consist of two functional materials: a spin source and a magnetic material. Spin source materials possess a strong spin orbit coupling, enabling efficient interconversion between charge and spin current. Magnetic materials are used to process and archive the information via the interaction between the local magnetic moment and the spin current generated from spin source. Considerable efforts have been put into the design of materials and devices in the past decades to realize the electrical control of magnetic switching. However, a number of key challenges still remain to be addressed for the practical application. In this paper, we reviewed the development of a range of novel materials for both the spin source and the magnetic functionalities, particularly the complex oxides and organic spintronic materials. We also discussed and highlighted several key issues, such as the mechanism and manipulation of SOT and the large-scale integration of SOT-based devices, which merit more attention in the future.

Spintronics, an emerging interdisciplinary field at the intersection of physics, materials science, and information technology, utilizes interactions between the charge and spin of electrons to interconvert electrical and magnetic signals, and has attracted considerable interest for next-generation logic and memory devices. The field of spintronics began with the discovery of giant magnetoresistance (GMR) in 1988 and has produced large-scale commercial applications. Since then, a range of exotic spintronic phenomena have been discovered, resulting in a boom in information science and technology. Tunneling magnetoresistance (TMR) in magnetic tunnel junctions (MTJs) has led to the development of scalable magnetic random access memory (MRAM). Spin transfer torque (STT) has enabled the commercialization of MRAMs with all-electrical reading and writing. STT-MRAMs are being used as a replacement for embedded flash memory and static random-access memory (SRAM). Despite the above commercial applications, new discoveries in physics and innovations in materials design are urgently required for the development of high-performance, high-speed, low-power, and non-volatile devices in order to satisfy the rapidly increasing demands for big data, artificial intelligence, and the Internet of Things.

Spin orbit coupling (SOC) with mechanisms such as spin current generation via the spin Hall effect (SHE) (Fig. 1a) or non-equilibrium spin accumulation at the surface or interface with inversion symmetry breaking via the Rashba–Edelstein effect (Fig. 1b) can give rise to a new family of torques, namely, spin orbit torques [1] (SOTs), thereby providing a new route to novel spintronic devices.

SOT-based devices are typically composed of two classes of materials, namely, spin-source and magnetic materials. The model system is a bilayer heterostructure comprising heavy metals (HM) and ferromagnetic (FM) metals or alloys. In the HM/FM heterostructures, when an electric current is applied in plane, a spin current is generated perpendicular to the plane of the HM layer, which exerts torques on local moments of the adjacent FM layers, transfers orbital angular momentum from the lattice to the spin, and leads to magnetization switching (Fig. 1c). SOT can work in a three-terminal MRAM configuration, allowing for improved device endurance and faster and more energy-efficient electrical manipulation of magnetic order. In addition to current-induced magnetization switching, SOT is also able to drive high-frequency oscillation (Fig. 1d), fast motion of domain walls or exotic topological textures (Fig. 1e), and generation of spin waves (Fig. 1f), showing great potential for applications such as oscillators, racetrack memory, neuromorphic computing, and spin logic gates.

HMs, including 5d transition metals like Pt [2] and Ta [3], are the most common spin source materials owing to their intrinsic SHE. Using different HMs, SOTs of various magnitudes and signs have been found to be successful at switching FM with either in-plane anisotropy (IPA, e.g., NiFe) or perpendicular magnetic anisotropy (PMA, e.g., Co, CoFeB). In addition to the well-established HM/FM system, a range of new materials has been studied to realize a more efficient SOT and lower power

* Corresponding author.
E-mail address: feng.luo@nankai.edu.cn (F. Luo).

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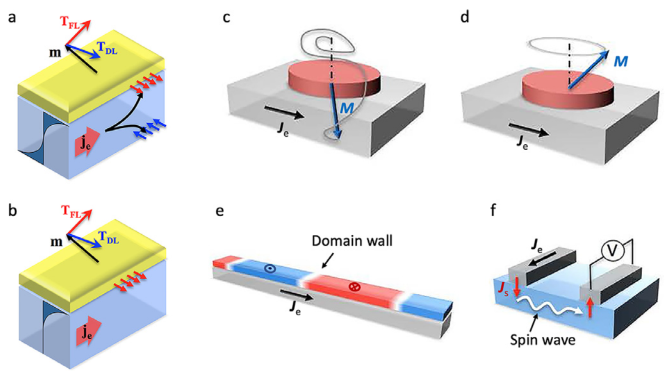

Fig. 1. Mechanisms and applications of Spin orbit coupling. (a, b) Charge-to-spin conversion mechanisms including the SHE (a) and Rashba–Edelstein effect (b). Both mechanisms produce damping-like and field-like torques. The red and blue arrows correspond to the field-like and damping-like torques, respectively. (c-f) Spin orbit torques are able to induce magnetization switching (c), high-frequency oscillation (d), domain wall or magnetic topological texture motion (e), and spin wave generation (f). $\boldsymbol{J}_e$, $\boldsymbol{J}_s$, and $\boldsymbol{M}$ are the charge current, spin current, and magnetic moment, respectively [1].

consumption. Herein, we will review several representative material systems designed for both spin source and magnetic materials and highlight several key topics in SOT-based spintronic devices to provide a broad perspective on novel SOT-based applications.

In addition to HMs, various novel spin source materials have been studied in order to realize strong spin-charge conversion. Topological insulators (TIs, e.g., $Bi_xSe_{(1-x)}$ [4]) have been reported to exhibit considerable SOT via SHE. Certain magnetic materials that comprise heavy elements, such as antiferromagnetic (AFM) alloys (e.g., IrMn and PtMn), have also been reported to show large SOT efficiency, providing more choices for the design of spin source materials [5]. Meanwhile, materials with inversion symmetry breaking, such as Weyl semimetals like transition-metal dichalcogenides (TMDs, e.g., WTe_2 [6]), are another choice of spin source for realizing spin-charge conversion via the Rashba–Edelstein effect. Non-centrosymmetric magnetic crystals, particularly the Heusler compound (e.g., NiMnSb [7]), a half-metal ferromagnet, have also been reported to exhibit a noticeable Rashba–Edelstein-induced SOT, providing a pathway for realizing spin-charge conversion in a single ferromagnet for SOT-based spintronics.

Complex oxides exhibit a broad range of fascinating properties stemming from the interplay between charge, spin, lattice, and orbital degrees of freedom and have become an important branch of SOT-based spintronics [8]. SOT-driven magnetization switching has been realized in $SrIrO_3/SrRuO_3$ heterostructures at 70 K [9], in which $SrIrO_3$ and $SrRuO_3$ function as the spin source and the magnetic layer, respectively. The magnetic anisotropy of $SrRuO_3$ can be tuned by alternating the epitaxial growth orientation or strain, offering possibilities of tilting its easy axis away from the out-of-plane direction, thereby breaking the symmetry and enabling field-free switching.

In addition, the strong Rashba SOC in the d bands of the two-dimensional electron gas (2DEG) at the $LaAlO_3/SrTiO_3$ interface [10] enables efficient spin-to-charge conversion, providing a new platform for the design of novel spin-orbitronics (Fig. 2). For instance, combined the SOC materials with multiferroic materials, magnetoelectric-spin-orbit (MESO) devices, wherein magnetoelectric coupling allows voltage control of writing and the inverse Rashba–Edelstein effect enables electrical reading, have been proposed[11], showing potential for new types of ultralow-power device applications. Devices that integrate ferroelectricity into the 2DEG, namely, ferroelectric-spin-orbit (FESO) devices, will allow non-volatile voltage-controlled switching without magnetic layers [12], providing new opportunities for the design of ultralow-power logic and memory devices. However, realizing this type

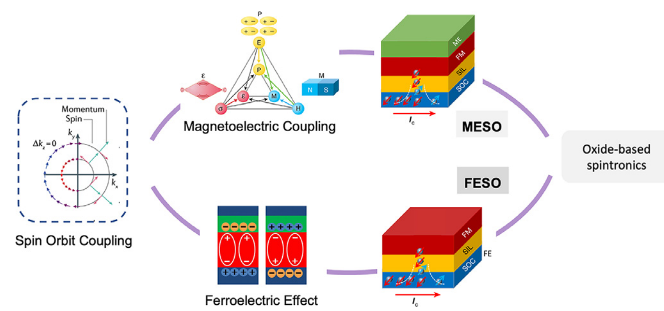

Fig. 2. Integrating SOC with magnetoelectric coupling or the ferroelectric effect into MESO or FESO devices, allowing the realization of voltage-controlled all-oxide-based spintronics for ultralow-power and non-volatile applications.

of control above room temperature with oxide-based spintronics remains a challenge and merits further exploration.

Among magnetic materials, in addition to the common FM metals or alloys, ferrimagnets (FIM) and antiferromagnets (AFM) have drawn increasing interest for dynamic applications. FIM alloys, typically composed of rare earth metals and transition metal elements (e.g., GdFeCo), allow not only a large SOT efficiency at their magnetization compensation point but also a high SOT-driven domain wall velocity at their angular momentum compensation point. FIM insulators [13], including rare-earth iron garnets (ReIG) like $Tm_3Fe_5O_{12}$ (TmIG) and $Bi_xY_{3\text{-}x}Fe_5O_{12}$ (Bi:YIG), allow for a long spin propagation length and fast domain wall velocity switching owing to the low Gilbert damping, showing more potential for future SOT-based spin wave devices. Through strain/interface engineering, substitution, and composition design, considerable control over the properties, including PMA, damping, compensation temperature, domain wall velocity, and spin mixing conductance, can be realized. In particular, the successful integration of ReIG with Si paves the way for more energy-efficient oxide-based spintronics.

In addition to inorganic systems, SOT has been realized in organic systems, providing alternatives for both spin sources and magnetic materials and offering the great advantage of fine-tuned molecular engineering of their spin-related properties in addition to their low cost, environmental friendliness, and flexibility. The introduction of heavy elements can endow organic materials, such as metal-organic complexes and hybrid organic inorganic perovskites, with a large SOC. For instance, a large Rashba coefficient, i.e., a measure of charge-spin conversion efficiency, was observed in two-dimensional hybrid perovskites, with the magnitude of the Rashba coefficient being 1-2 orders larger than that in inorganic quantum wells [14–15]. The Rashba coefficient could be effectively tuned by both organic and heavy metal replacements as well as external stimuli, such as light irradiation [16]. The chirality of functional organic molecules can be transferred to their complexes, which can act as a spin-selective layer [17–18]. In this case, SOT may be achieved without a magnet.

Organic materials are mainly composed of light elements, such as C, H, and O, and hence exhibit relatively low Gilbert damping. Recently, vanadium tetracyanoethylene ($V(TCNE)_x$, x~1-2), a room-temperature organic ferrimagnet, has shown extremely low Gilbert damping (3×10^{-4} to 5×10^{-5}) [19–20] that is comparable to or even better than that of ReIG. The low Gilbert damping of the magnetic layer in the SOC is beneficial for lowering the critical current of magnetization switching. Moreover, the magnetic properties of organic materials can be tuned by atom/molecule replacement. For instance, the ferrimagnetic order can be converted into an antiferromagnetic order by replacing V and $(TCNE)^-$ in $V(TCNE)_x$ with Mn and $(C_4(CN)_8)^-$ [2], respectively [21], and the magnetic relaxation rate varies with different ligands in single-molecule magnet Co(II) imido complexes [22]. In addition, ubiquitous vacancies and defects in organic materials can form

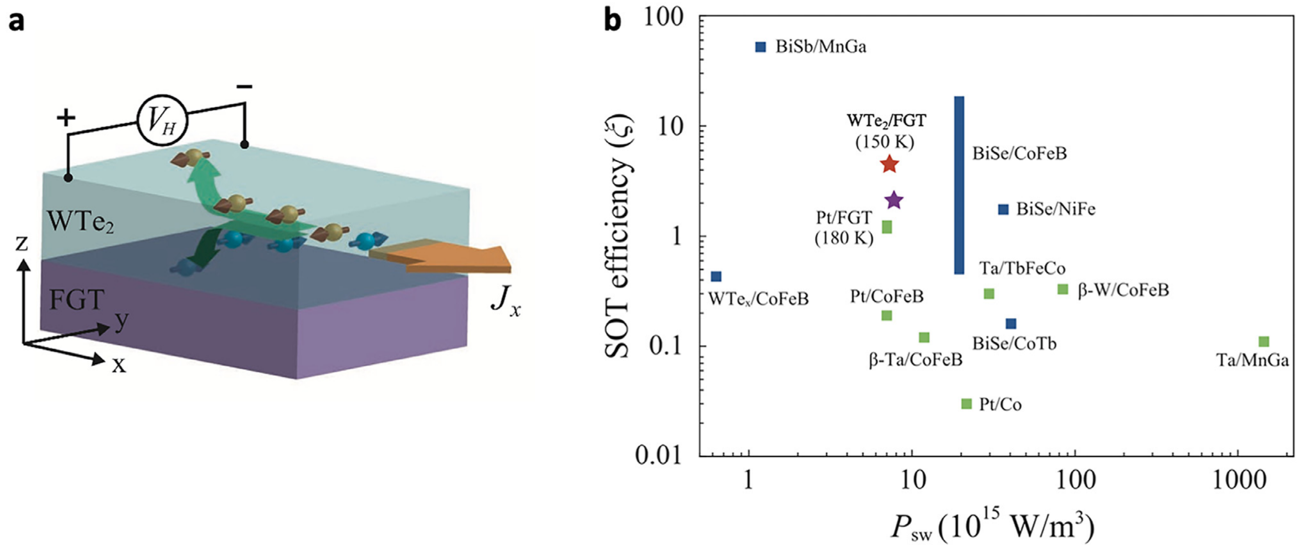

Fig. 3. 2D SOT-based device. (a) The schematics of a WTe_2/FGT heterostructure. The charge current (J_x, yellow arrow) applied to WTe_2 generates a spin current that is injected into the FGT along the z direction, which exerts a torque on the magnetization of the FGT. Ball symbols and arrows represent electrons and their spin, respectively. (b) Comparison of SOT efficiency and dissipation power density for magnetization switching [26].

local magnetization or spin clusters, which can enable field-free magnetization switching and spin propagation.

Although numerous efforts have been made for the exploration of new materials for SOT-based spintronics, a number of open questions and challenges still remain. Here, we highlight several key topics that merit further investigation.

(1) **SOT mechanism**. A better understanding of the SOT mechanism is of great importance for developing SOT-based spintronic materials and devices. In addition to the two well-established mechanisms for spin-charge conversion, namely, the spin Hall and Rashba–Edelstein effects, unconventional mechanisms have been also observed, such as SOT induced by the anomalous Hall effect or planar Hall effect and extra spin sources that originate from orbital to spin conversion [23], providing new knobs for manipulating the SOT. On the other hand, the SOT could be split into damping-like torque (DLT) and field-like torque (FLT) components, which are analyzed in terms of the symmetry. Specifically, DLT is usually referred to as spin Hall torque, whereas FLT is referred to as spin orbit or Rashba torque, based on the assumption that the torque related to the transfer and absorption of angular momentum would have a dissipative character whereas that arising from the Rashba–Edelstein effect would be of field-like character. Given the universal existence of the interfacial Rashba effect in HM/FM heterostructures, clarifying the respective contributions of the DLT and FLT from the spin Hall and Rashba–Edelstein effects requires further investigation.

(2) **Enhancing the SOT switching efficiency.** The SOT switching efficiency is a measure of the ability of the SOT to switch magnetization, which depends on the charge-to-spin conversion efficiency of spin source materials and the saturation magnetization of magnetic materials. For spin source materials, increasing the resistivity in most HMs with the intrinsic SHE can yield a marked enhancement in the charge-to-spin conversion efficiency, i.e., the spin Hall angle (SHA), but the drawback is that the power consumption may also increase. Therefore, further exploration of new avenues, such as HM alloying, structural design, and the introduction of new spin generation mechanisms, is required to enhance the SOT switching efficiency.

(3) **Voltage control of SOT**. Controlling the magnetism using the voltage is a highly attractive approach for energy-efficient information technologies. Voltage control of SOT switching is highly desirable but rarely realized because the SOT is essentially determined by the intrinsic properties of the materials and is not sensitive to the external electric field. Recently, the spin Hall angle in the topological insulator Bi_2Se_3 was reported to be effectively tuned by an electric field across the piezoelectric substrate as a result of both charge doping and the strain effect [24]. Utilizing voltage-driven ion migration effects, ferroelectric and dielectric layers, or voltage-induced strain modulation via a piezoelectric substrate can allow magnetic-field-free control of SOT in various systems. The integration of such functional layers into well-established MRAM processing, particularly lowering the voltages required to produce a marked modulation of the SOT, is still challenging and requires further research.

(4) **2D materials for SOT-based devices.** Recent studies on 2D materials have revealed fascinating physics phenomena, such as SOC and ferromagnetism. SOT-induced magnetization switching has been realized in magnetic van der Waals materials, such as Fe_3GeTe_2 [25] (FGT), at low temperatures. Through integration with TMD Weyl semimetals, which are a new class of spin source materials, SOT-driven switching in an all-van der Waals heterostructure (WTe_2/FGT) is also realized at 150 K [26], resulting in both good SOT efficiency and low dissipation power density, as shown in Fig. 3. The search for 2D magnets with Curie temperatures above room temperature and exploration of the integration of 2D magnets with 2D TMDs will open a new avenue to ultrahigh-density and ultralow-power SOT-based spintronic devices.

(5) **Large-scale integration of SOT-based devices**. To integrate SOT-MRAMs with 12-inch COMS-compatible technology, a number of key issues, in fields ranging from materials science to processing technology, need to be addressed. Designing high-performance MTJs using spin source materials with low resistivities and large SHAs and realizing magnetic field-free switching is central to the practical application of SOT-MRAMs and remains a major challenge. On the other hand, more efforts should be made to develop appropriate patterning and etching technologies for SOT-based devices at the sub-10-nm node and optimize the interconnect layout, with the aim of obtaining wafer-scale homogeneous SOT-based device arrays.

Beyond the aforementioned topics, the following problems should also be considered to enable further improvements or new directions in SOT-based spintronic device applications [27].

a) Low-power read-out of SOC or SOT rather than tunnel magnetoresistance for a new type of SOT-based spintronics.

b) Neuromorphic computing or stochastic computing using SOT-based spintronic devices.
c) Development of 3D spintronics for ultrahigh-density memory.
d) Incorporating photonics with SOT-based spintronics to develop optical interconnects in electronics.

Declaration of Competing Interest

The authors declare that they have no conflicts of interest in this work.

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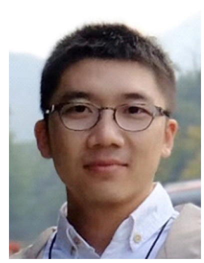

Shuai Ning is appointed as an associate professor in the School of Materials Science and Engineering at Nankai University since 2021, preceded by four years at Massachusetts Institute of Technology as a Postdoctoral Associate, working with Prof. Caroline A. Ross in the Department of Materials Science and Engineering. He received a Bachelor's degree and a PhD degree from Tsinghua University in 2012 and 2017, respectively, both in Materials Science and Engineering. His current research interest is in functional oxide thin films and nanocomposites; magnetic, spintronic, ferroelectric and multiferroic materials.

Feng Luo received the B. S. degree from Peking University in 1999 and Ph. D. degree from Peking University in 2004. From 2010 to 2020, he had held a senior research professor position at IMDEA-Nanoscience (Madrid), Spain. From 2021 he has been appointed as a chair professor at the School of Material Science and Engineering in Nankai University. His research interest includes Micro/Nano Fabrication and Ultra-Precision Manufacturing for Applications in Magnetic Hard Disk Storage, Magnetic Random Access Memory (MRAM) and Magneto-Optical Sensors; Tuning Physical Properties by Design and Controlling: Interface Engineering at Atomic Scale and Lithography Patterning; Advanced Characterization Techniques Based on X-ray and Electrons.