

Thin-Film Magnetic Skyrmions for Spintronic Devices

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Magnetic skyrmions are chiral spin textures characterized by a winding number. These nanoscale entities possess topological stability and can be driven by an ultralow current density. Since their discovery in bulk chiral magnets and magnetic multilayer thin films, they have attracted extensive research due to their potential as information carriers in spintronic devices. In particular, thin-film magnetic skyrmions have garnered significant attention because they can be stabilized at room temperature, offer high tunability of material parameters, and are compatible with standard semiconductor processing technologies. However, several critical challenges remain before they can be practically applied. This article provides a comprehensive review of the recent significant advancements and major issues in thin-film skyrmion-based spintronic devices. Firstly, this work introduces the physical mechanisms and stabilization methods of magnetic skyrmions across various magnetic thin film materials, summarizing the current state of skyrmion sizes in most thin film materials. This work then discusses the dynamics of thin-film skyrmions, focusing on their precise creation, deterministic motion, and efficient detection, particularly through electrical means. Furthermore, this work explores the potential applications of thin-film magnetic skyrmions in memory, logic, and neuromorphic devices. Lastly, this work summarizes the critical challenges that need to be addressed before all-electrical skyrmionic device applications can become viable and offer perspectives for future research.

processes. In recent years, the discovery of topological spin textures, exemplified by magnetic skyrmions, has offered potential solutions to these challenges and has opened up new opportunities for the development of high-density, low-power, and high-speed spintronic devices.^[1]

Magnetic skyrmions are nanoscale topological spin vortices with chiral structures, exhibiting quasiparticle-like properties.^[2,3] These configurations are mostly stabilized by the Dzyaloshinskii-Moriya interaction (DMI), arising from broken inversion symmetry in thin films or bulk noncentrosymmetric chiral magnets.^[4,5] Skyrmions can be engineered to nanometer-scale sizes and manipulated with ultralow current densities, making them energy-efficient information carriers. Their unique properties position them as a cornerstone for next-generation spintronic devices, enabling high-density data storage and low-power logic operations.

Magnetic skyrmions were first identified in bulk B20 chiral magnets under low-temperature conditions and, typically, in the presence of strong external magnetic fields.^[6–13] For practical integration into devices, however, skyrmions must be stabilized at room temperature and in zero

or weak magnetic fields.^[14,15] This challenge has been addressed by leveraging the interfacial DMI in sputtered magnetic multilayers (Figure 1a), enabling the stabilization of thin-film skyrmions at room temperature and their efficient manipulation via current-induced torques.^[16–19] Sputtered thin films further offer exceptional tunability of material parameters, critical for tailoring skyrmionic properties, and ensure compatibility with conventional semiconductor manufacturing processes.^[20] Notably, in addition to magnetic skyrmions, other topological spin textures such as high-order anti-skyrmions, three-dimensional magnetic Hopfions, and skyrmion bags have been also stabilized in sputtered magnetic multilayers or their nanoscale disks at room temperature.^[21–24] These diverse topological spin textures not only pave the way for research in topological magnetism but also offer significant flexibility for information encoding.

Over the past decade, advancements in thin-film magnetic skyrmions have spurred numerous reviews addressing topological physics, skyrmion generation/manipulation, and applications.^[25–31] This review focuses on key recent advancements in thin-film magnetic skyrmions, particularly in stabilizing ultrasmall skyrmions across diverse materials, enabling

1. Introduction

As the world transitions into the big data era, traditional magnetic storage technologies are increasingly unable to cope with the exponential growth of data volumes. Moreover, efforts to enhance storage density are constrained by fundamental physical limitations, such as thermal instability and challenges in data-writing

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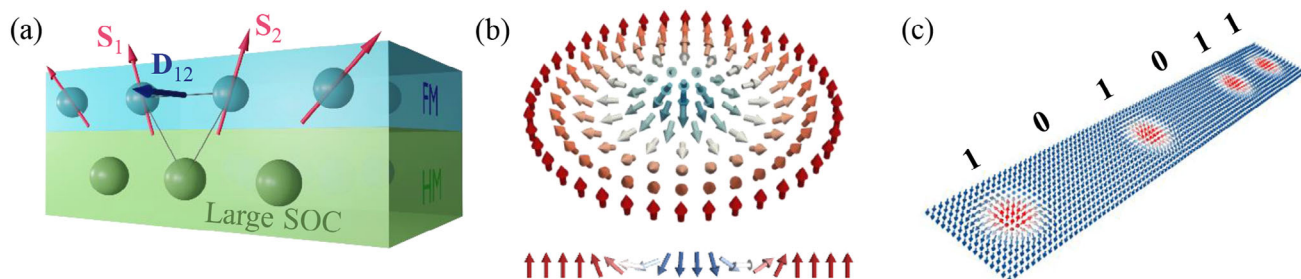


Figure 1. a) Schematic of an interfacial Dzyaloshinskii-Moriya interaction (DMI) at the interface between a thin ferromagnetic (FM) layer and a heavy metal (HM) layer with a large spin-orbit coupling (SOC). In this case, the local DMI vector $\mathbf{D}_{12}$ is perpendicular to the plane of the triangle formed by two atoms of the FM layer and the one of the HM layer.^[14] b) Spin configuration of a Néel-type skyrmion. The magnetization is pointing up on the edge and pointing down in the center. The cross-section of this skyrmion is also depicted. c) Schematic illustration of skyrmions on the magnetic track. Information is encoded by the presence and absence of magnetic skyrmions, which represent the bits “1” and “0”.

precise creation and deterministic motion of skyrmions on magnetic tracks, and enhancing tunneling magnetoresistance (TMR) readout efficiency. This review is organized as follows: Section 2 introduces the physical mechanisms underlying skyrmion stabilization in thin-film materials and surveys stabilization strategies across diverse material systems, including ferromagnets, ferrimagnets, and synthetic antiferromagnets. It also summarizes typical skyrmion sizes in magnetic multilayers and explores opportunities for size reduction. Section 3 highlights recent progress in current-driven skyrmion dynamics, focusing on advancements in precise creation, deterministic motion, and efficient TMR detection of skyrmions in multilayer structures. Section 4 evaluates the potential of skyrmions for applications in memory, logic, and neuromorphic computing devices. Section 5 concludes with a discussion of future research directions.

2. Magnetic Skyrmions in Thin Film Materials

2.1. Stabilization Mechanism for Magnetic Skyrmions

The magnetic structure in thin films can be derived from its magnetic Hamiltonian

$$H_{\text{eff}} = - \sum_{i \neq j} J_{ij} (\mathbf{S}_i \cdot \mathbf{S}_j) + \sum_{i \neq j} D_{ij} \cdot (\mathbf{S}_i \times \mathbf{S}_j) - K \sum_i (\hat{n}_i \cdot \mathbf{S}_i)^2 + E_{\text{DDI}} \quad (1)$$

where $\mathbf{S}_{ij}$ is the magnetic moment on site i and j , J_{ij} and D_{ij} are the Heisenberg exchange interaction and DMI constants between $\mathbf{S}_i$ and $\mathbf{S}_j$, respectively, and K is the magnetic anisotropy constant associated with the easy axis along the unit vector $\hat{n}_i$. E_{DDI} describes the magnetic dipole–dipole energy. Unlike J_{ij} and K , a finite DMI exists only in noncentrosymmetric systems. In the magnetic thin films, the inversion symmetry is broken at the interface, which gives rise to a finite interfacial DMI. The interfacial DMI can be further enhanced by the nonmagnetic heavy metal (HM) layer with strong SOC adjacent to the ferromagnetic (FM) layer, as indicated in Figure 1a. The interfacial DMI constant can be written as $D_{ij} = D_{ij} \cdot (\mathbf{z} \times \mathbf{r}_{ij})$, where $\mathbf{z}$ is a unit vector perpendicular to the interface and $\mathbf{r}_{ij}$ is a unit vector pointing from site i to site j . In the

micromagnetic scale, the DMI energy density of the spin structure can be expressed as:^[25,32–35]

$$E_{\text{DM}} = D \cdot \left(m_x \frac{\partial m_x}{\partial x} - m_x \frac{\partial m_z}{\partial x} + m_z \frac{\partial m_y}{\partial y} - m_y \frac{\partial m_z}{\partial y} \right) \quad (2)$$

where m_x, m_y, m_z are the components of the normalized magnetization $\mathbf{m} = \mathbf{M}/M_s$. DMI constant D is related to the DMI strength D_{ij} and has the dimension of energy per area.

The Heisenberg exchange interaction in the first term of Equation (1) favors the collinear alignment of magnetic moments, while the magnetic anisotropy in the third term aligns these moments along their easy axes. In contrast, DMI in the second term induces a noncollinear arrangement, which is essential for forming chiral magnetic structures such as skyrmions and chiral domain walls. Skyrmions can be categorized into two main types: Néel-type and Bloch-type. Notably, Néel-type skyrmions are commonly found in thin films, where the magnetization rotates in-plane by 2π around an axis perpendicular to the film, as depicted in Figure 2b. In contrast, Bloch-type skyrmions are mainly observed in bulk systems. The key difference between these two types lies in the orientation of their magnetization rotation planes in a cross-sectional view. Specifically, for Néel-type skyrmions, the spin rotation planes are parallel to the radial direction, whereas for Bloch-type skyrmions, the magnetization rotation planes are perpendicular to the radial direction of the cross-section.

A magnetic skyrmion is a topologically protected magnetic vortex structure. Its topology is defined by the topological number (skyrmion number) G :

$$G = \frac{1}{4\pi} \int m \cdot \left(\frac{\partial m}{\partial x} \times \frac{\partial m}{\partial y} \right) dx dy \quad (3)$$

where m is the normalized local magnetization. The topological number $G = \pm 1$ is associated with a magnetic skyrmion, while $G = 0$ corresponds to topologically trivial spin structures.^[2] Magnetic skyrmions exhibit topological protection because their topological charge cannot change through continuous spin rotations, preventing their creation or annihilation via such processes. This inherent stability arises from the conservation of their topological invariant, which ensures robustness against local perturbations.

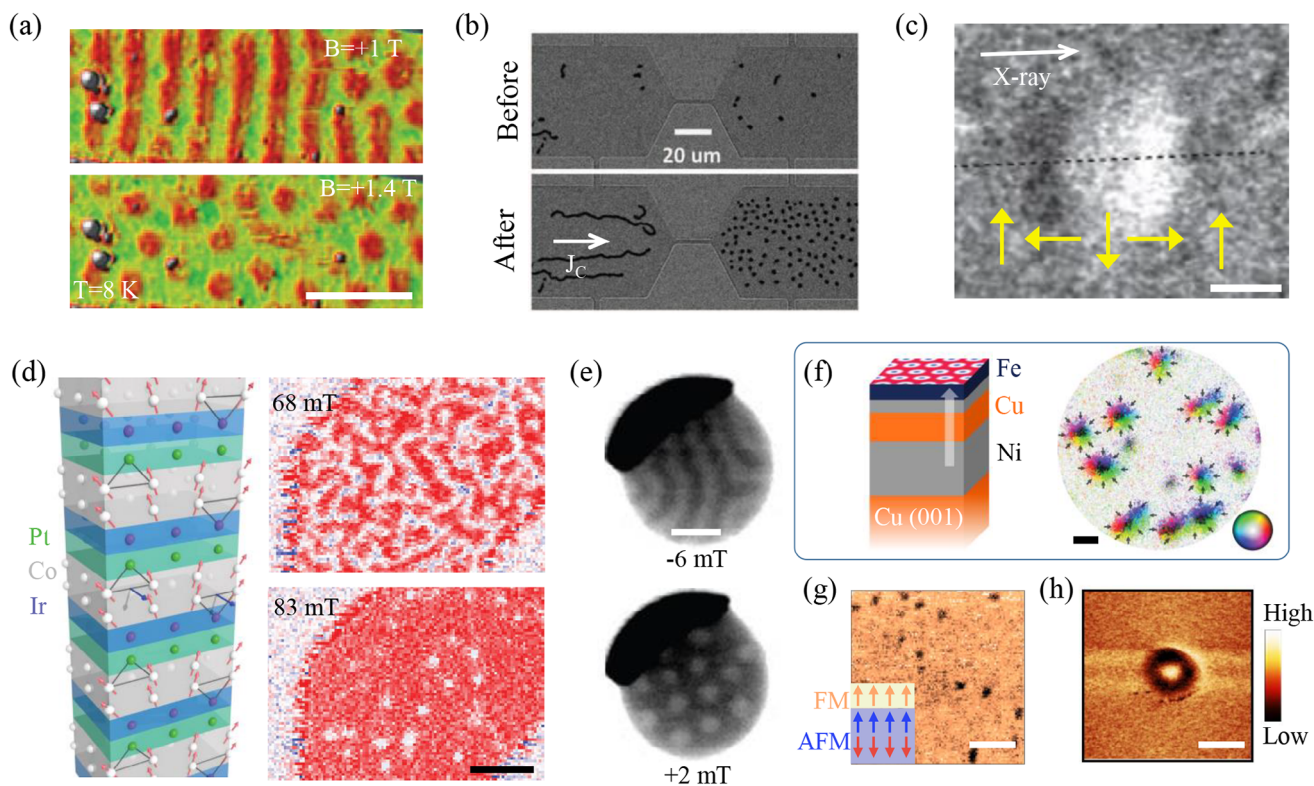


Figure 2. a) The stripe domains (top) and skyrmions (bottom) observed in Pd/Fe/Ir(111) structure at 8 K by using spin-polarized scanning tunneling microscopy (SP-STM), under the external field of +1 and +1.4 T. Scale bar, 25 nm. Reproduced with permission.^[40] Copyright 2013, American Association for the Advancement of Science. b) Skyrmions in Ta/CoFeB/TaO_x trilayer, before and after applying a current pulse through a constriction, as seen by magneto-optical Kerr effect (MOKE) microscopy. Reproduced with permission.^[16] Copyright 2015, American Association for the Advancement of Science. c) A Néel-type skyrmion in Pt/Co/MgO square dot of 420-nm-width is observed by X-ray magnetic circular dichroism photoemission electron microscopy (XMCD-PEEM), which can directly determine the spin chirality of the skyrmion, as shown by the yellow arrows in the inset. Scale bar, 100 nm. Reproduced with permission.^[41] Copyright 2016, Nature Publishing Group. d) Schematic illustration of [Ir/Co/Pt]_n multilayers with additive Dzyaloshinskii-Moriya interaction (DMI) and the observed labyrinth domains and skyrmions by magnetic force microscopy (MFM), under the perpendicular field of 68 and 83 mT. Scale bar, 300 nm. Reproduced with permission.^[19] Copyright 2016, Nature Publishing Group. e) The stripe domains and skyrmions in [Pt/Co/Ta]_n disk of 2-μm-diameter imaged by scanning transmission X-ray microscopy (STXM), under the external field of -6 and +2 mT. Scale bar, 500 nm. Reproduced with permission.^[18] Copyright 2016, Nature Publishing Group. f) The film stack of Fe/Ni/Cu/Ni/Cu(001) multilayer with interlayer exchange coupling and the skyrmions observed by SPLEEM at zero field. Scale bar, 200 nm. Reproduced with permission.^[42] Copyright 2020, American Institute of Physics. g) The skyrmions in the exchange-biased Pt/Co/NiFe/IrMn multilayers imaged by an N-V magnetometry at zero field. Scale bar, 300 nm. Reproduced under terms of the CC-BY license.^[43] Copyright 2020, American Physical Society. h) The MFM images of a skyrmion in Ir/Fe/Co/Pt multilayered nanodot of 200-nm-diameter at zero field. Scale bar, 200 nm. Reproduced under terms of the CC-BY license.^[44] Copyright 2019, American Physical Society.

We note that several mechanisms, such as long-range magnetic dipole interactions,^[36,37] frustrated exchange interactions,^[38] and four-spin exchange interactions,^[39] can also support whirling magnetic textures, including magnetic skyrmions. However, magnetic skyrmions stabilized by the interfacial DMI offer several advantages, including well-defined chirality and small size. These properties make them promising candidates for data storage applications. For example, in a skyrmion racetrack memory device, the presence of a skyrmion on the track typically represents a bit “1,” while the absence of a skyrmion represents a bit “0,” as illustrated in Figure 1c.

2.2. Skyrmions Stabilized in Metallic Thin Film Materials

With the help of the interfacial chiral DMI, Néel-type magnetic skyrmions have been successfully stabilized in a variety of

metallic thin films, including epitaxial ultrathin film and sputtered polycrystalline multilayer systems. Magnetic materials such as ferromagnets, ferrimagnets, and (synthetic) antiferromagnets have been implemented in these thin films. In the following section, we will discuss the stabilization of skyrmions within these systems.

2.2.1. Ferromagnetic Skyrmions

Since the initial experimental observation of Bloch skyrmions in bulk chiral magnets MnSi, Fe_{0.5}Co_{0.5}Si, and FeGe,^[6,7,10] the stabilization of skyrmions in thin film materials has gained significant importance, especially considering their potential compatibility with semiconductor processing technology. Romming et al. first directly imaged thin-film magnetic skyrmions in a Pd/Fe bilayer epitaxially grown on the Ir(111) surface using spin-

polarized scanning tunneling microscopy (SP-STM) at an ultralow temperature ($T = 8$ K) and a high magnetic field ($B = 1.4$ T),^[40] as shown in Figure 2a. They also demonstrated the electrical writing and deletion of single magnetic skyrmions in ultrathin Pd/Fe/Ir(111) films in a controllable manner at 8 K. However, stabilizing skyrmions at ultralow temperatures is not ideal for future spintronic applications, as practical applications require room-temperature operation and compatibility with CMOS technology.

In 2015, Jiang et al. achieved a milestone in thin-film skyrmions by creating magnetic skyrmions at room temperature (RT) in a Ta/CoFeB/TaO_x asymmetric trilayer with a geometric constriction, as depicted in Figure 2b.^[16] This creation utilized electrical control under an external field at RT. Subsequent efforts focused on transitioning from low-temperature skyrmions in epitaxial films to RT skyrmions in sputtered multilayers. Boulle et al. stabilized RT skyrmions in nanoscale square dots of sputtered Pt/Co/MgO trilayers, which exhibit strong interfacial DMI.^[41] The Néel-type spin chirality in these skyrmions was directly observed via X-ray magnetic circular dichroism photoemission electron microscopy (XMCD-PEEM), as shown in Figure 2c. Further DMI enhancement was achieved by inserting a FM layer between two HMs (e.g., [Ir/Co/Pt]_{1n} and [Ir/Fe/Co/Pt]_{2n} multilayers), reducing stable skyrmion sizes to sub-100 nm dimensions (Figure 2d).^[19,20] These multilayers also enhance magnetic contrast in imaging techniques and destabilize uniform magnetization due to increased demagnetizing fields. Notably, the [Pt/Co/Ta]₁₅ asymmetric multilayer, which exhibits partially canceling DMI, still supports skyrmions in multilayered disks, as shown in Figure 2e.^[18] These skyrmions can be readily manipulated electrically due to the enhanced spin-orbit torque effect present in the Pt/Co/Ta trilayer.

Magnetic skyrmions have now been successfully stabilized in various ferromagnet-based multilayers at room temperature, including [Pt/Co/X]_n, [Ir/Fe/Co/Pt]_n, and [HM/CoFeB/MgO]_n, where X represents HMs, antiferromagnetic metals, or oxides. Early research on FM skyrmions focused on achieving room-temperature and zero-field (ZF) stability.^[25] The periodic stacking of magnetic multilayers not only enhances magnetic contrast but also significantly improves the thermal stability of magnetic skyrmions, which is crucial for their potential applications in data storage. For instance, in Ta/CoFeB/TaO_x (MgO) trilayers, the Brownian motion of skyrmions, triggered by thermal fluctuations at room temperature, poses a significant challenge to maintaining data storage stability.^[45–47]

The stabilization of RT FM skyrmions at zero field can be achieved in magnetic multilayers by leveraging interlayer exchange coupling, exchange bias, and geometric confinement.^[48–53] Figure 2f illustrates the stabilized RT FM skyrmion ground states at zero fields in chiral Ni/Cu/Ni/Fe magnetic multilayer structures with a nonmagnetic Cu spacer layer. This stabilization is primarily enabled by interlayer exchange coupling.^[42] Furthermore, exchange bias at the antiferromagnet/ferromagnet (AFM/FM) interface, as shown in Figure 2g, has been utilized to achieve zero-field skyrmion formation. In this case, significant spin-orbit torques in PtMn and IrMn antiferromagnets allow for energy-efficient current control.^[43] Figure 2h demonstrates the formation of zero-field skyrmions in Ir/Fe/Co/Pt multilayer nanodisks, providing a valuable plat-

form for studying the behavior of nanoscale skyrmions under geometric constraints.^[44]

Despite the limited tunability of FM layers in multilayers, structures such as CoFeB/MgO remain ideal for compatibility with existing magnetic tunnel junction (MTJ) materials. Recent advancements highlight TMR as a highly effective method for electrical skyrmion detection. FM multilayers have also emerged as a key model system for studying skyrmion responses to diverse stimuli, including mechanical strain,^[54–56] temperature variations,^[57] light exposure,^[51,58] ion irradiation,^[52,59] and so forth. These investigations provide critical insights into tailoring skyrmion properties for practical applications.

2.2.2. Ferrimagnetic and Synthetic Antiferromagnetic Skyrmions

The key feature of current-driven FM skyrmion motion is the skyrmion Hall effect, which causes additional motions of skyrmions transverse to the current direction due to their emergent magnetic field (topological charge).^[60,61] This effect is detrimental to applications such as skyrmion racetrack memory, as it complicates precise control of skyrmion trajectories and can lead to their annihilation at device edges. Theoretical studies have predicted efficient current-driven skyrmion motion without the skyrmion Hall effect for antiferromagnetic skyrmions.^[62] However, the absence of net magnetization in antiferromagnets presents significant challenges for detecting them. Ferrimagnetic or synthetic antiferromagnetic materials, where the spins are coupled in a similar way to antiferromagnets, have garnered considerable attention from the spintronic community as they offer potential solutions to these challenges.^[63]

Ferrimagnets, such as rare earth-transition metal (RE-TM) alloys, typically consist of two or more inequivalent magnetic sublattices that are antiferromagnetically coupled. This results in spin dynamics as fast as those in antiferromagnets due to the antiferromagnetic exchange interactions. Although the spins are coupled antiferromagnetically, ferrimagnets exhibit a finite, but small, net magnetization, allowing detection using conventional techniques applied to ferromagnets.^[64–67] Synthetic antiferromagnets (SAF) consist of two FM layers separated by a nonmagnetic spacer layer, coupled antiferromagnetically through an interlayer Ruderman–Kittel–Kasuya–Yosida (RKKY) interaction.^[68–71] Compared to crystalline antiferromagnets, the interlayer exchange coupling in SAF is weaker, enabling easier manipulation of the synthetic antiferromagnetic state and spin textures.^[72,73] Additionally, when the thicknesses of the two FM layers differ slightly, the small uncompensated magnetization in SAF can be detected using traditional methods such as magneto-optical Kerr effect (MOKE) and magnetic force microscopy (MFM). Thus, ferrimagnets and synthetic antiferromagnets combine the advantages of both ferromagnets and antiferromagnets, leading to significant research efforts focused on ferromagnetic and synthetic antiferromagnetic skyrmions, as illustrated in Figure 3a.

Woo et al. first reported the stabilization of ferrimagnetic skyrmions in [Pt/GdFeCo/MgO]₂₀ multilayers through interfacial DMI.^[74] They used element-specific scanning transmission X-ray microscopy (STXM) to directly confirm the antiferromagnetically coupled spins of GdFeCo ferrimagnetic skyrmions at

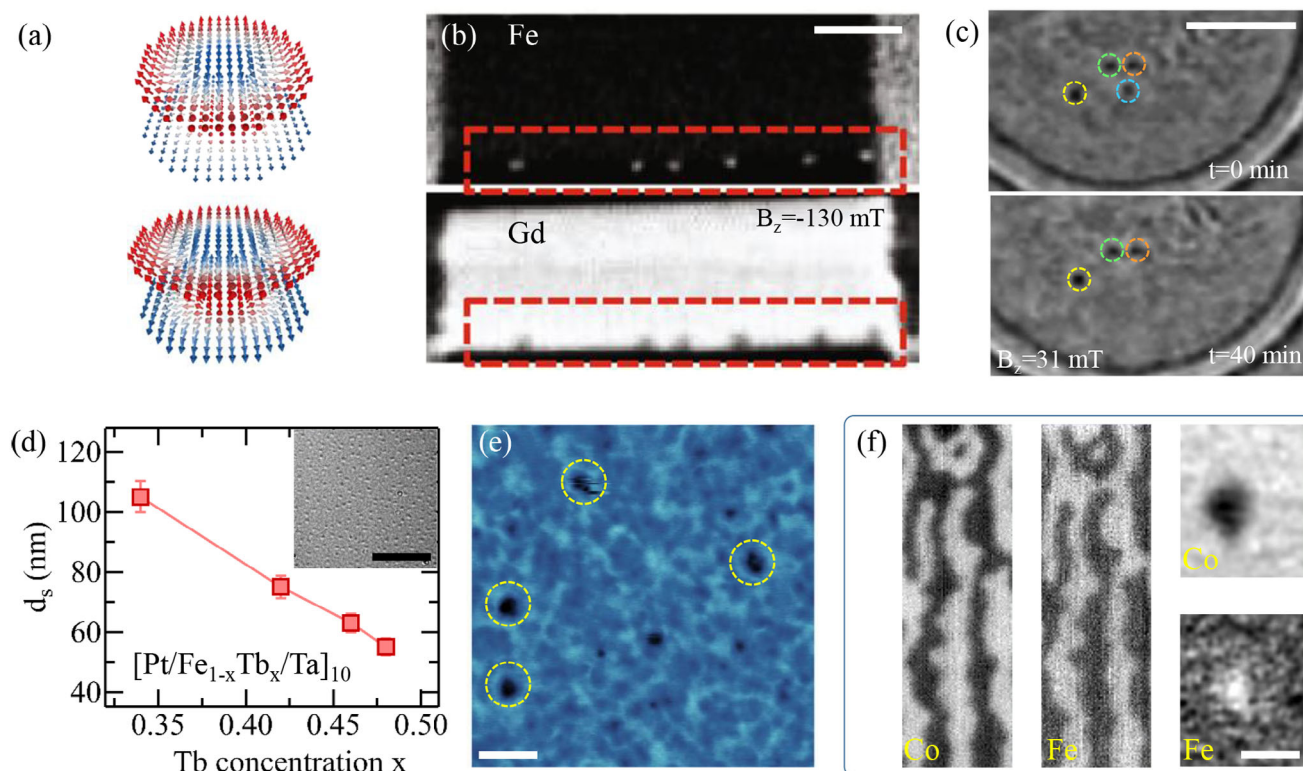


Figure 3. a) Schematic of a ferrimagnetic skyrmion (top) and a synthetic antiferromagnetic skyrmion (bottom). The direction and size of the arrows denote the magnetization direction and relative magnitude, respectively. b) Scanning transmission X-ray microscopy (STXM) images of GdFeCo ferrimagnetic skyrmions acquired at $B_z = -130$ mT. Dark and bright contrasts correspond to magnetization oriented up and down, respectively. The top and bottom panels show the corresponding images acquired at the Fe L₃ and Gd M₅ edges. Scale bar is 1 μm. Reproduced under terms of the CC-BY license.^[74] Copyright 2018, Nature Publishing Group. c) X-ray holography images of Co_{0.44}Gd_{0.56} ferrimagnetic skyrmions after injecting a nucleation current pulse (top panel) and after 40 min acquired at $B_z = 31$ mT. Skyrmions are outlined by the circles for clarity. Scale bar is 250 nm. Reproduced with permission.^[75] Copyright 2018, Nature Publishing Group. d) The skyrmion size as a function of Tb concentration x in [Pt/Fe_{1-x}Tb_x/Ta]₁₀ magnetic multilayers. The inset is the Lorentz transmission electron microscopy image of [Pt/Fe_{0.52}Tb_{0.48}/Ta]₁₀ sample acquired at $B_z = 0.8 B_s$, where B_s is the saturation field. Scale bar is 1 μm. Reproduced under terms of the CC-BY license.^[76] Copyright 2023, ACS Publications. e) Magnetic force microscopy (MFM) image of Pt/Co/Ru/Pt/Co/Ru SAF multilayer with a bias layer under external perpendicular field $B_z = 60$ mT. The synthetic antiferromagnetic skyrmions are labeled with the yellow circles. Scale bar is 500 nm. Reproduced with permission.^[78] Copyright 2020, Nature Publishing Group. f) X-ray magnetic circular dichroism STXM (XMCD-STXM) images of Pt/Co/NiFe/Co/Ru/Pt/Co/Ru SAF multilayers acquired at the Co L₃ and Fe L₃ edges for the left two panels. An isolated skyrmion is observed at the top of the image. XMCD-STXM images of the skyrmion acquired at the Co L₃ and Fe L₃ edges for the right two panels. Scale bar is 500 nm. Reproduced under terms of the CC-BY license.^[79] Copyright 2022, Nature Publishing Group.

the absorption edges of Fe (L₃) and Gd (M₅), as shown in Figure 3b. Fully compensated ferrimagnets, due to their reduced stray fields, can accommodate much smaller RT skyrmions compared to traditional ferromagnets. Figure 3c illustrates ultra-small ferrimagnetic skyrmions with an average size of 20 nm in Pt/CoGd/TaO_x trilayers. This highlights the capacity of these materials to form ultrasmall skyrmions with diameters down to 20 nm even at RT.^[75] Owing to the highly tunable magnetic properties of ferrimagnets, the size and density of ferrimagnetic skyrmions have been systematically controlled via composition modulation, as depicted in Figure 3d.^[76] Wu et al. have also demonstrated the stabilization of ferrimagnetic skyrmions on the topological insulator (BiSb)₂Te₃ by moderately tuning the magnetic anisotropy of GdFeCo ferrimagnets. This approach can provide a large interfacial DMI and sizable spin-orbit torque.^[77]

Through moderate tuning of perpendicular magnetic anisotropy (PMA), RKKY antiferromagnetic coupling, and interfacial DMI, the stabilization of synthetic antiferromagnetic

(SAF) skyrmions at RT has been achieved in multilayer structures such as Pt/Co/Ru/Pt/Co/Ru, Pt/Co/CoFeB/Ir/Co/CoFeB/W, and Pt/Co/NiFe/Co//Ru/Pt/Co/Ru.^[78–81] Notably, Legrand et al. stabilized SAF skyrmions at zero fields in a [Co/Pt]₃/Co/Pt/Co/Ru/Pt/Co/Ru multilayer by incorporating a [Co/Pt]₃ bias layer,^[78] as shown in Figure 3e. Juge et al. directly imaged isolated SAF skyrmions in Pt/Co/NiFe/Co/Ru/Pt/Co/Ru multilayers using STXM at the Co and Fe L₃ absorption edges,^[79] confirming their antiferromagnetic coupling, as depicted in Figure 3f.

Due to their low magnetization and antiferromagnetic coupling, compensated ferrimagnets and synthetic antiferromagnets (SAFs) enable the stabilization of magnetic skyrmions that are both ultrasmall and capable of ultrafast spin dynamics. The characteristics of these skyrmions, such as their size and dynamic behavior, can be highly tuned through modifications of their composition or layer thickness, a flexibility that is not commonly found in FM counterparts. However, current ferrimagnetic

and synthetic antiferromagnetic materials that host magnetic skyrmions are not compatible with conventional MTJ materials such as CoFeB/MgO/CoFeB, posing a challenge for their TMR detection in skyrmionic devices. Resolving this compatibility challenge is critical to enabling the practical deployment of ferrimagnetic and synthetic antiferromagnetic skyrmions across diverse applications.

2.3. Skyrmion Size

The skyrmion size is a critical factor influencing the scalability and storage density of skyrmionic devices. A magnetic skyrmion comprises a core, an outer domain, and a domain wall that separates them. The skyrmion radius, R , is typically defined as the distance from the center to the contour where the out-of-plane magnetization (m_z) equals zero, marking the boundary between the core and outer domain. The domain wall width, w , quantifies the thickness of the transition region between these domains, reflecting how abruptly the magnetization changes from the core to the outer domain. The size of magnetic skyrmions can be qualitatively estimated by analyzing the total energy of an ultra-thin FM film without an external magnetic field^[82,83]

$$E(R, w) = 4\pi d \left[A \left(\frac{R}{w} + \frac{w}{R} \right) - \frac{\pi}{2} DR + KwR \right] \quad (4)$$

where A , D , K , M_s are the exchange stiffness, the interfacial DMI constant, the magnetic anisotropy constant, and the saturation magnetization, respectively. Through the minimization of total energy concerning the skyrmion size R and domain wall width w , the analytic formulas of R and w can be obtained as:

$$R = \pi D \sqrt{\frac{A}{16AK^2 - \pi^2 D^2 K}} \quad (5)$$

and

$$w = \frac{\pi D}{4K} \quad (6)$$

The skyrmion size R and domain wall width w are independent of each other, but both are jointly influenced by the competitions of A , D , and K . The skyrmion size R always decreases with A , while both R and domain wall width w increase with D . Since skyrmion size R must be real and finite, the inequality $16AK^2 > \pi^2 D^2 K$ must be satisfied. This inequality establishes important constraints on the material parameters: the upper bound for D is determined by $D < \frac{4}{\pi} \sqrt{AK}$, while the lower bounds for A and K are given by $A > \frac{\pi^2 D^2}{16K}$, and $K > \frac{\pi^2 D^2}{16K}$, respectively. These subtle relationships imply the challenge of generating skyrmions with a controllable size in the experiment, as discussed later.

Since the initial stabilization of micrometer-scale RT skyrmions in Ta/CoFeB/TaO_x trilayer, significant progress has been made in reducing skyrmion size in thin-film materials. To date, ultrasmall skyrmions have been successfully stabilized at RT, largely due to advancements in material engineering and a deeper understanding of the interplay between exchange stiffness, DMI, magnetic anisotropy, and external

magnetic fields. For example, by optimizing multilayer structures, researchers have achieved enhanced DMI, enabling the stabilization of sub-100 nm and even sub-50 nm skyrmions at RT in [Pt/Co/Ir]₁₀ (Figure 2d) and [Ir/Fe/Co/Pt]₂₀ asymmetric multilayers, respectively.^[19,20] At the magnetization compensation temperature, Caretta et al. stabilized ferrimagnetic skyrmions with an average diameter of 20 nm in a Pt/Co₅₆Gd₄₄/TaO_x trilayer (Figure 3c).^[75] Additionally, current-induced spin-orbit torques have enabled the observation of 20 nm skyrmions in [Pt/Co/Ir]₁₅ multilayers at RT.^[84] However, these ultrasmall skyrmions often exhibit poor stability and tend to annihilate rapidly, posing challenges for the practical application of skyrmionic devices.

Here, the experimentally observed skyrmion sizes in various trilayer and multilayer structures at room temperature have been summarized in Table 1. Note that some magnetic skyrmions are stabilized at room temperature with the assistance of an external magnetic field, which can also influence their sizes. Compared to the 20 nm bit size in conventional hard disk drives (HDDs), further reduction of skyrmion sizes in thin films is critical to achieve competitive storage density. Notably, skyrmion sizes exhibit significant variability even within similar material systems, often due to inhomogeneous growth conditions or random defects in sputtered magnetic multilayers. Such variability underscores the need to optimize multilayer quality alongside size reduction. Recent studies demonstrate that skyrmion size can be systematically controlled by tuning material parameters, such as DMI, exchange stiffness, and magnetic anisotropy. For instance, enhancing DMI or adjusting anisotropy has enabled the stabilization of smaller skyrmions in both isolated and crystalline configurations. Additionally, precise control over thin-film growth conditions (e.g., deposition rate, substrate temperature) and the design of magnetic alloys with tailored compositions have proven effective in reducing skyrmion size. These advances highlight the potential for engineering ultrasmall, stable skyrmions for practical device applications.

3. Electrical Creation, Motion, and Detection of Skyrmion

The complex magnetism of material systems and the unique properties of magnetic skyrmions result in highly intricate dynamics under external stimuli. Advancing skyrmion-based technologies requires developing precise methods for creating, controlling, and detecting skyrmions, particularly through electrical means. This section explores recent advancements in the electrical creation, motion, and detection of skyrmions, identifies areas poised for significant progress, and forecasts upcoming breakthroughs in the field over the next few years.

3.1. Electrical Creation

Over the past decade, researchers have developed various strategies to create magnetic skyrmions in magnetic multilayers. These techniques include the use of magnetic fields, thermal excitation, light exposure, electric currents (and fields), and other relevant methods. For example, in typical magnetic multilayers such as [Pt/Co/Ta]₁₅, a labyrinthine stripe domain phase is observed

Table 1. Comparison of the sizes of room temperature magnetic skyrmions experimentally observed in various thin-film materials, including ferromagnets (FM), ferrimagnets (FIM), and synthetic antiferromagnets (SAFs).

Material systems	Skyrmion size [nm]	Magnetic field [mT]	Methods	Magnetism	Imaging techniques
[Pt/Co/Ta] _n	50, ^[85] 70, ^[86] 100, ^[56,57,87,88] 120, ^[18] 150, ^[54,89] 210 ^[55]	93, 110, 202, 2, 84, 50	Magnetic, thermal, strain	FM	MFM, LTEM, STXM, MTXM
[Pt/Co/Ir] _n	20, ^[84] 50 ^[19] 60, ^[90,91] 80 ^[92,93]	233, 68, 44, 46	Electric, magnetic,	FM	MFM, STXM, MTXM
[Pt/Co/Fe/Ir] _n	40, ^[20] 50, ^[20,44,94] 80 ^[20,95]	150, 100, 10	Magnetic	FM	MFM
[Pt/Co/W] _n	200, ^[96] 220 ^[97]	148, 0	Magnetic	FM	LTEM
[Pt/Co/Ru] _n	200 ^[98]	23	Thermal	FM	MFM
[Pt/Co ₇₀ B ₃₀ /Ir] _n	40, ^[99] 500 ^[100]	4, 50	Electric	FM	STXM
[Pt/Co/Ni/Ir] _n	200 ^[101]	480	Magnetic	FM	LTEM
[Pt/Co/IrMn] _n	100, ^[52] 150 ^[51]	0, 0	Electric, optical	FM	LTEM, STXM
[Pt/Co/MgO] _n	100 ^[102]	107	Electric	FM	MTXM
[Pt/CoFeB/MgO] _n	120, ^[61] 130, ^[57] 180, ^[103] 190, ^[104,105] 200, ^[18] 300 ^[106]	30, 25, 20, 20, 30, 0	Magnetic, thermal, electric	FM	MTXM, STXM, XH, XP
[Ta/CoFeB/MgO] _n	90, ^[107] 140 ^[57]	150, 25	Magnetic, thermal	FM	MTXM, XP
[W/CoFeB/MgO] _n	200 ^[108]	30	Electric	FM	STXM
[Pt/GdFeCo/MgO] _n	150, ^[109] 160 ^[74]	110, 130	Electric	FIM	STXM
[Ir/CoGd/Pt] _n	200 ^[110]	54	Magnetic	FIM	MTXM
[Pt/CoGd/Pt] _n	70 ^[111]	0	Geometrical	FIM	MFM
[Mn ₃ Sn/CoTb/SiN _x] _n	150 ^[112]	104	Magnetic	FIM	LTEM
Pt/CoGd/Ta	20 ^[75]	31	Electric	FIM	XH
Pt/CoGd/W	100 ^[113]	0	Electric	FIM	STXM
[Pt/FeTb/Ta] _n	45 ^[76]	185	Magnetic	FIM	LTEM
[Pt/Co/Tb/Al] _n	160 ^[114]	41	Electric	FIM	MFM
Pt/Co/Ru/Pt/Co/Ru	50, ^[78,115] 210 ^[81]	100, 15	Magnetic	SAF	MFM
Pt/CoFeB/Ir/CoFeB/W	1700 ^[80]	0.2	Magnetic	SAF	MOKE
Pt/NiFe/Ru/Pt/Co/Ru	200 ^[79]	180	Magnetic	SAF	STXM

Furthermore, the auxiliary fields, skyrmion creation methods, magnetism of thin-film materials, and imaging techniques are also summarized in this table. MFM, magnetic force microscopy; LTEM, Lorentz transmission electron microscopy; STXM, scanning transmission X-ray microscopy; MTXM, magnetic transmission X-ray microscopy; XH, X-ray holography; XP, X-ray ptychography; MOKE, magneto-optical Kerr effect microscopy.

at zero magnetic fields, while isolated skyrmions or skyrmion lattices can be stabilized by applying an appropriate perpendicular magnetic field.^[18–20] However, using a magnetic field for skyrmionic devices is not ideal due to high energy consumption. Thermal gradients have also been used to create skyrmions, typically requiring an on-chip heater to establish a local thermal gradient across the entire multilayer structure.^[57] However, thermal gradients can be difficult to control precisely, and the temperature increase may alter the magnetic properties of the skyrmion-hosting multilayers. Optical methods, including traditional lasers, have been employed to produce single large magnetic bubbles and clusters of skyrmions experimentally.^[58] This is achieved through mechanisms such as laser field interaction or local heating using ultrafast lasers. Nevertheless, the size of these formations is generally limited by the wavelength of light. Additionally, the requirement for an ultrafast laser source complicates device design, and scaling down the optical paths can be challenging.

Electrical methods have become the primary approach for generating magnetic skyrmions, playing a crucial role in the initial discovery of RT skyrmions in thin-film materials. Electrical meth-

ods offer a viable pathway for skyrmion generation, essential for advancing skyrmion-based spintronic devices. Typically, electrical methods involve mechanisms such as spin-transfer torque (STT), spin-orbit torque (SOT), the effects of current-induced Oersted fields and Joule heating. Notably, in some cases, the Oersted field and Joule heating induced by current can dominate skyrmion generation.^[18,57] Spin-transfer torque involves injecting a spin-polarized current into a magnet, transferring the angular momentum between neighboring magnetic moments via conduction electrons, and thereby changing the magnetization direction.^[116] Spin-orbit torque, on the other hand, usually arises from the spin Hall effect in HMs with strong SOC.^[117–119] The interaction between the spin current and the magnet generates a torque that can efficiently manipulate the magnetization, including the creation of skyrmions.

Previous studies have demonstrated the creation of single skyrmions or skyrmion clusters at arbitrary locations within micrometric magnetic tracks using current pulses. **Figure 4a** shows the electrical generation of magnetic skyrmions in a magnetic stripe in the absence of an external magnetic field. The labyrinthine domains in the top panel transform into multiple

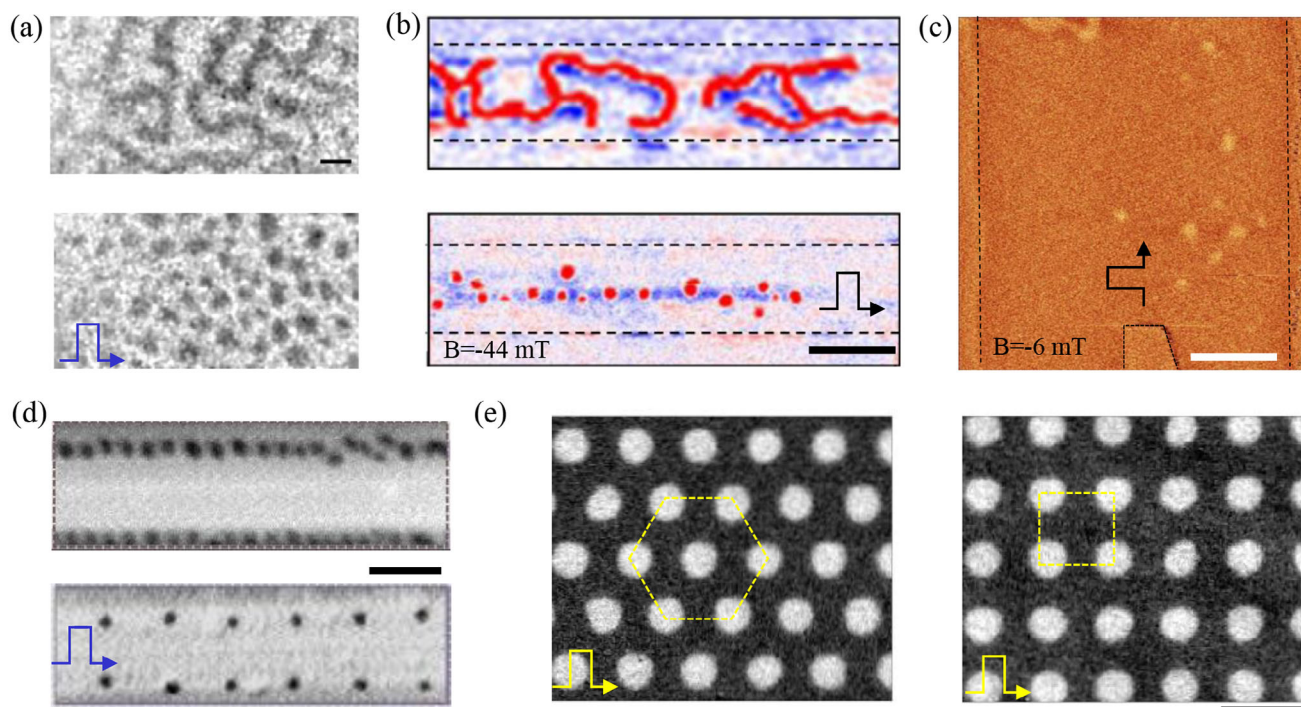


Figure 4. a) Magnetic transmission X-ray microscopy images of the magnetic domain states taken before and after the application of current pulse at $B_z = 0$ mT. The labyrinth domain can transform into a group of magnetic skyrmions. Scale bar is 5 μm . Reproduced under terms of the CC-BY license.^[105] Copyright 2018, Nature Publishing Group. b) Magnetic force microscopy (MFM) images of the 1 μm wide track made of $[\text{Pt}/\text{Co}/\text{Ir}]_{10}$ multilayer before (top) and after (bottom) the injection of 1000 current pulses of 200 ns. The randomly distributed isolated skyrmions on the track can be obtained. Reproduced under terms of the CC-BY license.^[90] Copyright 2017, ACS Publications. c) The MFM image of skyrmions electrically generated by a Ti/Au injection finger of specific geometry under external perpendicular field $B_z = -6$ mT. The dashed line denotes the position of the Ti/Au finger. Scale bar is 1 μm . Reproduced under terms of the CC-BY license.^[120] Copyright 2017, Nature Publishing Group. d) Current-induced skyrmion precise creation on line and in a dot array areas irradiated by a focused He^+ -ion beam. The images are taken by STXM. Scale bar is 500 nm. Reproduced under terms of the CC-BY license.^[124] Copyright 2022, ACS Publications. e) Current-induced hexagonal and square skyrmion lattice formation in Ta/CoFeB/MgO multilayers deposited on silicon substrates with patterned circular indentations. The images are taken by a polar magneto-optical Kerr effect (MOKE) microscopy under a perpendicular magnetic field $B_z = 0.12$ mT. Scale bar is 10 μm . Reproduced under terms of the CC-BY license.^[125] Copyright 2024, Science China Press.

skyrmions after the application of an electrical pulse, which are randomly distributed throughout the entire magnetic stripe.^[105] To reduce the number and size of electrically created skyrmions, Legrand et al. injected a current pulse along a 1 μm wide magnetic track while applying a perpendicular magnetic field. As shown in Figure 4b, the number of created skyrmions is significantly reduced, and they are positioned at the center of the track rather than being fully distributed within it.^[90] Furthermore, a nonmagnetic finger can be designed for electrical contact with the magnetic stripe, as indicated by the dashed line in Figure 4c. This design enables the local generation of skyrmions at the electrode pad.^[120] While this method can create individual skyrmions, the generated skyrmions tend to be randomly distributed along the magnetic track when multiple electrical current pulses are injected. Similar situations can occur in other magnetic tracks with specific geometries, such as notches or constrictions, which serve as nucleation sites for skyrmions.^[16,121–123]

Recent advancements have significantly improved the precision of electrically creating skyrmions at specific locations in magnetic stripes.^[126,127] This progress is largely attributed to the introduction of artificial nucleation sites, which require tailored structural or magnetic designs for skyrmion-hosting multilayers.

For example, local modifications of magnetic anisotropy via beam irradiation or the use of concave surfaces have been successfully employed to deterministically generate skyrmions through electrical means. Figure 4d illustrates the current-induced precise creation of skyrmions in line and dot array areas irradiated by a focused He^+ -ion beam.^[124] Light-ion irradiation can subtly alter magnetic properties such as coercivity, magnetic anisotropy, and DMI at the nanoscale, thereby creating well-defined skyrmion nucleation sites. However, these artificially introduced skyrmions, due to material degradation, are not easily movable and are not readily implementable in constructing skyrmionic devices. Furthermore, Zhao et al. demonstrated the current-induced formation of hexagonal and square skyrmion lattices in Ta/CoFeB/MgO multilayers by spin-orbit torques, by patterning concave surface topography with designed arrays of indentations on standard silicon substrates, as shown in Figure 4e.^[125] This approach, which involves fabricating indentation arrays on standard silicon substrates, may be compatible with standard semiconductor processing technology. Additionally, the deterministic electric-field generation of skyrmions has been demonstrated in magnetic multilayers, which is believed to significantly reduce energy dissipation.^[128–130] For the

advancement of skyrmion-based memory devices, a profound understanding of the nucleation mechanisms in magnetic tracks with artificial nucleation sites is essential to achieve the deterministic electrical creation of individual skyrmions at desired positions.

Although significant progress has been made in the deterministic electrical generation of individual skyrmions, methods such as light-ion irradiation and specific indentation design can complicate device fabrication. Moreover, as illustrated in Figure 4, the precise creation of skyrmions at desired positions still requires an external field, which hinders the development of all-electrical skyrmionic devices. Recently, MTJ structures have been utilized to electrically write skyrmions in MTJ cells at zero fields, achieving ultralow critical current density and energy consumption.^[95,131] The spin polarization direction generated is aligned with the magnetization direction of the free layer, enabling efficient skyrmion writing. More importantly, MTJs are currently the most promising method for the electrical detection of magnetic skyrmions, a topic that will be explored in the subsequent section. Consequently, the electrical generation of skyrmions via spin-polarized currents in MTJ cells stands out as a promising method, offering both precision and CMOS process compatibility, which facilitates smooth integration into existing semiconductor fabrication processes.

3.2. Electrical Motion

For skyrmionic devices, the deterministic motion of magnetic skyrmions along magnetic tracks is as crucial as their precise creation. To date, the displacement of magnetic skyrmions has been achieved through various methods, including magnetic field gradients,^[132] thermal fluctuations or gradients,^[57] acoustic waves,^[133,134] mechanical strain^[135] and electric currents or fields.^[16,18] Focusing on all-electrical skyrmionic devices, this section will concentrate on electrical methods. In magnetic multilayer structures such as [HM1/FM/HM2]_n, current-induced spin torques, particularly SOTs, have emerged as a promising approach for electrically manipulating skyrmions.

Before exploring experimental observations of current-induced skyrmion motion, we first establish a theoretical framework for skyrmion dynamics in two-dimensional systems driven by SOTs. Assuming a magnetic skyrmion behaves as a rigid spin texture, its steady motion under SOT can be described by a modified Thiele equation^[2,63,136–139]:

$$\mathcal{G} \times \mathbf{v} - \alpha \mathcal{D} \cdot \mathbf{v} + 4\pi \mathcal{B} \cdot \mathbf{j}_{\text{HM}} = 0 \quad (7)$$

Here $\mathcal{G} = (0, 0, \mathcal{G})$ is the gyrotropic coupling vector and $\mathcal{G} = 1/4\pi \int \mathbf{m} \cdot (\partial_x \mathbf{m} \times \partial_y \mathbf{m}) dx dy$ is related to the topological charge of skyrmions. $\mathbf{v} = (v_x, v_y)$ is the skyrmion moving velocity along the direction of x and y axes. α is the magnetic damping coefficient of magnetic materials and $\mathcal{D}$ is the dissipative tensor. The tensor $\mathcal{B}$ quantifies the spin-orbit torque efficiency and $\mathbf{j}_{\text{HM}}$ is the current density of HMs. The first, second, and third terms in Equation (1) correspond to the topological Magnus force, the dissipative force, and the driving force, respectively. Specifically, the topological Magnus force causes the transverse motion (v_y) of magnetic skyrmion with respect to the electric current direction

(x -axis), a phenomenon known as the skyrmion Hall effect,^[60,61] as illustrated in Figure 5a. Notably, the Thiele equation does not account for pinning effects in materials or the internal degrees of freedom of skyrmions, which can influence current-driven dynamics. When an electric current is applied along the x -axis, a simple expression of the skyrmion velocities can be derived:^[63,138]

$$\begin{cases} v_x = \frac{-\alpha \mathcal{D}}{\mathcal{G}^2 + \alpha^2 \mathcal{D}^2} B j_{\text{HM}} \\ v_y = \frac{\mathcal{G}}{\mathcal{G}^2 + \alpha^2 \mathcal{D}^2} B j_{\text{HM}} \end{cases} \quad (8)$$

Here the coefficient B is linked to the spin Hall torque. The skyrmion Hall effect can be further quantitatively described by the skyrmion Hall angle θ_{sk} , defined as $\tan \theta_{\text{sk}} = v_y/v_x = -\mathcal{G}/\alpha \mathcal{D}$.

In thin-film systems, SOTs, which arise from the spin Hall effect and/or the interfacial Rashba–Edelstein effect, have been utilized as the driving force for current-induced skyrmion motion.^[28,140,141] Néel-type skyrmions can be stabilized in heterostructures composed of HMs and FM layers, with their chirality determined by the sign of the interfacial DMI. The current-driven motion of these chiral spin textures is governed by both the SOT and the interfacial DMI.^[142] Therefore, the magnitude and sign of both the DMI and SOT are critical for achieving efficient and reliable skyrmion motion.

Figure 5b illustrates the current-induced skyrmion motion investigated in stripe devices fabricated from FM [Pt/Co/Ta]_n multilayers. It is important to note that skyrmion annihilation and unsynchronized motion of skyrmions along the magnetic tracks can be observed upon a series of current pulse injections.^[18] The velocity of skyrmion motion is a crucial parameter for quantifying current-driven skyrmion dynamics. For most FM skyrmions, current-induced motion is absent at low current densities due to extrinsic pinning effect. Slightly above a critical current density, skyrmion motion becomes observable, corresponding to a creep and depinning process. As the current density increases, the velocity of skyrmion motion also increases linearly, transitioning into a flow regime. Figure 5c depicts the typical skyrmion velocity as a function of the applied current density.^[18] This relationship suggests that the pinning effect of local defects and disorder in the thin film materials significantly influences current-driven skyrmion dynamics.

In addition to longitudinal motion along the current direction, transverse motion (v_y) perpendicular to the current direction can also arise due to the intrinsic skyrmion Hall effect induced by the finite topological charge $\mathcal{G}$. This transverse motion is generally unfavorable for improving the efficiency of skyrmion motion.^[143] The skyrmion creation and annihilation may also occur during current-induced skyrmion motion, which poses a significant challenge for the reliability of skyrmionic devices. Although current-induced skyrmion motion has been demonstrated, the velocities driven by SOT in commonly studied FM films are typically limited to around 100 m s^{−1}. Moreover, the dynamics of these skyrmions are highly impacted by the intrinsic skyrmion Hall effect, which can lead to skyrmion annihilation at the device edges before they reach very high velocities.

Recent studies have shown that the skyrmion Hall angle can be reduced or even canceled in materials with reduced or canceled magnetization, such as ferrimagnets or synthetic

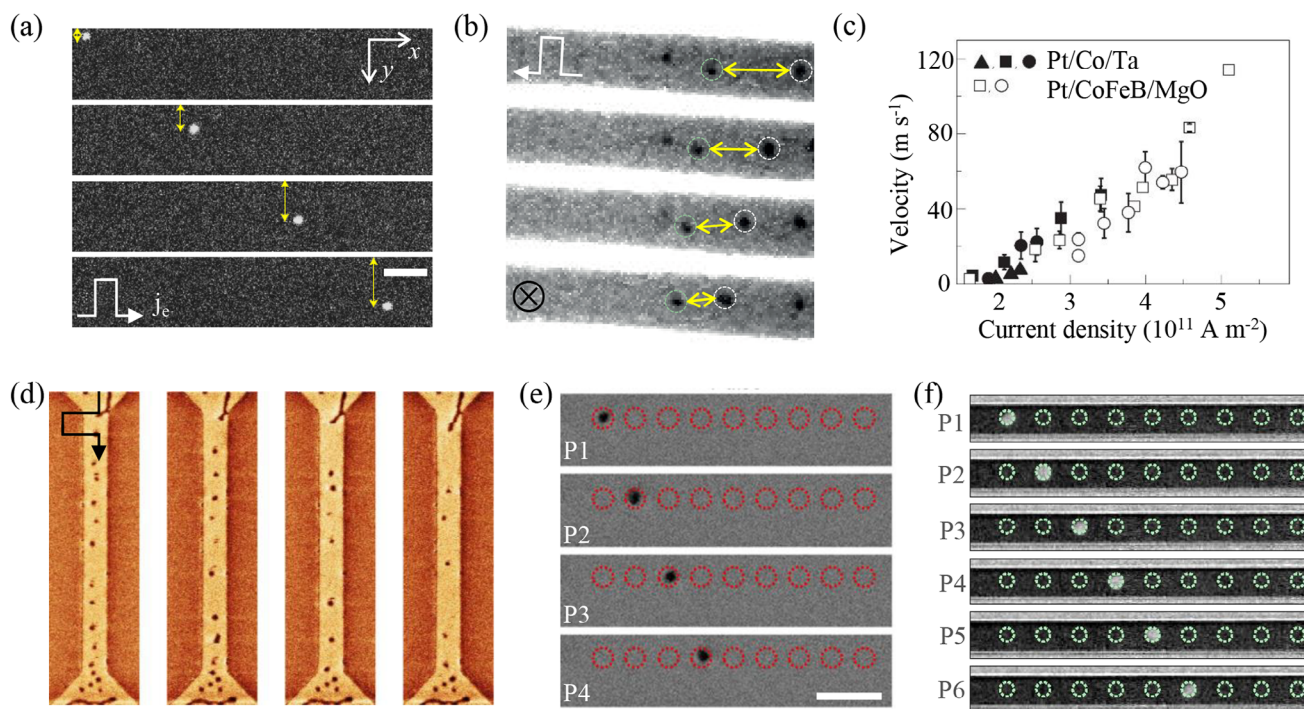


Figure 5. a) Snapshots of current-induced skyrmion motion at $j_e = 2.6 \times 10^6 \text{ A cm}^{-2}$ and under a perpendicular field $B_z = 0.5 \text{ mT}$. Besides the longitudinal motion (v_x) along the current direction, a transverse motion (v_y) can be also observed, which is indicated by the yellow arrows. Scale bar is $5 \mu\text{m}$. Reproduced with permission.^[60] Copyright 2017, Nature Publishing Group. b) Sequential scanning transmission X-ray microscopy (STXM) images showing the skyrmion motion in $2 \mu\text{m}$ wide $[\text{Pt}/\text{Co}/\text{Ta}]_{15}$ magnetic track after injecting current pulses, with an amplitude of $j_e = 2.2 \times 10^7 \text{ A cm}^{-2}$. The individual skyrmions are outlined in dashed circles. Along the track, the unsynchronized motion of skyrmions is displayed by the yellow arrows. Reproduced with permission.^[18] Copyright 2016, Nature Publishing Group. c) The skyrmion velocities in $[\text{Pt}/\text{Co}/\text{Ta}]_{15}$ and $[\text{Pt}/\text{CoFeB}/\text{MgO}]_{15}$ magnetic tracks as a function of the current density. Reproduced with permission.^[18] Copyright 2016, Nature Publishing Group. d) The current-induced ferrimagnetic skyrmion motion in $1 \mu\text{m}$ wide $[\text{Pt}/\text{Co}/\text{Tb}/\text{Al}]_5$ track after application of 10 ns wide current pulse in between two images with $j_e = 3.5 \times 10^7 \text{ A cm}^{-2}$ under an external perpendicular field $B_z = -41 \text{ mT}$. Reproduced under terms of the CC-BY license.^[144] Copyright 2024, Nature Publishing Group. e) Polar magneto-optical Kerr effect (MOKE) images of the deterministic motion of an individual skyrmion captured after applying successive electrical current pulse. The artificial shifting sites indicated by the red dashed circles are introduced onto the magnetic track by using laser irradiation. Scale bar is $10 \mu\text{m}$. Reproduced under terms of the CC-BY license.^[126] Copyright 2023, ACS Publications. f) Polar MOKE images of the deterministic and long-distance motion of a single skyrmion along a one-dimensional racetrack taken after applying each current pulse of amplitude $j_e = 2.4 \times 10^6 \text{ A cm}^{-2}$. The artificial shifting sites indicated by the green dashed circles are introduced onto the magnetic track by pre patterning circular indentations of $2 \mu\text{m}$ diameter onto standard silicon wafers. Reproduced under terms of the CC-BY license.^[125] Copyright 2024, Science China Press.

antiferromagnets. For ferrimagnetic and synthetic antiferromagnetic skyrmions, the antiparallel alignment of magnetic sublattices can lead to antiferromagnetic-like ultrafast spin dynamics and the cancellation of the net topological charge G_{net} . Consequently, it is anticipated that ferrimagnetic and synthetic antiferromagnetic skyrmions will exhibit fast motion with a significantly reduced skyrmion Hall effect. For instance, the skyrmion Hall angle can be largely reduced or eliminated in synthetic antiferromagnetic thin films and at the angular momentum compensation point in ferrimagnetic.^[144] Recently, fast skyrmion motion has been achieved in nearly compensated ferrimagnetic and synthetic antiferromagnetic films through moderately tuning the compensated magnetization.^[81,113,114] Figure 5d shows the fast motion of 160 nm -sized ferrimagnetic skyrmions on $1 \mu\text{m}$ -wide tracks fabricated from $[\text{Pt}/\text{Co}/\text{Tb}/\text{Al}]_5$ multilayers with a skyrmion velocity of 400 m s^{-1} . The fully compensated magnetization results in enhanced spin-orbit torques in the multilayers. Additionally, antiferromagnetic coupling between two sublattices and the low net magnetization has led to the ef-

fective inhibition of the skyrmion Hall effect. Therefore, due to the enhanced spin-orbit torques and reduced skyrmion Hall effect, ferrimagnetic skyrmions can efficiently move along the track nearly without any transverse deflection. Table 2 summarizes the current-driven dynamics of magnetic skyrmions on the magnetic tracks, including key parameters such as skyrmion size (d_{sk}), depinning threshold current density (J_C^{th}), skyrmion velocity (v_{sk}), and skyrmion mobility (v/J). Notably, an external field is still required to maintain isolated magnetic skyrmions on the magnetic tracks. Among the different types of skyrmions, ferrimagnetic and synthetic antiferromagnetic skyrmions currently exhibit the highest skyrmion velocity and mobility.

Although significant progress has been made in achieving fast skyrmion motion and reducing the skyrmion Hall angle, the movement of skyrmions in magnetic tracks remains randomly pinned and unsynchronized, which can decrease the reliability of skyrmionic devices. To achieve controlled movement of skyrmions, artificial shifting sites can be introduced onto

Table 2. Comparison of current-driven dynamics of room temperature (RT) magnetic skyrmions by spin-orbit torques in magnetic tracks made of ferromagnets (FM), ferrimagnets (FIM), and synthetic antiferromagnets (SAF) multilayers, including track width w , skyrmion size d_{sk} , skyrmion velocity v , depinning threshold current density j_C^{th} 10^{10} A m $^{-2}$, and skyrmion mobility v/j 10^{10} m ^{3} A $^{-1}$ s $^{-1}$.

Material system	w [μ m]	d_{sk} [nm]	v [m s $^{-1}$]	j_C^{th}	v/j	Magnetism
Ta/CoFeB/TaO $_x$	60	1000	2.5×10^{-5}	0.01	7.1×10^{-4}	FM ^[16]
[Pt/CoFeB/MgO] $_{15}$	2	200	120	20	3.14	FM ^[18]
[Pt/Co/Ta] $_{15}$	2	200	40	20	1.43	FM ^[18]
Ta/CoFeB/TaO $_x$	20	2700	0.4	2	0.27	FM ^[145]
[Pt/Co/Ir] $_{10}$	1	80	40	10	1.47	FM ^[90]
Ta/CoFeB/TaO $_x$	10	1000	0.7	1	0.16	FM ^[60]
[Pt/CoFeB/MgO] $_{15}$	2	110	100	5	2.2	FM ^[61]
Pt/Co/MgO	3	156	100	35	2.86	FM ^[146]
[Pt/CoFeB/MgO] $_{15}$	2	80	80	25	3.2	FM ^[103]
[Pt/GdFeCo/MgO] $_{20}$	2	180	50	15	2	FIM ^[74]
Pt/CoGd/W	10	2500	610	45	10.3	FIM ^[113]
[Pt/Co/Tb/Al] $_5$	1	160	400	30	4.28	FIM ^[114]
Pt/Co/Ni/Au/Ni/Co/Pt	1	160	60	30	4	SAF ^[120]
Pt/CoFeB/Ir/CoFeB/W	10	1500	5	50	0.1	SAF ^[80]
Pt/Co/Ru/Pt/Co/Ru	3	215	900	50	23	SAF ^[81]

the magnetic track. For example, laser irradiation can be used to introduce skyrmion locators onto the magnetic track, creating well-defined skyrmion shifting sites. Figure 5e displays the consecutive motion of a skyrmion between neighboring locators after applying a series of current pulses.^[126] Alternatively, artificial shifting sites can be introduced by patterning circular indentation arrays on silicon substrates, which can then be used to fabricate magnetic multilayers with naturally introduced shifting sites on the subsequently deposited films.^[125] One-dimensional racetrack devices based on these films have demonstrated long-distance deterministic current-induced motion of individual skyrmions between neighboring indentations, as shown in Figure 5f. Introducing these artificial shifting sites can result in an unavoidable pinning effect, which depends on the laser fluence and indentation depth. By modulating the fluence and depth, the resulting pinning effect can be significantly mitigated.

These approaches offer promising solutions for achieving controlled and reliable skyrmion motion, which is essential for the development of skyrmionic devices. However, the current size of skyrmions is typically on the micrometer scale, which is too large for achieving high-density skyrmionic devices. In the future, it may be possible to incorporate deterministic shifting sites onto magnetic tracks with sub-100 nm widths, enabling the hosting of ultrasmall skyrmions tens of nanometers in size. Recently, steady motion of 80-nm-size skyrmions with a negligible skyrmion Hall angle was demonstrated in a 100-nm-wide FeGe magnetic track fabricated using focused ion beam (FIB) technology.^[147] Achieving deterministic and rapid motion of skyrmions with a negligible skyrmion Hall effect is crucial for the development of future skyrmionic devices. This remains a long-term objective in the field, with ongoing research focusing on further reducing skyrmion size and enhancing the stability and controllability of their motion.

3.3. Electrical Detection

As previously discussed, the electrical creation and motion of skyrmions have been the primary focuses of experimental research in the past decade. However, electrical detection of skyrmions compatible with semiconductor processing technology remains to be adequately addressed, which is considered one of the most crucial steps for realizing all-electrical skyrmionic devices. In recent years, the electrical detection of skyrmions has been achieved through various phenomena, including the anisotropic magnetoresistance effect,^[148,149] topological Hall effect,^[20,94,150] anomalous Hall effect,^[92,93] anomalous Nernst effect,^[57,98] and TMR effect.^[86,95,131,151–155] Among these methods, MTJs have emerged as a promising route to efficiently and electrically detect individual skyrmions through TMR, thanks to their large electrical readout signals and CMOS compatibility. In this section, we will review recent important progress on the efficient TMR detection of skyrmions stabilized in MTJ cells.

The MTJ is the fundamental building block of magnetoresistive random access memory (MRAM) technology, typically consisting of two metallic FM layers separated by a thin insulating barrier, such as CoFeB/MgO/CoFeB, as shown in Figure 6a. The resistive states of the MTJ are determined by the spin orientations of the free layer and the reference layer. The TMR is lower when the magnetization directions are parallel and higher when they are antiparallel. For conventional uniformly magnetized MTJs, the TMR exhibits binary resistive states,^[95] as depicted in the inset of Figure 6b. To achieve TMR read-out of skyrmions, it is essential to stabilize magnetic skyrmions within the free layers of MTJ cells and ensure their presence and absence for efficient electrical detection. Therefore, magnetic multilayers hosting RT skyrmions, such as [Pt/Co/Ta] $_n$, exhibit FM coupling with the bottom CoFeB layer, which serves as the entire free layer and is

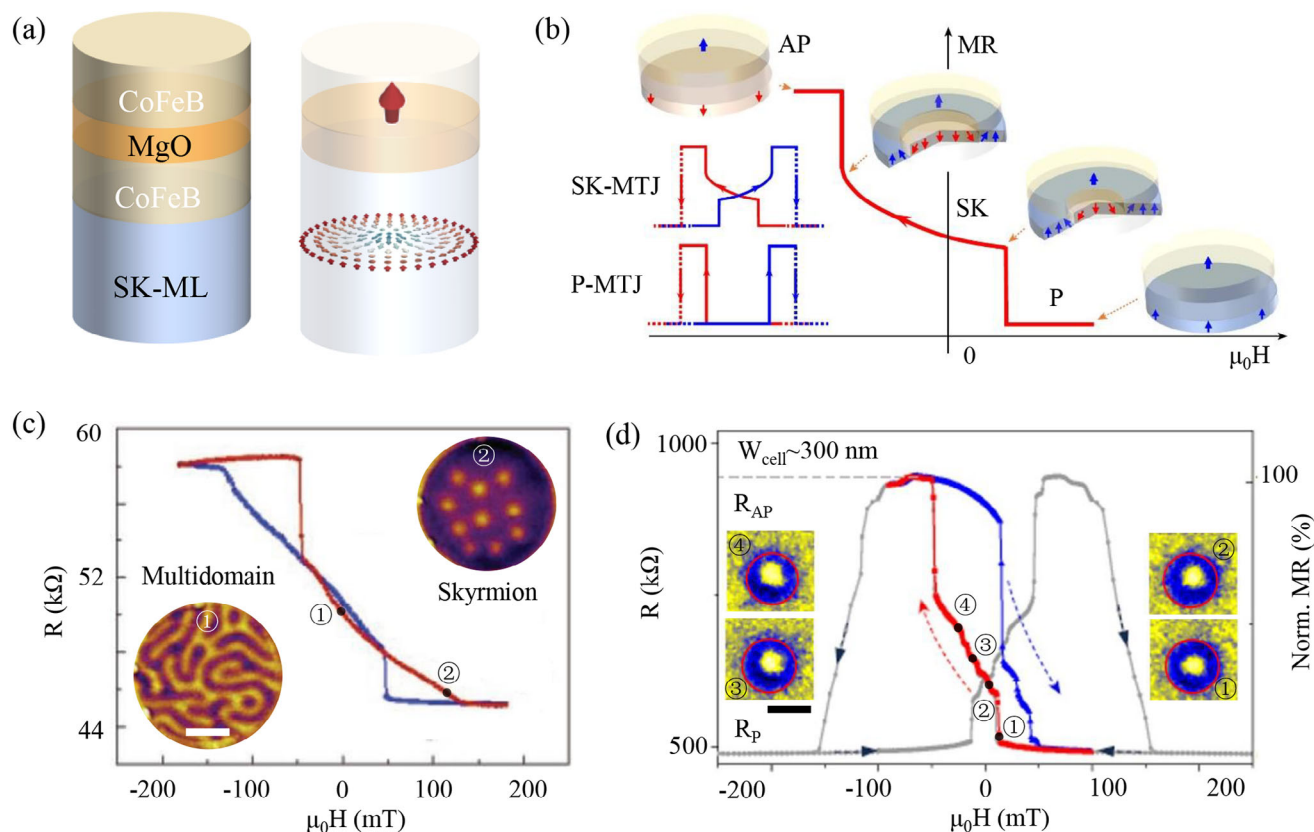


Figure 6. a) A schematic of the skyrmionic magnetic tunnel junction (MTJ) stack including the top reference layer, MgO layer, and bottom free layer. The skyrmion multilayer hosts room temperature (RT) skyrmions, which can be imprinted into the bottom CoFeB free layer through magnetostatic interlayer coupling. The right panel shows a schematic of a Néel-type skyrmion in the free layer of a skyrmionic MTJ. b) The magnetoresistance evolution as a function of field expected for skyrmionic MTJ device with the up-oriented reference layer. In addition to the uniform parallel and antiparallel magnetization states, some intermediate magnetoresistance values related to skyrmion states can be expected. The left inset depicts the major loops for skyrmionic MTJ and traditional perpendicular MTJ. Reproduced with permission.^[95] Copyright 2024, Nature Publishing Group. c) The minor magnetoresistance hysteresis loop related to the skyrmion layer. The inset shows the magnetic force microscopy (MFM) images of the labyrinth domain at zero field (labeled by ①) and the isolated skyrmions at $B_z = 124$ mT (labeled by ②). Scale bar is 500 nm. Reproduced under terms of the CC-BY license.^[154] Copyright 2022, Wiley-VCH GmbH. d) The magnetoresistance hysteresis loop $R(H)$ for skyrmionic MTJ cell device of 300 nm diameter in the measured and normalized units, depicting the major and minor loops. The red and blue arrows indicated the sweeping directions. The inset shows the MFM images of the evolution of skyrmion states in the MTJ cell along the up-sweeping direction (red arrows), which are labeled by the numbers ①, ②, ③, and ④. Scale bar is 200 nm. Reproduced with permission.^[95] Copyright 2024, Nature Publishing Group.

crucial for stabilizing the skyrmions through the DMI, as illustrated in Figure 6a. However, the sizes of MTJ cells still exceed those of skyrmions, resulting in multiple resistive states beyond the binary resistive states,^[95] as presented in Figure 6b. The TMR values in MTJs hosting skyrmions depend on the sizes and densities of the stabilized skyrmions within the free layer.

Although intermediate resistive states have been observed in skyrmion-based MTJs, Guang et al. first clearly demonstrated the electrical detection of multiple magnetic skyrmions within micrometric MTJ cells, achieving a TMR ratio of $\approx 20\%$. They simultaneously imaged the stabilized skyrmions within the cells using MFM,^[154] as shown in Figure 6c. Further, they realized zero-field micrometric skyrmions within perpendicularly magnetized MTJ cells through the antiferromagnetic exchange bias effect.^[86] Recently, a significant breakthrough was achieved by Chen et al., who demonstrated the wafer-scale realization of nanoscale skyrmionic MTJs hosting individual RT skyrmions.^[95] The maximum TMR ratio reached 70% and this value strongly

depends on the varying sizes of individual skyrmions within the MTJ cells. Figure 6d depicts the TMR major and minor loops with perpendicular field sweeping for the skyrmionic MTJ (SK-MTJ) device. Moreover, they demonstrated the ability to write skyrmions, reverting a uniform magnetization state to a skyrmion state through electric voltage, representing a more energy-efficient approach than current state-of-the-art methods. Furthermore, Zhao et al. recently achieved a 100% TMR ratio in skyrmionic MTJs and demonstrated the electrical detection of mobile skyrmions through time-dependent TMR changes.^[155] These works highlight the potential for highly efficient and reliable skyrmion detection in MTJ-based devices.

While electrical detection of skyrmions using MTJs has been demonstrated, most skyrmions remain immobile, confined within the MTJ cells, and stabilized by external fields. Additionally, the varying sizes of the detected skyrmions lead to a range of intermediate resistive states, unlike the binary (parallel and antiparallel) states typically seen in uniformly magnetized MTJs.

Therefore, it is crucial to stabilize zero-field skyrmions of fixed sizes in multilayer materials, which can be easily integrated into MTJ devices as a complete free layer. To enable high-density skyrmionic devices, both the sizes of zero-field skyrmions and the MTJ cells will need to be further reduced.

For skyrmionic devices that host moving skyrmions, achieving accurate and efficient TMR detection of moving skyrmions is critical for their practical applications. Considering the deterministic motion of skyrmions discussed previously, an array of MTJ cells can be fabricated at designated shifting sites along the magnetic track, ensuring reliable and accurate electrical detection. With the application of efficient spin-orbit torque, skyrmions can be deterministically moved among shifting sites by injecting an electric current pulse. When a skyrmion is shifted to a site beneath an MTJ cell, both its position and presence on the track can be directly detected through TMR. This capability is pivotal for all-electrical skyrmionic devices, where precise creation, deterministic motion, and efficient detection of magnetic skyrmions by electrical means are the most critical aspects.

4. Skyrmionic Device Applications

4.1. Skyrmion Memory Devices

Skyrmions have a variety of applications in the fields of memory, logic, and other spintronic devices.^[1] One of the most widely studied potential applications is the skyrmion racetrack memory device, which builds upon the domain wall (DW) racetrack memory first proposed by Parkin et al. in 2008.^[156] Currently, HDDs are the primary storage devices that store digital information using nanoscale magnetic elements. However, they still rely on the mechanical movement of platters where data is stored in the form of magnetic patterns, leading to slower processing speeds. In the past decade, the concept of racetrack memory has garnered significant attention as it can eliminate the necessity of mechanical movement in traditional HDDs.

Following the experimental discovery of magnetic skyrmions, Fert et al. promptly proposed the concept of skyrmion racetrack memory, which employs magnetic skyrmions as information carriers.^[14,15] Compared with current-induced DW motion, the driving current density required for skyrmion motion can be theoretically reduced to $10^6 \text{ A} \cdot \text{m}^{-2}$, which is several orders of amplitude smaller than that of DW motion ($10^{11} \text{ A} \cdot \text{m}^{-2}$). This ultralow electrical current requirement makes skyrmion racetrack memory more efficient, leading to lower power consumption. The data information could be encoded in magnetic tracks through the presence or absence of ultrasmall skyrmions, representing logical “1” or “0”, respectively. The spacing between data bits can be of the order of the skyrmion size, which is much smaller than the spacing in a DW racetrack. Due to their ultrasmall size, skyrmions are well-suited for meeting the requirements of high-density data storage. In addition, due to their inherent topological protection, magnetic skyrmions can navigate around defects in materials and this topological stability enhances the reliability of skyrmion racetrack memory.

Building upon the discussed precise creation, deterministic motion, and efficient detection of skyrmions, we introduce a prototype for an all-electrical skyrmion racetrack memory device exploiting skyrmionic MTJs, as illustrated in **Figure 7a**. To en-

sure reliable operation, artificial shifting sites are strategically embedded along the magnetic tracks. These MTJ structures enable the creation and detection of moving skyrmions at designated sites. Under zero-field conditions, spin-polarized currents precisely generate individual skyrmions at artificial sites beneath MTJ cells. A subsequent horizontal current along the track drives these skyrmions deterministically to adjacent sites. When a skyrmion reaches an MTJ cell designated for readout, its presence and position are directly detected via TMR. However, current designs rely on relatively large skyrmions, constrained by the dimensions of artificial sites and the magnetic properties of host materials. To realize high-density, all-electrical skyrmionic memory, critical steps include optimizing materials to shrink skyrmion size and advancing fabrication to miniaturize artificial sites. These innovations will refine device architecture and functionality, driving progress toward more efficient, high-density memory solutions.

4.2. Skyrmion Transistors and Logic Gates

Beyond their utility in memory devices, magnetic skyrmions are poised to redefine next-generation computing architectures. Their inherent topological stability, nanoscale sizes, and ultralow power consumption position them as prime candidates for transistors and logic gates.^[157–169] These attributes not only enable seamless integration with skyrmionic memory systems but also catalyze the development of advanced architectures that merge high-density memory and processing capabilities, paving the way for energy-efficient, compact computing solutions.

Skyrmion transistors leverage the topological stability and controllability of skyrmions, using their presence or absence to define the “on” and “off” states. These states are electrically detected via TMR. By applying small electric fields or currents, skyrmions can be reliably toggled between the two states, enabling transistors with low power consumption and high endurance. As depicted in **Figure 7b**, in the “off” state, both an electric current and a voltage gate are active. The current induces spin-orbit torque, driving the skyrmion toward a detection site, while the gate alters local magnetic anisotropy to block its motion. In contrast, the “on” state activates only the driving current (with the gate off), allowing the skyrmion to deterministically reach the detection site.^[157] Its arrival is then directly detected by TMR.

Skyrmions can be also harnessed to build logic gates (e.g., AND, OR, NOT, NAND, NOR) by encoding logical “1” and “0” through their presence or absence.^[170] Logical operations are executed by manipulating skyrmions via spin-orbit torques. For example, in a skyrmion-based OR gate (**Figure 7c**), a skyrmion at either input site ensures one appears at the output (logical “1”), while absence at both inputs yields a logical “0,” detectable via TMR.^[158] Additionally, antiferromagnetic skyrmions, controllable via electric currents/fields, offer ultralow energy consumption and high storage density for logic gate designs.^[171] A recent study demonstrated low-energy logic circuits using synthetic antiferromagnetic skyrmions, outperforming FM counterparts in efficiency.^[172] Overall, Skyrmion-based transistors and logic gates represent a transformative pathway to high-performance, low-power electronics, promising to redefine computing architectures for the future.

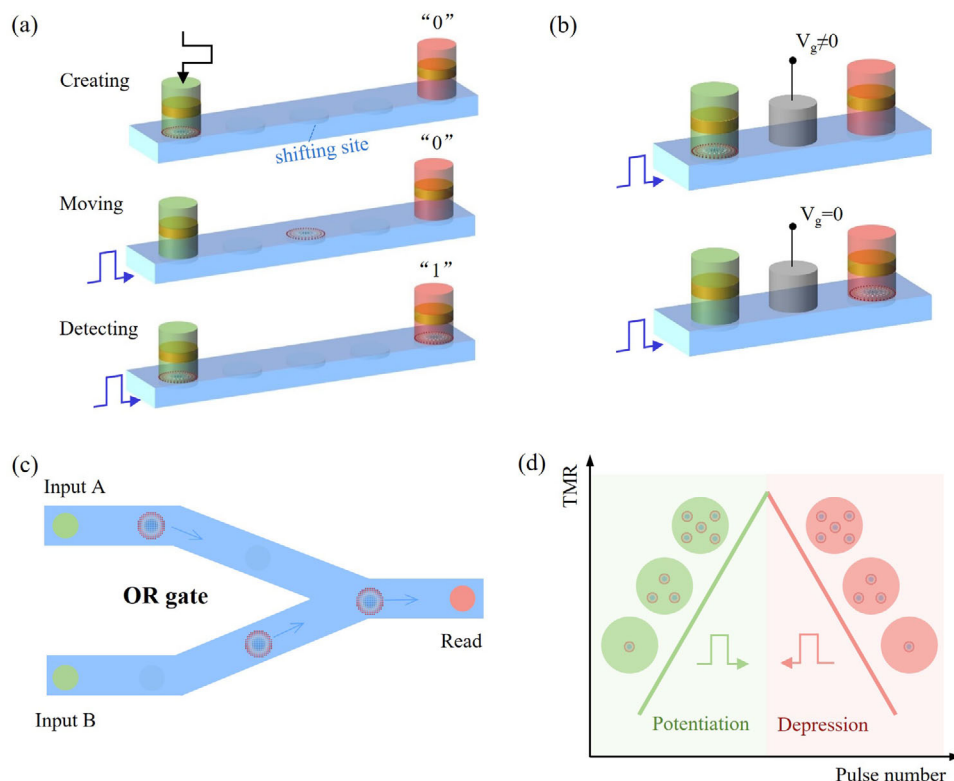


Figure 7. a) A prototype all-electrical skyrmion racetrack memory device. By utilizing vertical spin-polarized current, a skyrmion is precisely created at the shifting site beneath the magnetic tunnel junction (MTJ) cell. Upon the application of horizontal current pulses, a single skyrmion can be deterministically moved to the neighboring shifting sites. When a skyrmion is shifted to the site beneath the MTJ cell for reading, a skyrmion can be accurately and efficiently detected through tunneling magnetoresistance (TMR). b) Schematic illustration of a skyrmion transistor. Two shifting sites are introduced beneath the left and right MTJ cells. The gating voltage is employed to alter the perpendicular magnetic anisotropy in the voltage-gated region.^[157] c) A design of skyrmion OR logic gate, which is based on precise creation, deterministic motion, and efficient detection of skyrmion.^[158] d) A schematic of the performance curves of an ideal skyrmionic artificial synaptic device, where the normalized TMR changes linearly to the injected current pulses. The green and red areas correspond to the TMR ratio change during potentiation and depression, respectively. The insets also present the skyrmion populations within MTJ cells after injecting current pulses during potentiation and depression process with opposite polarities.

4.3. Skyrmion Neuromorphic Computing Device

In recent years, skyrmion-based neuromorphic devices are an emerging class of brain-inspired systems that harness the topological stability, nanoscale sizes, and low-current operation of magnetic skyrmions to emulate artificial synapses and neurons for advanced unconventional computing.^[173–177]

Skyrmion-based artificial synapses mimic the behavior of biological synapses, where the strength of the synaptic connection can be modulated. In these devices, the presence and manipulation of skyrmions represent the synaptic weight. By applying electric currents or fields, skyrmions can be created and deleted, thereby simulating the potentiation and depression operations in synapses. For instance, Song et al. demonstrated electrical pulse controlled accumulation/dissipation of skyrmions in ferrimagnetic multilayers, mimicking synaptic weight changes.^[178] These synapses can enable neuromorphic tasks such as pattern recognition. Figure 7d shows the ideal potentiation and depression processes of the biological synapses based on the SK-MTJ, where the skyrmion counts can be accurately detected via TMR. Additionally, skyrmion-based neurons can be designed to perform the leaky-integral-and-fire function, which is a fundamental opera-

tion in neural networks.^[173] These neurons can integrate inputs over time and fire when a certain threshold is reached.

The nanoscale sizes of skyrmions enable high-density synaptic/neuronal integration, while their low-current manipulation ensures ultralow power consumption—critical for energy-efficient computing. Their intrinsic topological stability guarantees robustness against perturbations, ensuring reliable neuromorphic operation. These devices may excel in applications such as pattern recognition, data processing, and cognitive computing. For instance, a recent study demonstrated skyrmion-based systems achieving $\approx 87\%$ accuracy on the CIFAR-10 dataset,^[179] validating their suitability for complex tasks. Skyrmion-based neuromorphic devices thus offer a viable pathway to next-generation computing systems that prioritize efficiency, scalability, and low power consumption.

5. Conclusions and Outlook

In summary, recent years have witnessed significant progress in thin-film magnetic skyrmions, including their static and dynamic properties and their potential applications in various spintronic devices. The stabilization of RT thin-film magnetic skyrmions in

various magnetic materials, such as ferromagnets, ferrimagnets, and synthetic antiferromagnets, has been demonstrated through the use of interfacial DMI. These achievements provide a broad platform for skyrmionic research. Specifically, the stabilization of skyrmions at zero field has been further realized by utilizing interlayer exchange coupling, exchange bias, and geometric confinement. Through parameter optimization of thin-film materials, skyrmion sizes can be reduced to below 50 nm, critical for high-density skyrmionic devices. For practical applications, all-electrical skyrmionic devices require precise creation, deterministic motion, and efficient detection of skyrmions. With the introduction of artificial sites, these operations have been independently realized by electrical means at room temperature. Lastly, the potential applications of skyrmionic devices have been discussed, and these devices are compatible with standard semiconductor processing technologies. This compatibility is crucial for integrating skyrmionic devices into existing technological frameworks, paving the way for future advancements in spintronic memory and logic devices.

Despite progress in thin-film magnetic skyrmions, key challenges persist for practical applications. First, skyrmion sizes in thin-film materials remain large and variable compared to conventional HDD bit sizes. This is exacerbated by reliance on CoFeB/MgO-based MTJs for electrical detection. To unlock skyrmion potential, new skyrmion-hosting materials research and material optimization are critical to achieve ultrasmall, uniform skyrmions. Second, the need for external magnetic fields during skyrmion manipulation hinders large-scale integration. Additionally, artificial sites created via laser irradiation or micro-fabrication are still too large for future memory devices. Third, prioritizing all-electrical skyrmion memory, logic, and neuromorphic devices is urgent. While recent advances in electrical detection/manipulation are promising, breakthroughs are needed to overcome existing hurdles and realize skyrmion-based technologies.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

magnetic skyrmions, skyrmionic devices, skyrmion dynamics, skyrmion size, thin-film materials

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