# Magnetic Skyrmions for Future Potential Memory and Logic Applications: Alternative Information Carriers

Wang Kang, Xing Chen, Daoqian Zhu, Sai Li, Yangqi Huang, Youguang Zhang, and Weisheng Zhao
Fert Beijing Research Institute, Advanced Innovation Center for Big Data and Brain Computing,
Beihang University,
Beijing, 100191, China
{wang.kang, xing.chen0118, daoqian_zhu, saili, yangqi.huang, zyg, weisheng.zhao}@buaa.edu.cn

***Abstract*—Magnetic skyrmions are swirling topological configurations, which are mostly induced by chiral interactions between atomic spins in non-centrosymmetric magnetic bulks or in thin films with broken inversion symmetry. They hold promise as information carriers in future ultra-dense, low-power memory and logic devices owing to the nanocale size and extremely low spin-polarized currents needed to move them. To date, an intense research effort has led to the identification, creation/annihilation, motion and manipulation of skyrmions at room temperature. Meanwhile, a rich variety of skyrmion-based device concepts and prototypes have been proposed, indicating the considerable potential of magnetic skyrmions in future electronic applications. However, current studies mainly focus on physical or principle investigations, whereas the electrical design methodology, implementation and evaluations are still lacking. In this paper, we will bring the readers in the "design, automation and test (DAT) society" the current status and outlook of skyrmions in relation to future potential racetrack memory and neuromorphic computing applications. Most importantly, we also want to evoke the effort from the DAT society to address the challenges, e.g., all-electrical manipulation of skyrmions at room temperature, for the research and development of practical skyrmion-based electronics.**

***Keywords—Magnetic skyrmions, Neuromorphic computing, Racetrack memory, Spintronics***

## I. Introduction

Moore's law, by which the technology industry has mapped out its progress during the past half century, is the cornerstone of modern integrated circuits [1]. However, as the continual miniaturization of CMOS technology, the increased power dissipation owing to the inevitable leakage currents caused by the quantum effect [2] has become one of the most critical issues, leading to the failure of this famous empirical principle [3]. As a consequence, lots of efforts have been involved to search for alternatives or complementary technologies that can provide solutions to further downscaling of the CMOS technology. Spintronics, which aims at utilizing electron spin property rather than electron charge to store and process information [4, 5], has attracted broad attention over the last three decades. Taking advantages of the unique properties of electron spin, the storage and manipulation of information exhibit some unique properties, such as nonvolatility and low power [6], which outperform most conventional semiconductor techniques. Therefore, spintronics has been extensively expected to be one of the most potential candidates in the next post-Moore's law era, especially for the emerging topological particle-like spin configurations known as magnetic skyrmions for alternative information carriers [7-9].

Magnetic skyrmions are swirling topological configurations, which are mostly induced by chiral interactions between atomic spins in non-centrosymmetric magnetic bulks or in thin films with broken inversion symmetry. Owing to their intrinsic properties in nanoscale size, extremely low depinning current densities, high motion velocity and topological stability [9-12], they hold promise as information carriers in future ultra-dense, low-power memory and logic devices. Furthermore, the standby energy consumption and heat generation during the processing and transportation of information can be efficiently reduced thanks to the nonvolatility, which is the common superiority of spintronic devices in comparison with CMOS. Hence, integrated circuits based on magnetic skyrmions have great potential in the future. The potentials have facilitated intensive researches of magnetic skyrmions, both theoretically and experimentally. To date, advances have been made in the identification, creation/annihilation, motion and manipulation of skyrmions at room temperature (RT), which are the preconditions to employ skyrmions in practical devices. In the meantime, a rich variety of skyrmion-based device concepts and prototypes have been proposed, indicating the considerable potential of skyrmions for future electronic applications.

In this paper, we will review the current status and outlook of skyrmions concerning future memory and logic applications. The rest of this paper is organized as following: In Section II, we briefly introduce the fundamentals of magnetic skyrmions. Next, elementary functionalities of skyrmions are presented in Section III. Section IV illustrates several potential applications of skyrmions in terms of racetrack memory and neuromorphic computing. Afterwards, we review the main challenges for the applications of skyrmions in Section V. Finally, in Section VI, we conclude the paper.

## II. Skyrmions Fundamentals

The existence of magnetic skyrmions as particle-like states was first studied theoretically in 1989 by Bogdanov et al. [13]. Afterwards, corresponding theoretical calculations as well as micromagnetic studies on skyrmions have been performed, among which the theory predicting the existence of chiral skyrmions in B20-type bulk helimagnets [14] caused of broad concern. It was in 2009 that the first experimental observation of skyrmions in B20-type chiral materials was made by Mühlbauer et al. [7], which gave a boost to the researches of magnetic skyrmions. However, the early observations of skyrmion lattice or isolated skyrmions were performed at low temperature in the presence of a magnetic field. Recently,

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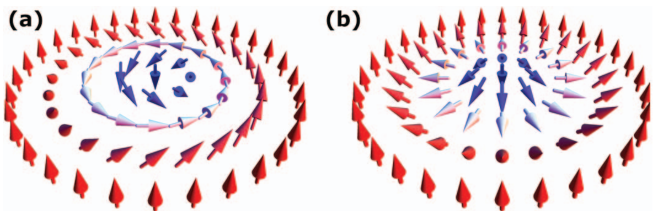


Fig. 1. Bloch-type and Neel-type skyrmions. (a) In a Bloch-type skyrmion, the spins rotate in the tangential planes, i.e., perpendicular to the radial directions, when moving from the core to the periphery. (b) In a Neel-type skyrmion, the spins rotate in the radial planes from the core to the periphery [12].

observing skyrmions at RT without a magnetic field has been achieved [15, 16], which is a key milestone for the practical applications of skyrmions. The origin of skyrmions can be briefly explained as a consequence of competition between the ferromagnetic exchange coupling, the Dzyaloshinskii-Moriya interaction (DMI, bulk or interfacial) and other energies in magnetic systems lacking inversion symmetry. As illustrated in Fig. 1, there are generally two types of skyrmions, Bloch-type and Neel-type skyrmions, which corresponds to the different symmetries of interactions between spins, depending on the material properties [11]. In most systems, the chiral DMI determines the configuration of skyrmions. Specifically, the Bloch-type chiral skyrmion, as denoted in Fig. 1(a), originates from the bulk DMI in B20-type materials, whereas the interfacial DMI favors the Neel-type hedgehog skyrmion, as shown in Fig. 1(b). Note that the DMI is a critical parameter which stabilizes skyrmions and impacts the skyrmion size [10]. Consequently, it's now a hot research topic to seek materials with high DMI as well as approaches to modulate it.

## III. Elementary Functionality of Skyrmions

To utilize skyrmions in practical electronics, the elementary functionality, e.g., identification, creation/annihilation, motion and manipulation, are of great significance, especially at RT.

### *A. Skyrmion creation/annihilation and identification*

Efficient creation/annihilation and identification ought to be achieved since the reproducible writing/deleting and reading operations are the basic requirements for any applications. The basic idea of creating skyrmions is to overcome the potential barrier so as to induce a topological transition of the magnetic textures. So far, various concepts, e.g. heat, magnetic field, voltage and electrical current [16-19], have been proposed to realize skyrmion creation at the custom-defined position of a device. From a practical standpoint, skyrmion nucleation through an electrical current is the method with most potential, thus being mostly studied in theory [17, 18] and evidenced in experiments [16, 19]. Apart from the conventional methods, Zhou et al. proposed another method to create skyrmions through topological conversion from a domain wall pair with micromagnetic simulations [20], which was verified by Jiang et al. [21] in experiments, subsequently. This method can be applied to design novel racetrack memories with unique functions, as will be discussed in section V.

The skyrmion annihilation process is somewhat the inversion of skyrmion nucleation while the methods are similar. By applying heat, magnetic field, electrical current, skyrmion annihilation can be achieved at the specific sites in a device. Besides, skyrmions can also be destroyed when being pushed to the boundary under a driving current. Skyrmion detection can be enabled through either the topological Hall effect (THE) or the magnetoresistance effect [22-25]. However, the former method is difficult to integrate in electronic circuits [22], whereas the latter one can achieve fully electrical skyrmion detection [24, 25]. In addition, another all-electrical skyrmion detection scheme, which has been employed experimentally to achieve the detection of individual skyrmions in PdFe/Ir(111) has been proposed based on the tunneling noncollinear magnetoresistance (NCMR) effect [23].

### *B. Skyrmion motion*

The applications of skyrmions will be restricted to a large extent unless they can be moved. To date, skyrmions can be driven by an electrical current via either spin transfer torque (STT) or spin orbit torque (SOT) originating from spin Hall effect (SHE) [9, 11, 17, 26]. However, as illustrated in [11, 17, 27], SOT is preferable for skyrmion motion in future low-power electronic designs of skyrmion-based integrated circuits since the SOT method has a higher drivability, thus being more energy efficient, particularly when the heavy metal (HM) where the charge current flows has a low resistivity. During the skyrmion motion, there exists an phenomenon, known as skyrmion Hall effect (SKHE), due to the skyrmion topology. Under a driving current, skyrmions will possess a longitudinal velocity along the nanotrack while simultaneously moving toward the nanotrack edge owing to the Magnus force [28], which may lead to the annihilation of skyrmions. Therefore, some studies aim to settle this problem. Micromagnetic simulations show that a current pulse sequence with constricted pulse duration instead of a DC current is more favorable for skyrmion motion for practical electronic designs [27]. By contrast, Zhou et al. [29, 30] focus on eliminating the topological number of skyrmions, thus suppressing the SKHE. In addition to the current driving method, magnons [31] or temperature gradients [32] have also been explored to control the motion of skyrmion. Nevertheless, these methods are still under theoretical development and require further experimental investigations.

### *C. Skyrmion manipulation*

Skyrmion manipulation is another critical elementary functionality required for employing skyrmions in electronic applications since electrically controlling the dynamics of skyrmion motion, in particular, the speed and direction, will enable us a broader perspective to the information storage and processing, such as skyrmion transistors and logic gates. Besides, utilizing a voltage rather than a current is expected to bring lower power consumption for skyrmion-based devices/circuits. Theoretically, this can be realized by designing a desired energy landscape artificially during the skyrmion motion process. One optional solution is to utilize the voltage controlled magnetic anisotropy (VCMA). To verify the idea, Kang et al. [27] study the pinning/depinning of a skyrmion along a nanotrack under the VCMA effect via micromagnetic simulations. Their results show that skyrmions move step by step along the nanotrack under the control of the electrical field gates, confirming the feasibility of manipulating skyrmions through the proposed method. Moreover, Wang et al. [33] investigated the electric

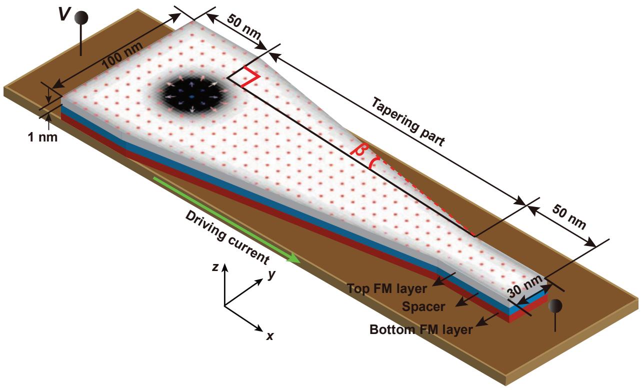


Fig. 2. Schematic of the width-varying nanotrack. The length of the tapering part in the middle varies from 100nm to 300 nm, leading to different slopes, which is defined as $k = \tan(\beta)$. The two segments of the parallel tracks are 100nm wide, 50nm long on the left side and 30nm wide, 50nm long on the right side, respectively [37].

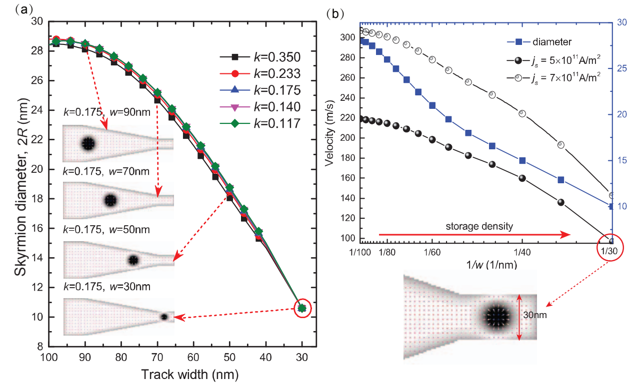


Fig. 3. (a) Diameter of the skyrmion as a function of the track width and slope (w and k), when flowing along the width-varying nanotrack. Note that the diameter of the skyrmion is about 10nm when w equals 30nm by pushing the skyrmion into the parallel track on the right side, denoted by the red cycle. (b) Tradeoff between the nanotrack width (storage density) and the skyrmion motion velocity (data access speed) in parallel tracks. Here, we use the reciprocal of the nanotrack width to denote the memory density and the skyrmion motion velocity to indicate the data access speed [37].

field induced skyrmion motion along an irregular path from an experimental perspective, where the skyrmion can be guided along desired trajectories with controllable speed by modulating the electric field.

## IV. Electronic Applications of Skyrmions: Case Studies

We present two case studies of skyrmion-based electronics, including racetrack memory and neuromorphic computing.

### *A. Skyrmion-based racetrack memory*

Racetrack memory (RM), a new storage scheme in which information flows along a nanotrack, has been considered as a potential candidate for high-density storage. The first proposed domain wall-based racetrack memory (DW-RM) [34], which has attracted intense studies since 2008, relies on a train of up or down magnetic domains separated by domain walls (DWs). Similar to the DW-RM, skyrmion-based RM (Sky-RM) [14, 26, 27], where binary information is encoded by a sequence of skyrmions, however exhibit advantageous properties compared with domain walls because of their high level of integration. On the one hand, the diameter of a compact skyrmion can be compressed considerably via decreasing the nanotrack width. On the other hand, the spacing between bits (down to several nanometers) in a nanotrack can be of the order of the skyrmion diameter, which may enable Sky-RM to achieve a higher storage density than DW-RM (hardly below 30–40 nm) [17]. Moreover, the critical depinning current density for skyrmion motion is much smaller than that of DWs, as was predicted by theories and observed in experiments [35].

Although some numerical studies and experiments have been performed to control the morphology and formation of highly geometrical magnetic skyrmions in constricted geometry [36], the motion of extremely small skyrmions in narrow nanotracks has not been thoroughly investigated yet. Here we consider a width-varying nanotrack, as shown in Fig. 2 [37]. A skyrmion is initially nucleated at the left side of the nanotrack and then actuated to the right end under a driving current flowing through the heavy metal under the nanotrack via SHE. It can be explicitly observed the compression process of the diameter of the skyrmion by the tapered width of the nanotrack, as presented in Fig. 3(a). In addition, one interesting finding reveals that skyrmions with small sizes, which may be inaccessible to typical approaches by means of directly injecting a spin-polarized current, could be obtained by utilizing this structure. Therefore, this finding is feasible for generating nanoscale skyrmions in skyrmionic applications with ultra-dense density. It is also numerically demonstrated that the velocity of the skyrmion varies during the motion, since the repulsive force of the nanotrack edges acting on the skyrmion as well as the driving force created by the SHE associated with the size of the skyrmion have a joint impact on the skyrmion motion in this structure. By further analyzing the skyrmion dynamics in parallel nanotracks with different widths, a general summary on the tradeoff between the nanotrack width (storage density) and the skyrmion velocity (data access speed) is concluded, as displayed in Fig. 3(b), which may provide guidelines in designing racetrack-type skyrmionic applications.

Another advantage of skyrmions is that the flexibility of their shapes and trajectories in curved tracks. By contrast, the motion of DWs will be seriously affected, which may lead to the distortion of their shapes in curved tracks. Considering this, skyrmions will show dominant superiorities in data access operations in contrast with DWs. In conventional DW-RM, the adjacent DWs are interactive through the magnetic domains. Hence, the update/deletion/insertion of one single or several data bits in a nanotrack should first readout all the data bits in the nanotrack to a buffer, then update/delete/insert the desired data bits in the nanotrack, finally restore the updated word into the nanotrack. This process consumes significant energy and time, particularly for a relatively large track, greatly degrading the memory performance. Remarkably, with our proposed Sky-RM [38], as shown in Fig. 4, the update/deletion/insertion of one or multiple data bits can be directly implemented by adding two extra access terminals in the nanotrack. Moreover, this novel Sky-RM design can be further extended to enable information interaction among multiple nanotracks.

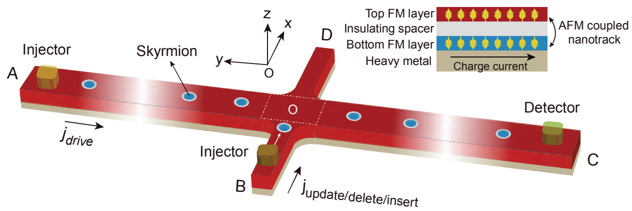


Fig. 4. Schematic of the proposed Sky-RM structure with random information update/deletion/insertion, which consists of four main parts: two injectors for skyrmion creation, a detector for skyrmion detection, a cross-shaped nanotrack (with four terminals denoted as A, B, C, and D, respectively), and peripheral control circuits (which are not shown in the figure) [38].

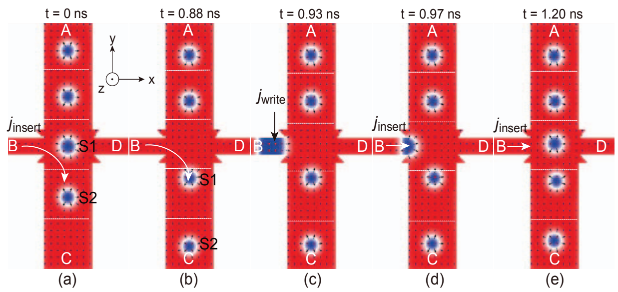


Fig. 5. Top views of the nanotrack (snapshots at different times) of the process of the information insertion operation for a data bit "1." (a) and (b) Skyrmions and nonskyrmions (data bits) between O and C move toward C a step, leaving an empty bit at the intersection bit zone under the current $j_{insert}$. (c) A DW pair is created at terminal B after applying current $j_{write}$. (d) and (e) Skyrmion is driven into the intersection bit zone to realize the insertion operation under the current $j_{insert}$ [38].

In comparison with the update operation, deleting/inserting a data bit from/into a data word is more complicated as the word length will be changed. A case study of the insertion operation is illustrated in Fig. 5 and the procedure is elaborated as the following steps.

1) First locate the bit zone position that needs to insert a data bit to the intersection bit zone of the cross-shaped nanotrack via applying a $j_{driven}$ between A and C (while B and D are floating).

2) Then $j_{driven}$ is switched OFF, terminal B and C become ON (while A and D are floating), a $j_{insert}$ pulse is applied between B and C to drive the data bits between O and C to move toward C a step, leaving an empty bit (i.e., bit "0") at the intersection bit zone of the cross- shaped nanotrack, as shown in Fig. 5(a) and (b).

3) Afterward, $j_{insert}$ is switched OFF, and either a skyrmion (bit "1," with a $j_{write}$) or a nonskyrmion (bit "0," with no $j_{write}$) is created at terminal B depending on the desired inserting data bit value, as shown in Fig. 5(c). Here, the skyrmion creation is through DW conversion after applying a $j_{insert}$.

4) A $j_{insert}$ is applied between terminal B and D (while A and C are floating) to drive the skyrmion or nonskyrmion into the intersection bit zone to insert the desired data bit, as shown in Fig. 5(d) and (e).

5) Finally, $j_{insert}$ is switched OFF (B and D are floating), and the normal data access operation continues.

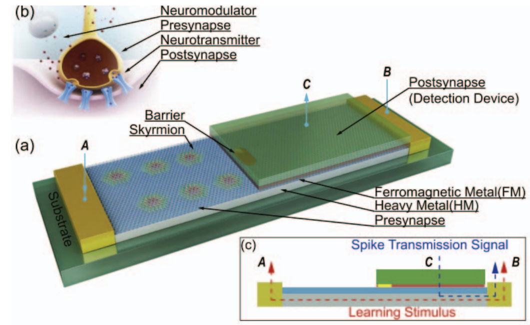


Fig. 6. (a) Schematic of the proposed skyrmionic synaptic device. To mimic a neuromodulator, as shown in (b), a bidirectional learning stimulus flowing through the HM from terminal A to terminal B (or vice versa) drives skyrmions into (or out of) the postsynapse region to increase (or decrease) the synaptic weight, as shown in (c), mimicking the potentiation/depression process of a biological synapse [42].

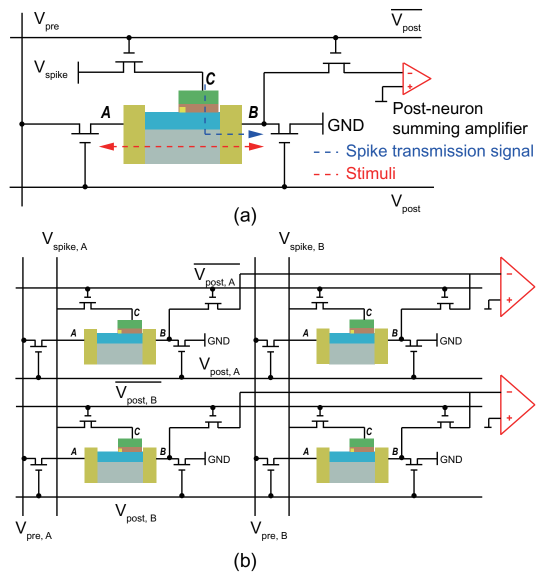


Fig. 7. (a) Illustration of the learning and spike-transmission operations of the proposed skyrmionic synaptic device. (b) Corresponding synapse array [42].

## *B. Skyrmion-based Neuromorphic Computing*

Neuromorphic computing, inspired by the biological nervous system [39, 40], has attracted considerable attention for its amazing capability in recognition and classification at a fraction of power. Intensive research has been conducted in this field for developing artificial synapses and neurons, attempting to mimic the behaviors of biological synapses and neurons, which are two basic elements of a human brain. Recently, magnetic skyrmions have been investigated as promising candidates in neuromorphic computing design, which is an active research field with great potential apart from the traditional Boolean logic [41]. Here we set our sights on two carefully-designed neuromorphic devices, the skyrmion-based synaptic device [42] and the skyrmion-based artificial neuron device [43], respectively. Fig. 6(a) shows the schematic of the proposed skyrmionic synaptic device. The primary components of the device are a FM layer (e.g., Co) on a HM (e.g., Pt) layer and an energy barrier. The FM layer and the HM together form a nanotrack for skyrmion motion. This nanotrack is divided into

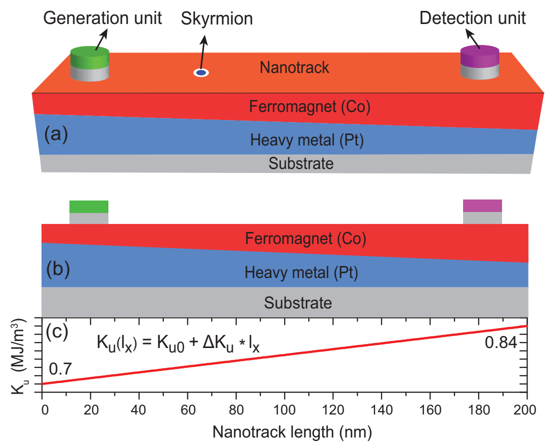


Fig. 8. (a) Schematic of the proposed skyrmion-based artificial neuron device; (b) The front cross-section view; (c) The linear increase of the PMA value along the nanotrack [43].

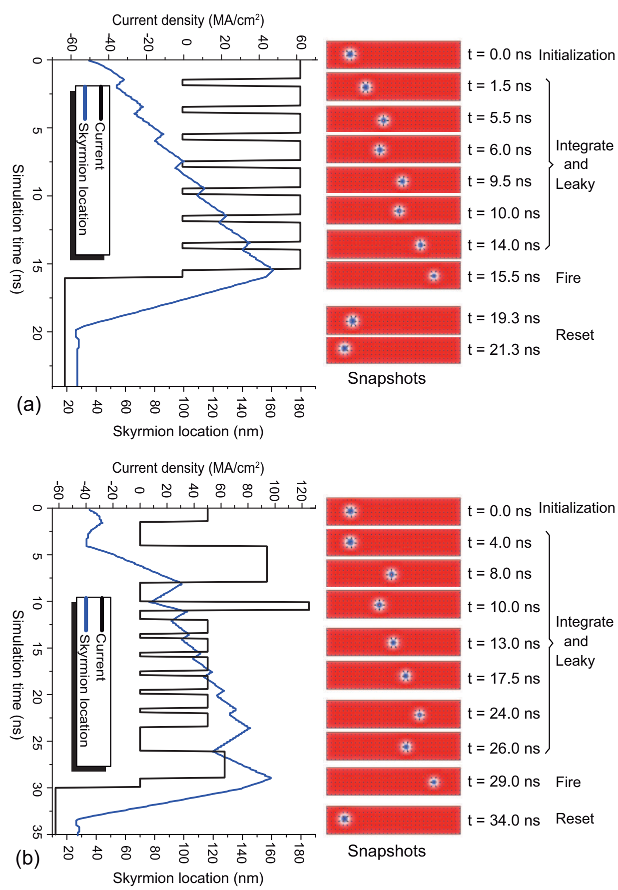


Fig. 9. Micromagnetic simulations of the proposed skyrmion-based artificial neuron under different strategies. A skyrmion is driven by (a) a homogeneous and (b) an inhomogeneous input spike current respectively on a nanotrack with linearly increasing PMA, exhibiting "leaky-integrate" behaviors [43].

two parts, referred to as presynapse and postsynapse regions, by an artificial energy barrier, which can be achieved by changing the local capping layer to another material with a higher perpendicular magnetic anisotropy (PMA) than that of the FM layer or alternative mechanisms. Fig. 7(a) shows the proposed skyrmionic synaptic device with peripheral circuits to demonstrate the learning and spike transmission functions and Fig. 7(b) depicts a corresponding synapse array. Herein, Vspike denotes the spike voltage of the pre-neuron, Vpre and Vpost are the programming voltages from the pre- and post-neurons controlling the learning stimuli.

Our proposed skyrmion-based neuron device is illustrated in Fig. 8 in 3D and section-view respectively. The nanotrack is composed of a FM layer and a HM layer. The highlight lies in the particular design of the FM layer, which is optimized, e.g., by tuning the thickness of the FM layer, in order to generate a linear PMA (i.e., $k_u(l_x) = k_{u0} + \Delta k_u * l_x$) along the nanotrack. Initially, a skyrmion is generated at the origin (i.e., under the generation unit) of the nanotrack. Then, if one or several pre-neurons spike, the accumulated input spike currents ($I_{spk-in}$, modulated by the connected synapses) stimulate the skyrmion motion along the nanotrack if the current density exceeds the skyrmion depinning current density. During the skyrmion motion process, the energy barrier of the nanotrack gradually grows because of the linear increase of the PMA energy. Thus, the skyrmion motion dynamics depend on the competition between the gradient PMA energy of the nanotrack and the driving force of the accumulated input spike current, which depends then on the amplitude and frequency of the spike currents from pre-neurons. Fig. 9 illustrates the micromagnetic simulations of the skyrmion-based artificial neuron under a homogeneous (Fig. 9(a)) and inhomogeneous (Fig. 9(b)) spike current, which exhibits 'leaky-integrate-fire' neuronal behaviors. With simple single-device implementations, our proposed artificial skyrmionic devices may enable us to build a dense and energy-efficient spiking neuromorphic computing system.

## V. CHALLENGES

The manipulation of skyrmion by electrical current will take a dominant role in skyrmionic applications from a technological perspective. For energy-efficient operations, large spin-Hall angles and Rashba coefficients are strongly desired. However, the two current-related parameters, i.e., DMI and Ku are normally difficult to be independently adjusted, because of the coexistence of spin-Hall torque, Rashba torque, and Zhang-Li torque in a multilayer system when being injected by an electric current, thus resulting in magnetization dynamics being material-specific [44, 45]. Therefore, it is crucial to figure out the specific role of each torque in order to control the skyrmion motion with multiple spin torques acting cooperatively.

In addition, thermal stability of magnetic skyrmions at RT is a big challenge for electronic applications while various approaches have been proposed to address this problem. Atomic-scale simulations suggest that the lifetimes of isolated skyrmions can be improved by increasing the DMI [46]. In addition, asymmetric multilayer structures have been adopted to provide additive interfacial DMI to improve the thermal stability of individual skyrmions as well [47]. It has been experimentally demonstrated that stable sub-100 nm individual skyrmions can be obtained at RT in such multilayer structures, however a better control of the size of skyrmions, as a pending question, is necessary to be addressed for applications [48].

## VI. Conclusion

This article has reviewed the current status and outlook of skyrmions in relation to future memory and logic applications. After giving a brief introduction of the fundamentals and some elementary functionalities of magnetic skyrmions, we present our two recent works as case studies of potential applications of skyrmions in terms of racetrack memory and neuromorphic computing. Nevertheless, many challenges still remain to tackle and there is a long way before the practical applications of skyrmions. we want to evoke the effort from the DAT society to be involved in this emerging direction for the research and development of practical skyrmion-based electronics.

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