Magnetic skyrmion-based synaptic devices

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Abstract
Magnetic skyrmions are promising candidates for next-generation information carriers, owing to their small size, topological stability, and ultralow depinning current density. A wide variety of skyrmionic device concepts and prototypes have recently been proposed, highlighting their potential applications. Furthermore, the intrinsic properties of skyrmions enable new functionalities that may be inaccessible to conventional electronic devices. Here, we report on a skyrmion-based artificial synapse device for neuromorphic systems. The synaptic weight of the proposed device can be strengthened/weakened by positive/negative stimuli, mimicking the potentiation/depression process of a biological synapse. Both short-term plasticity and long-term potentiation functionalities have been demonstrated with micromagnetic simulations. This proposal suggests new possibilities for synaptic devices in neuromorphic systems with adaptive learning function.

Supplementary material for this article is available online

Keywords: skyrmion, neuromorphic, synaptic plasticity, short-term plasticity, long-term potentiation

(Some figures may appear in colour only in the online journal)

Introduction

Neuromorphic computing, inspired by the biological nervous system, has attracted considerable attention recently [1–5]. Owing to its massively paralleled nature, power efficiency, robustness against fault/variation, and combination of memory and computation, it is highly efficient in cognition- and perception-related tasks [1]. The computing architecture of human brain consists of billions of neurons which are highly connected by junctions termed as synapses. Neurons generate stimuli (spikes) when they are activated by integrating stimuli from other connected neurons. The spikes are modulated during propagating through the synapses, also called as synaptic transmission. It is believed that this spiking generation and transition are responsible for information flowing and processing behind the human learning and cognition [6]. The synapses function by changing their connection strength as a result of the neural activities, known as synaptic plasticity. In recent decades, a variety of nanoelectronic devices have been proposed to emulate synapses, including phase-change memories [7, 8], Ag–Si memories [9], and resistive memories [10–12], etc. Recently, some emerging devices with features analogous to biological synapses have been discovered, offering new opportunities for artificial synapse design [13].

Magnetic skyrmions are nanoscale topologically stable particle-like spin textures, which are typically stabilized by Dzyaloshinskii–Moriya interaction (DMI) in either non-centrosymmetric bulk ferromagnets or magnetic thin films [14–16]. Although first experimentally observed in bulk
ferromagnets, recent studies have revealed that skyrmions can be more stable in magnetic multilayers [17]. Since the first experimental observation of skyrmions in 2009 [18], they have attracted extensive research interest, from the perspectives of physical fundamentals to electronic applications. Owing to their small size, robustness against process defects, and low depinning current density [19, 20], skyrmions have considerable potential for use as information carriers in future ultra-dense, high-speed and low-power spintronic devices, such as racetrack memories [21, 22] and logic gates [23, 24]. Recently, stable skyrmions have been experimentally observed and manipulated at room temperature [17, 25–29], further highlighting their potential. Furthermore, the intrinsic properties of skyrmions enable to design new devices with unique functionalities that may be inaccessible to conventional electronic devices.

One of the intrinsic features of skyrmions is their particle-like behavior, due to which, multiple skyrmions can aggregate, exhibiting potential for multi-valued storage devices with skyrmions as information carriers. The states of such a device can be modulated by an electric current that drives skyrmions into or out of the device. Such characteristics are analogous to those of a biological synapse, in which the weight can be dynamically adapted to a changing environment, i.e., the synaptic plasticity. In a biological synapse, synaptic plasticity is achieved based on signal propagation by the release of neurotransmitters [30]. For artificial synapses, the capability responsible for short-term plasticity (STP), long-term potentiation (LTP), and temporal dynamics is the foundation of learning in neuromorphic applications.

In this letter, we propose a novel skyrmion-based artificial synapse device for neuromorphic systems. The synaptic weight of the proposed device can be modulated by an electric current and be measured through the magnetoresistance effect. The polymorphism, synaptic plasticity (both STP and LTP) of the proposed device were investigated through micromagnetic simulations.

Methods

The proposed skyrmion-based artificial synaptic device was numerically simulated by solving the Landau–Lifshitz–Gilbert equation with spin transfer torque as follows [14]:

$$\frac{dm}{dt} = -\gamma |m| \times h_{\text{eff}} + \alpha m \times \frac{dm}{dt} + u \times \frac{m}{t} \times (m_p \times m),$$

where $m = M/M_s$ is the reduced magnetization, $M_s = 580 \text{ kA/m}$ is the saturation magnetization, $\gamma = -2.211 \times 10^3 \text{ mA}^{-1}\text{s}^{-1}$ is the gyromagnetic ratio, $h_{\text{eff}} = H_{\text{eff}}/M_s$ is the reduced effective field, $\alpha = 0.3$ is the Gilbert damping, $t$ is the thickness of the ferromagnetic (FM) layer, $u = \gamma (h j P/2eM_s)$, $j$ is the density of the spin current, and $P = 0.4$ is the spin polarization. The direction of the spin polarization is along $+y$. The parameters are chosen from a 0.4 nm thick Co layer on an Pt substrate, adopted from [14].

The TMR calculation is done by a differential method, considering that the whole magnetic tunnel junction (MTJ) device consists of many 2 nm $\times$ 2 nm uniform cells in the x-y plane [31]. The conductance of each cell is obtained by the extended Julliere’s model [32, 33] which can be shown as:

$$G = G_0 \left( \frac{1 + p^2 \cos \theta}{1 + p^2} \right),$$

where $G_0$ is the conductance when the magnetization is perfectly parallel to the reference layer, $p$ is the spin polarization which is set to be 0.4 in our simulation, and $\theta$ is the magnetization of each cell with respect to the reference layer.

The nanotrack was designed with a default size of 528 nm $\times$ 120 nm $\times$ 1 nm an exchange stiffness of $A = 15 \text{ pJ/m}$, a perpendicular magnetic anisotropy constant of $K_u = 0.7 \text{ MJ/m}^3$, and a DMI constant of $D = 3 \text{ mJ/m}^3$. The barrier was a rounded rectangle with dimensions of 40 nm $\times$ 56 nm and a higher PMA constant of $K_u = 0.84 \text{ MJ/m}^3$. A discretization of 2 nm $\times$ 2 nm $\times$ 1 nm was used in our simulation. Impacts of the DMI constant and the barrier PMA are discussed in the supplementary.

Results and discussion

Skyrmionic synapse structure

Figure 1(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 heavy metal (HM, e.g., Pt) and an energy barrier. The FM layer has PMA, and the DMI is generated at the interface between the FM layer and the HM. The FM layer and the HM together form a nanotrack for skyrmion motion. This nanotrack is divided into two parts, referred to as presynapse and postsynapse regions, by an artificial energy barrier with a higher PMA than that of the FM layer. This energy barrier is located at the center of the nanotrack and is counted for the postsynapse region. It can be achieved by changing the local capping layer with another

![Figure 1](image-url)
material which can generate a higher PMA [34]. Alternative mechanisms like voltage controlled magnetic anisotropy [24] can also be used to build a region with different PMA. Here we consider a higher PMA of the barrier in our simulations. In the case of a lower PMA barrier, the device can still work with a skyrmion pinned in the barrier. Besides, the behavior of skyrmions are very similar for both a sharp or smooth transition barrier. Details are shown in the supplementary information. This device structure is analogous to a biological synapse, as shown in figure 1(b). To illustrate the synaptic plasticity of the device, a side view of the device is shown in figure 1(c). In the spike transmission mode, the spike produced by a pre-neuron is modulated by the weight (magnetoresistance) of the synaptic device, which generates a post-synaptic spike current from terminal C to terminal B. During the learning phase, a bidirectional charge current flows through the HM, injecting a vertical spin current into the FM layer from terminal A to terminal B (or vice versa) and driving skyrmions into (or out of) the postsynapse region to increase (or decrease) the synaptic weight, mimicking the potentiation/depression process of a biological synapse. The proposed device provides decoupled spike-transmission and learning channels (see figure 1(c)). The channel between terminal A and terminal B, which is called a learning channel, is used to transmit learning stimuli from the pre-neurons. The channel between terminal C and terminal B, which is called the spike transmission channel, is used to transmit a spike current to the post-neurons. A detection device (e.g., a MTJ) is located on top of the postsynapse region to read the weight (magnetoresistance) of the synapse through the magnetoresistance effect [31].

Figure 2 illustrates the micromagnetic simulation results of the three primary operation modes of our proposed synaptic device: the initialization mode, the potentiation mode, and the depression mode. Before we illustrate the operation modes of the proposed synaptic device, we define two terms: (a) positive stimulus, which signifies an electric current with an amplitude of 5 MA cm$^{-2}$ flowing from terminal A to terminal B; and (b) negative stimulus, which signifies an electrical current with amplitude of 5 MA cm$^{-2}$ flowing from terminal B to terminal A. In the initialization mode (from 0 to 35 ns), skyrmions are generated in the presynapse region of the device. Owing to the repulsion between skyrmions and the nanotrack edges [35], a threshold value for the total number of skyrmions (11 skyrmions in our design, with a 120 nm wide nanotrack) in the presynapse region of the device will be reached. This threshold value determines the programming resolution of the synaptic weight of the device. In the potentiation mode (from 35 to 65 ns; see figure 2(b)), a positive stimulus drives skyrmions from the presynapse region into the postsynapse region, increasing the synaptic weight of the device. Similarly, in the depression mode (from 87 to 117 ns; see figure 2(c)), a negative stimulus drives skyrmions from the postsynapse region into the presynapse region, decreasing the synaptic weight of the device. The red curve in figure 2(d) shows the normalized mz (i.e., the average magnetization component in the $z$ direction) of the postsynapse region of the device. The shifting of mz corresponds to the variation in the skyrmion number and size. It should be noted that two skyrmions fail to pass through the barrier in both the potentiation and depression modes. This
Skyrmionic synaptic plasticity

Figure 3(a) shows the dependence of the saturation number of skyrmions during the initialization mode with respect to the size of the presynapse region of the device. Herein the length of the presynapse region was fixed (200 nm in this case). Because the area of the postsynapse region increases linearly with respect to the nanotrack width, a linear model can be used to characterize the relationship between the nanotrack width and the number of saturation skyrmions. Intuitively, a wider nanotrack can accommodate more skyrmions, indicating a larger capability of synaptic weight resolution. However, there are trade-offs among the synaptic weight resolution, processing speed, area, and energy consumption. The reason for this is that a wider nanotrack (with more skyrmions) requires a longer time to achieve a saturation state during the initialization mode and to change the same percentage of synaptic weight during the learning operation. In addition, a wider nanotrack requires a larger current amplitude to achieve the same current density, consuming more energy. Figure 3(b) shows the relationship between the programming speed (i.e., the number of skyrmions in the postsynapse region of the device) and the driving current density. Obviously, a larger current density results in a fast skyrmion motion and thus a higher programming speed. However, a maximum current density of 6 MA cm\(^{-2}\) exists in this device. If the driving current density extends beyond or equal to this threshold, the skyrmion will crash the edge of the device and be annihilated.

We also investigated the dynamics of the synaptic plasticity of the proposed device with respect to the stimulus characteristics. In specific, we considered three stimulus configurations: case 1, 1.5 ns in duration at 5 ns intervals, as shown in figure 4(b); case 2, 1 ns in duration at 2 ns intervals, as shown in figure 4(c); and case 3, 1 ns in duration at 5 ns intervals, as shown in figure 4(d). Each configuration consists of eight stimulus pulses. We monitored the magnetococonductance change of the postsynapse region of the device, expressed by the ratio to the magnetococonductance without skyrmions (\(G_0\)). As shown in these figures, cases 1 and 2 demonstrate an LTP property, while case 3 demonstrates an STP property [5, 39]. Compared with cases 1 and 3, with the same interval, a proper stimulus duration is required to transfer STP to LTP. Cases 2 and 3 demonstrate that the interval of the stimulus also plays an essential role in the synaptic plasticity of the proposed skyrmionic device.
device’s plasticity. To eliminate the effect of conductance variation due to skyrmion size oscillation, the Nsk is also calculated, as shown in figure 4(e), which corresponds to the above analyses.

The STP and LTP of the proposed synaptic device can be explained by the competition between the driving force provided by the electric current and the repulsion force provided by the barrier when the skyrmion passes through the barrier. When the skyrmion approaches the barrier, the repulsion force of the barrier increases, as shown in the energy profile of figure 4(a). Upon receipt of an input stimulus, the driving force of the electric current proceeds the skyrmion uphill along the force energy profile (from point 1 to point 2). However, the skyrmion falls back to point 1, if the input stimulus is not of sufficient duration and frequency, corresponding to STP. Otherwise, if the stimulus is of sufficient duration and/or frequency, the skyrmion will not have enough time to reach point 1 and ultimately will be able to pass the barrier until to point 3, corresponding to LTP. Once the skyrmion passes through the barrier, it is difficult to move back to the initial position. This behavior is consistent with the psychological model of a biological synapse.

**Circuit implementation**

Figure 5(a) shows the proposed skyrmionic synaptic device with peripheral circuits to demonstrate the learning and spike-transmission functions and figure 5(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. When a pre-neuron spikes, the spike voltage Vspike is transmitted through the synapse and is modulated by the synaptic weight of the device, thereby generating a resultant post-synaptic spike current (in blue). As long as the post-neuron does not spike, the spike-transmission current path remains activated. All the weighted spike currents from the pre-neurons will be transmitted to the post-neuron summing amplifier. Simultaneously, as soon as the pre-neuron...
spikes, a learning process is also conducted under the control of Vpre and Vpost. When a pre-neuron spikes, it also generates a programming voltage Vpre. As soon as the post-neuron spikes, Vpost, which is a short pulse, gets activated. Then the learning stimulus path turns on to drive skyrmions into or out from the postsynapse region of the device, modulating the synaptic weight. With the current density of 5 MA cm$^{-2}$, the total current needed to drive one unit in this circuit is around 36 uA (120 nm × 6 nm × 5 × 10$^{10}$ A m$^{-2}$, the thickness of the heavy metal is supposed to be 5 nm). Assume that the driving current of our device flows from a supply voltage of 1 V with a duration of 30 ns, which is long enough to set the device into any synaptic state, the energy consumption is around 1 pJ. This energy dissipation is smaller than most of the artificial synapses [40], indicating the potential of the proposed synapse device in practical applications.

Conclusion

In conclusion, we have proposed a skyrmionic device with synaptic plasticity for both short-term and long-term memory functions in neuromorphic applications. The spike-transmission and learning operations of the proposed device were demonstrated with micromagnetic simulations. The STP and LTP functions of the device were illustrated and discussed. The resolution of the synaptic weight can be adjusted based on the nanotrack width and the skyrmion size. The proposed device suggests new possibilities for the use of skyrmionic devices in neuromorphic applications.

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Author Contributions

WK and WZ developed the idea of using skyrmion as a synaptic information carrier. YH performed the micromagnetic simulation. YH and WK contributed equally to this work and should be considered as co-first authors. All the authors analyzed and discussed the data and co-wrote the manuscript.

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