Device geometry dependent deterministic skyrmion generation from a skyrmionium

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Abstract
A magnetic skyrmionium can be perceived as an association of two magnetic skyrmions with opposite topological charges. In this work, we have investigated the transformation of skyrmionium into multi-skyrmionic states via domain wall pairs in three different devices with variable geometric configurations. The same device geometries are considered for single ferromagnetic layer and synthetic antiferromagnetic system. It is observed that by tuning the current density, deterministic generation of skyrmions is possible via the spin transfer torque. The proposed device is efficiently adjustable to change the number of skyrmions also at room temperature. The results may lead to development of skyrmion-based devices for neuromorphic and unconventional computing.

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

Magnetic skyrmions are topologically protected, localized non-collinear textures which have antiparallel magnetization core with respect to the periphery [1]. Nanoscale size, gyrodynamics, and low driving current density make skyrmions promising for future spintronic applications such as information carriers [2], microwave devices [3, 4], spin-wave/magnon devices [5, 6], quantum computing [7, 8], logic devices [9, 10], digital information, data processing, and storage [11–15] etc. Skyrmions have been stabilized in a wide variety of magnetic structures like heavy metal (HM1)/ferromagnet (FM)/HM2 (or oxide) [16–20]. There are several underneath mechanisms to stabilize the skyrmions [21–27]. Among these, a fine tuning of interfacial Dzyaloshinskii–Moriya interaction (DMI) and effective anisotropy energy can lead to stabilization of skyrmions in thin films [28–31]. Till now, several ways have been proposed for skyrmion motion via spin-polarized current [32–34], magnetic field [35, 36], anisotropic gradient [37] and so on [20, 38].

However, the controlled motion of skyrmions is a big challenge for practical application due to the skyrmion Hall effect (SkHE) [39–41]. To overcome this significant obstacle caused by the magnus force, acting on the moving skyrmion, few strategies have been proposed [42, 43]. A promising way to minimize SkHE is by constructing an antiferromagnetically exchange-coupled bi-layer system which is commonly known as synthetic antiferromagnet (SAF), in which a skyrmion in the top layer accounting for \( Q = -1 \) and a skyrmion in the bottom layer accounting for \( Q = +1 \) form a common entity with \( Q = 0 \) [44, 45]. Further, skyrmionium, a composite doughnut-like structure with a core skyrmion with upward magnetization and peripheral skyrmion with downward magnetization, with a net topological charge, \( Q = 0 \), has been proven advantageous [46–48].

Recently, various types of devices have been proposed in which geometries play a pivotal role in control and manipulation of skyrmions to achieve desired applicability [9, 49, 50]. A comprehensive study of magnetic skyrmion dynamics in terms of size, velocity, energy, and stability in width-varying nanotracks by micromagnetic simulations has been reported [51]. Further, the controlled nucleations of skyrmions in nanodot and in MTJ array have been experimentally shown which highlights the potential of skyrmions...
neuromorphic computing [52, 53]. It has also been experimentally demonstrated that the transformation of stripe domain to magnetic skyrmion bubbles can be achieved using geometric constriction [19]. It has been shown that the skyrmions can be created from stripe domains using a static uniaxial strain/stress pulse at a geometrically constricted region [54]. The impact of skyrmion–skyrmion and skyrmion-edge repulsion on skyrmion-based racetrack memory has been investigated [55]. Further, a pair of skyrmions can be generated from skyrmionium using spin transfer torque (STT) in a single channel device [56]. However, the deterministic generation of multi skyrmionic states has not been studied extensively. In this work, we perform a systematic study demonstrating the conversion of a skyrmionium into various skyrmionic states on three different geometric designs. Also we have investigated the effect of current density to get different states of skyrmion in a single FM layer as well as in a SAF. The effect of temperature plays a crucial role in manipulating the nucleation and motion of these topological textures [57, 58]. In this context, we have also performed the simulations at room temperature (at 300 K) which shows a good agreement with the results of simulations at 0 K. The obtained results are interesting for interdisciplinary research on skyrmion-based neuromorphic and unconventional computing.

We have performed the micromagnetic simulation using Object Oriented MicroMagnetic Framework (OOMMF) [2] with the DMI extension [47]. The schematic of the representative devices are shown in figure 1. The concept of the device, showing source (S) as input terminal, channel (C) and detector (D) as output terminal, is illustrated in (a). Figures 1(b) and (c) show the devices with a single ferromagnetic and a SAF structure, respectively, with specified source (input) and detector (output) terminals. The detector is to sense the skyrmionic states and J represents the current density. For the simulations, we have considered 800 nm long and 300 nm wide sample with a thickness of 0.6 nm. The width of the narrow channel is 16 nm with notches at the terminals. We considered a cell size of 2 nm \( \times \) 2 nm \( \times \) 0.6 nm. We have considered three types of nanostructured designs in our simulations; with 1–1 channel (figure 2(a)), 1–2 channel (figure 2(b)) and 1–3 channel (figure 2(c)), named as Dvc-1, Dvc-2 and Dvc-3, respectively. In the simulations the current was applied in the in-plane (CIP) geometry. The modified Landau–Lifshitz–Gilbert (LLG) equation with STT term for the time-dependent spin dynamics for CIP geometry, is given by [44, 59]:

\[
\frac{dM}{dt} = -\gamma_0 M \times H_{\text{eff}} + \frac{\alpha}{M_s} \left( M \times \frac{dM}{dt} \right) + \frac{u}{M_s} \left( M \times \frac{dM}{dt} \right) \times \left( M \times \frac{dM}{dt} \right),
\]

where \( M \) is the magnetization, \( M_s \) is the spontaneous magnetization, \( t \) is the time, \( \alpha \) is the gitter damping constant and \( \beta \) is the strength of the non-adiabatic coefficient. However, for simulations at 300 K, the OOMMF extension for simultaneous simulation of spin-transfer torque and thermal fluctuation effects has been used [59]. The effective field is given by

\[ H_{\text{eff}} = -\frac{1}{M_s} \frac{\partial E}{\partial M} \] and the STT coefficient is given by

\[ u = \left| \frac{\partial H}{\partial M} \right| \frac{P}{2M_s} \]

The unit polarization direction is denoted by \( \hat{p} \), which is \( +\hat{z} \) for nucleating skyrmionium and \( +\hat{y} \) to drive the chiral structures in a forward direction. \( \gamma_0 \) is the gyro-magnetic ratio, \( \hbar \) is reduced Planck’s constant, \( e \) is the electronic charge, and \( \mu_0 \) is the vacuum permeability constant. The first and second terms in equation (1) describe precession and damping, respectively. The third and fourth terms account for the adiabatic and non-adiabatic contribution of the spin-transfer torque (STT). The values of exchange stiffness (\( A \)), Gilbert damping (\( \alpha \)), spin polarization (\( P \)), spontaneous magnetization (\( M_s \)), DMI factor (\( D \)), gyro-magnetic ratio (\( \gamma \)) and perpendicular magneto-crystalline anisotropy (\( K \)) are 15 pJ m\(^{-1}\), 0.3, 0.4, 580 kA m\(^{-1}\), 3.6 mJ m\(^{-1}\), 2.21276 \( \times \) 10\(^5\) mA\(^{-1}\) s\(^{-1}\) and 0.8 MJ m\(^{-3}\), respectively. Magnetic configurations have been relaxed solving the LLG equation up to a stopping criterion \( |\frac{dM}{dt}| \leq 0.01 \) degree ns\(^{-1}\).

In our system, we have taken \( \alpha = \beta \) for the single FM layer to avoid SkHE. From an experimental point of view, an excellent way to avoid the SkHE is by using a SAF layout. We have also reproduced our results in SAF layout by considering RKKY exchange coupling for our system with an inter-layer antiferromagnetic exchange coupling value of \( -2 \times 10^{-3} \) Jm\(^{-2}\). However, the coupling strength can be modulated depending upon the thickness of the spacer layer. For the SAF system, we have considered the strength of the non-adiabatic coefficient \( \beta \) of STT torque as 0.6, such that \( \beta = 2\alpha \), to achieve a higher velocity at same current density [60].

Figure 1. (a) Layout of the device concept showing source (S) as input terminal, channel (C) and detector (D) as output terminal. (b) and (c) show the device schematics for a single FM layer and SAF, respectively.
Figure 2. Snapshots of critical moments during the conversion process from skyrmionium to skyrmion in (a) 1–1 channel design: Dvc-1 (b) 1–2 channel design: Dvc-2 (c) 1–3 channel design: Dvc-3 for single FM layer at $J = 10.5 \times 10^{12}$ A m$^{-2}$.

A current density of $2.5 \times 10^6$ A m$^{-2}$ is applied at the $S$ terminal of the device in an annular fashion such that the spin polarization is anti-parallel to the initial magnetic configuration. The skyrmionium, with core radius 44 nm and peripheral radius 114 nm, is nucleated after the spin textures are relaxed at the input terminal of the device, as shown in figure 2 ($t = 0$ ns). The skyrmionium is driven through the narrow channel using STT along the current direction. As the skyrmionium reaches the narrow channel, it is peripheral spins collide at the edges (notches) and experience repulsion. Due to the applied current, the skyrmionium gets injected into the narrow channel while being converted into a domain wall. The spin textures of skyrmionium start to deform as it translates through the channel(s). The regions with $m_z > 0$ (red) and $m_z < 0$ (blue) is separated by the boundary with $m_z = 0$ (white). Two separate magnetic domains can be seen at 0.35 ns in the narrow channel(s). At 0.48 ns, the former DW pair is pushed forward and another DW pair is injected into the channel. The scope of the DW depend on the specific channel designs as they further develop according to the structure of the devices. In Dvc-1, the DW pair simply translate to the output terminal. Whereas, in case of Dvc-2 and Dvc-3, the DW pair get split at the junctions into two and three parts, respectively, which can be seen in figures 2(b), and (c) at 0.56 ns.

The conversion mechanism between a DW pair and a skyrmion has been already investigated in literature [61]. In a DW pair, we can see two open parallel boundaries touching the edges of the narrow channel, where the spin directions are oriented in a way to give a topological charge $Q = 0$ [61]. As the DW pair arrive at the end of the narrow channel they are squeezed to smaller sizes and tend to pass through the constricted terminal by the virtue of STT and repulsion [62, 63] from the later batch of DW pair. When the open boundary of first DW reaches the end of the channel, it tends to move outward if the driving force (STT) is strong enough to overcome the pinning at the notch. The STT compels the second boundary to expel out to form a closed loop (as in figure S2 ($t = 1.13$ ns channel (ii)), supplementary). The spin orientation of this loop is hedgehog and the topological charge $Q = 1$, resulting in skyrmion. The topologically protected skyrmions float in the output terminal of the device without interruption. Alternatively, the second DW pair may get pinned at the end of the narrow channel if the driving current is not enough to expel it out (as in figure S2 ($t = 3$ ns), supplementary). The critical current density for which the skyrmion ejection occurs at the end of the channel for Dvc-1, 2 and 3 are found to be $6.58 \times 10^{12}$ A m$^{-2}$, $6.85 \times 10^{12}$ A m$^{-2}$ and $7.51 \times 10^{12}$ A m$^{-2}$, respectively, in single FM. However, the current density in case of SAF is $3.75 \times 10^{12}$ A m$^{-2}$ for all three devices.

The number of skyrmions released depend on $J$. Figure 3(a) shows the number of skyrmions as a function of current density for the HM/FM bi-layer and SAF which explains that a specific skyrmionic state is achieved corresponding to a threshold value of the current density. For FM single layer, all possible number of skyrmions have been observed for all three devices. For Dvc-1, it is observed that by tuning the $J$, 1 or 2 skyrmions are generated. Similarly, in Dvc-2 and Dvc-3, the number of skyrmions at the detector terminal are 1–4 and 1–6, respectively. In the case of SAF, due to the RKKY torque [64], the domains in the narrow channel(s) do not get pinned at the terminal. Because of this, we observed that the ejected number of skyrmions are equal
to the number of channels or twice of it. For Dvc-1_SAF, Dvc-2_SAF and Dvc-3_SAF, the number of skyrmionic states are 1 or 2, 2 or 4 and 3 or 6, respectively. It should be noted that the velocity of spin textures (skyrmionium in the source terminal, DW in narrow channel, and skyrmions in the detector terminal) in SAF is almost twice that of the corresponding single FM layer devices for a fixed value of J. In our simulation, the skyrmionium to skyrmions transformation process is irreversible. The detail discussion about this irreversible process has been described in supplementary information.

To study the time delay between generation of each skyrmionic state, we have plotted the number of skyrmions as a function of time at 10.5 × 1012 A m⁻² and 12.4 × 1012 A m⁻² of current density. The orange and purple dotted lines pass over the initial and final states of skyrmions released at 10.5 × 1012 A m⁻² and 12.4 × 1012 A m⁻², respectively.

The topological number, as function of time achieved per device in the single FM layer. The trend is observed to be similar in case of SAF.

Further, we have performed the simulations at room temperature. As it has been observed earlier, most of the HM/FM system shows DMI value around 1–2 J m⁻², so lower DMI with room temperature simulations are quite appealing for practical application. Keeping this in view, we have performed the simulations at 300 K using D and J_{RKKY} values as 1.9 mJ m⁻² and −8 × 10⁻³ J m⁻², respectively, on SAF system. At 300 K, the size of the skyrmions decreases and ultimately annihilate in the strong RKKY coupling regime. Hence, we have considered lower J_{RKKY} coupling value for temperature dependent simulations. Figure 5 shows the snapshots of critical moments during the conversion process from skyrmionium to skyrmion at 300 K in 1–3 channel design (Dvc-3) for SAF at $J = 3.2 \times 10^{11}$ A m⁻².
geometry to achieve multi-skyrmionic states. It is observed that by tuning the current density, the deterministic generation of skyrmions is possible. The temperature dependent simulations also show a good consistency with simulations performed at 0 K. Hence, the device is more efficiently adjustable compared to other previously proposed magnetic devices, as it is easier to change the number of skyrmions. This type of designs can pave way for advancement of skyrmion-based memristors, spiking neural network (SNN), and other neuromorphic devices [65]. Geometry-dependent generation of skyrmions enable new functionalities that may be inaccessible to conventional technologies, thus, paving way towards unconventional computing hardware resolution.

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Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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