Manipulation of magnetic skyrmions in a locally modified synthetic antiferromagnetic racetrack

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In skyrmion-based racetrack-type memory devices, the information encoded by magnetic skyrmions may be destroyed due to the skyrmion Hall effect, which can be surmounted by using synthetic antiferromagnetic racetracks. Hence, the manipulation of skyrmions in the synthetic antiferromagnetic racetrack is important for practical applications. Here, we computationally study the interaction between a pair of skyrmions and a locally modified region in a synthetic antiferromagnetic racetrack, where the perpendicular magnetic anisotropy or thickness is locally adjusted to be different from that of the rest region of the racetrack. It is found that the skyrmions can be attracted, repelled, and even trapped by the locally modified region in a controllable manner. Besides, we demonstrate that the skyrmion location can be precisely determined by the locally modified region. The possible manipulation of skyrmions by utilizing locally modified regions in a synthetic antiferromagnetic racetrack may be useful for future skyrmion-based applications, such as the skyrmionic bit length definition.

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Racetrack memories have been extensively investigated due to their ultra-high information processing speed and low power consumptions, in comparison with memory technologies based on magnetization switching induced by Oersted fields and Joule effects. In a conventional racetrack memory, the information is written by creating magnetic domain walls through local magnetization switching, which can be realized by harnessing the effect of spin-transfer torque (STT). However, the information carried by domain walls may be destroyed or lost due to the domain wall susceptibility to imperfections at racetrack borders. Therefore, the racetrack memory with magnetic skyrmions acting as information carriers has been proposed to provide a potential route to overcome information loss caused by non-desired impurities and defects.

Magnetic skyrmions are nanoscale topological spin textures, which usually can be found in magnetic materials with asymmetric or frustrated exchange interactions. A number of theoretical and experimental works have shown that magnetic skyrmions can be used as building blocks for racetrack memories, logic computing devices, and bio-inspired applications. However, it is difficult to create single isolated skyrmions on the racetrack and avoid the skyrmion trajectory deviation due to the skyrmion Hall effect. Several works have been performed in order to overcome these obstacles for practical applications of skyrmion-based racetrack-type applications. For example, the generation of skyrmions on the track have been achieved with utilization of different approaches, such as transforming skyrmions from domain walls, creating skyrmions from notches, and creating skyrmions by unique electric pulses.

On the other hand, in order to avoid the detrimental effect of the skyrmion Hall effect, which prevents skyrmions from moving along the central line of the racetrack, several methods have been proposed recently. For examples, the racetrack modification by insertion of lateral stripes with higher perpendicular magnetic anisotropy (PMA), the utilization of ferromagnetic skyrmioniums and synthetic antiferromagnetic (SyAF) skyrmions, and the utilization of antiferromagnetic (AFM) skyrmions.

Since the skyrmion number is zero for AFM and SyAF skyrmions, they can strictly move along the central line of the racetrack, showing no skyrmion Hall effect. In this work, we numerically investigate the controllable manipulation of skyrmions in a SyAF racetrack by locally modifying the PMA under the framework of micromagnetics. Such an investigation is necessary for further applications and can be used for controlling the spacing between adjacent skyrmions, defining the bit length, where a magnetic tunnel junction (MTJ) could be placed to measure the skyrmion, defining the bits “0” or “1” whether the skyrmion is present or absent, and protecting skyrmions from external fluctuations such as stray fields from nearby racetracks, similar to what have been proposed and studied for domain wall-based racetracks. We use a protocol to create antiferromagnetically coupled Néel-type skyrmions with perpendicular spin-polarized current applied on the racetrack, as recently demonstrated by Zhang et al.

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FIG. 1. (a) A synthetic antiferromagnetic (SyAF) racetrack with 30-nm-long central region modified to have perpendicular magnetic anisotropy (PMA) constant $K_u$ different from that of the rest region of the racetrack $K_0$. There pairs of SyAF skyrmions are dislocated around 200 nm in 0.4 ns before the applied current of $j = 10 \times 10^{12}$ A m$^{-2}$ being switched off. (b) The top-layer skyrmion on the locally modified racetrack is expelled when the central region has $K_u < K_0$, while the bottom-layer skyrmion is repelled and decoupled of the top layer skyrmion. (c) The top-layer skyrmion is pinned at the border of the locally modified region when $K_u > K_0$, while the bottom-layer skyrmion is repelled and decoupled of the top layer skyrmion. See Supplementary Movie 1.

FIG. 2. (a) A SyAF skyrmion is presented near the thicker central region just after the application of a spin-polarized current. The top-layer and bottom-layer skyrmions are decoupled and the top-layer skyrmion is expelled for a distance about 30 nm at $j = 0$ after 0.5 ns, while the bottom-layer skyrmion is pinned just under the locally modified region. (b) A SyAF skyrmion stop near the thinner central region of the top racetrack, it is decoupled with the top-layer skyrmion pinned in the center of the locally modified region while the bottom-layer skyrmion is repelled around 30 nm at $j = 0$ after 1.5 ns. See Supplementary Movie 2.

As shown in Fig. 1(a), a spin-polarized current pulse of $j = 10 \times 10^{12}$ A m$^{-2}$ is first applied to drive the SyAF skyrmions into motion, which are displaced about 200 nm in 0.4 ns and stop near the 30-nm-long central region of the SyAF racetrack. The 30-nm-long central region is modified to have a higher or lower PMA constant $K_u$ than that of the rest region of the racetrack $K_0$. The default PMA constant of the racetrack $K_0 = 0.8 \times 10^6$ J m$^{-3}$ is defined based on the experimental CoPt layers, while PMA constant of the locally modified region $K_u = 0.6 \times 10^6 \sim 2.0 \times 10^6$ J m$^{-3}$ is assumed to be realized by using different materials.

Figure 1(b) shows the dynamic behavior of a SyAF skyrmion close to the locally modified region with $K_u < K_0$ under zero current (i.e., $j = 0$ A m$^{-2}$). The asymmetry of the PMA in the top layer of the racetrack leads to the motion as well as decoupling of the SyAF skyrmion, even at $j = 0$ A m$^{-2}$. The decoupling of the SyAF skyrmion depends on the strength of the interlayer coupling and may not occur if the relative AFM interlayer coupling is higher than $10^{-4}$ (see Supplementary Material). The top-layer skyrmion is expelled from the locally modified region about 20 nm in 1.5 ns, while the bottom-layer skyrmion is pinned just under the border of the locally modified region. A similar phenomenon is observed when the locally modified region has a higher PMA constant, namely, $K_u > K_0$, where the top-layer skyrmion is pinned at the border of the locally modified region and the bottom-layer skyrmion is repelled from the locally modified region after the decoupling of the SyAF skyrmion.

The results given in Fig. 1 indicates the possibility of manipulating skyrmions by locally modifying the PMA constant in a racetrack, which would be practically realized by utilization of different materials in a well defined region. However, the experimental realization of such a locally modified region demands several steps for the racetrack fabrication. The other possible method is the utilization of shape anisotropy to emulate the difference in the PMA constant. In this way, we forward to investigate the dynamic behavior of a SyAF skyrmion near the locally modified region, where the thickness of the locally modified region is tuned to be thicker or thinner than the rest region of the racetrack. Such a method has more compatibility with experimental nano-fabrication, because just one lithographic step and one ion milling step can be applied to create different regions on the racetrack developed with the same material.

Figure 2(a) shows the response of a SyAF skyrmion to a locally modified region, where the thickness is 0.5 nm thicker than the rest region of the racetrack. It is found that the top-layer skyrmion is expelled about 20 nm in 0.5 ns far from the central locally modified region, while the bottom-layer skyrmion is pinned just below the thicker region. Here we find that the ticker region is able to mimic the effect of a lo-
FIG. 3. Top views of the in-plane magnetization configurations of the SyAF racetrack. (a) The ground state of the unmodified SyAF racetrack ground state where in-plane magnetization configurations are naturally formed. Only the top layer is shown. (b) The unmodified racetrack including a SyAF skyrmion. Only the top layer is shown. (c) The locally modified racetrack including a SyAF skyrmion, where the central region between the dashed lines has a thicker thickness and thus behaving as lower PMA. The formation of extra in-plane magnetization configurations in the locally modified region leads to the skyrmion pinning and expulsion due to the dipole-dipole interaction. The skyrmion-like structure that appears inside the modified region on (d) is due to the skyrmion in the bottom layer, like an imprinted texture.

FIG. 4. (a) Evolution of the skyrmion pinning in the top layer of a SyAF racetrack, which demonstrates the utilization of locally modifications on the racetrack to form successive bits with length of 30 nm separated by 30 nm. The top-layer skyrmion is accommodated in each bit in 0.5 ns with the application of spin-polarized current pulses. (b) Time evolution of the topological number $Q$, reduced out-of-plane magnetization $m_z$, and applied current density $j$ corresponding (a).

Successively, the decrease in the racetrack thickness is studied by locally modifying the central region to be 0.5 nm thinner than the rest region of the racetrack, opposite to the previous case, the AF coupling is stronger in the thinner region, making the anisotropy stronger. As shown in Fig. 2(b), when a SyAF skyrmion is close to the thinner central locally modified region, the top-layer skyrmion is attracted to the central of the modified region, while the bottom-layer skyrmion is a bit expelled from the locally modified region. In order to understand why the local modifications of PMA constant and shape anisotropy (i.e., thickness) in the racetrack are able to induce the SyAF skyrmion decoupling and pin or expel top-layer/bottom-layer skyrmions, we continue to investigate the in-plane magnetization configurations of the SyAF racetrack.

Figure 3 shows the in-plane magnetization configurations for different steps, which are very small and not noticeable in Fig. 1 and Fig. 2 presenting the three-dimensional magnetization. The in-plane magnetization configuration of the ground state of the racetrack is given in Fig. 3(a), and the in-plane magnetization configuration of the relaxed racetrack including a Néel-type SyAF skyrmion is given in Fig. 3(b). As shown in Fig. 3(c), for the locally modified region with $K_u > K_0$ or a thinner thickness, two in-plane magnetization areas form in the borders of the locally modified region of the top racetrack, which match the in-plane magnetization configuration of the top-layer skyrmion. Similar behavior is observed in the bottom racetrack, however, the formed in-plane magnetiza-
tion areas don’t match the in-plane magnetization configuration of the bottom-layer skyrmion. Hence, when the top-layer skyrmion is close to the border of the locally modified region, it is attracted by DDI and pinned by Heisenberg exchange interaction, while the bottom-layer skyrmion is expelled by the same interactions. Figure 3(d) shows the in-plane magnetization configuration for the locally modified region with $K_u < K_0$ or a thicker thickness. Here, the in-plane magnetization configurations at the borders of the locally modified region are opposite to that observed in Fig. 3(c), therefore, following the same principle the top-layer skyrmion is expelled from the locally modified region and the bottom-layer skyrmion is attracted and pinning by the locally modified region.

The presented results suggest that it is possible to apply local modifications in the racetrack to generate bits, where the skyrmion is pinned, and in that position a MTJ could be fabricated to sense the skyrmion for information read-out processing. In order to test the shortest bit length we apply two separated spaces where the thickness of the racetrack is reduced by 0.5 nm. As shown in Fig. 4(a), we demonstrate that the skyrmion can travel between two bits in a controllable manner, where the locally modified regions are able to keep the skyrmion in a desired location for read-out measurement using MTJ. Figure 4(b) shows very small fluctuations in both top-layer and bottom-layer skyrmion topological numbers during their motion between the bits, indicating the locally modified region has tiny influence on the skyrmion structure.

In conclusion, we have investigated the dynamic behavior of skyrmions near the locally modified region of a SyAF racetrack, where the PMA constant or shape anisotropy is artificially adjusted. We have shown that it is possible to use the locally modified region to manipulate the skyrmion, such as defining the bit length and setting the right location to develop the read-out MTJ. We found that certain in-plane magnetization configurations are generated at the borders of the locally modified region, which can interact with the skyrmion. The SyAF skyrmion could be decoupled into a top-layer skyrmion and a bottom-layer skyrmion when it is close to the locally modified region, due to the DDI and exchange interaction between skyrmions and in-plane magnetization configurations at the borders of the locally modified region. Depending on the PMA constant or thickness of the locally modified region in relation to the rest region of the racetrack, the skyrmions can be either attracted or expelled by the locally modified region. We have also demonstrated that by using locally modified regions with thinner thickness and with small separation among each other, it is possible to move skyrmions between desired bit locations with very small driving current pulse.

METHODS

The micromagnetic simulations are performed with the GPU-accelerated micromagnetic simulator MuMax3, which solves the Landau-Lifshitz-Gilbert (LLG) equation augmented with the adiabatic STT.

\[
\frac{\partial\mathbf{m}}{\partial t} = -\gamma\mathbf{m} \times \mathbf{H}_{\text{eff}} + \alpha \left( \mathbf{m} \times \frac{\partial \mathbf{m}}{\partial t} \right) + \frac{\gamma h j P}{2e\mu_0 M_S} \left( \mathbf{m} \times \frac{\partial \mathbf{m}}{\partial x} \times \mathbf{m} \right) - \beta \gamma h j P \left( \mathbf{m} \times \frac{\partial \mathbf{m}}{\partial x} \right)
\]

where $\mathbf{m} = \mathbf{M}/M_S$ is the reduced magnetization, $M_S$ is the saturation magnetization, $\gamma$ is the gyromagnetic ratio with absolute value, $\alpha$ is the Gilbert damping parameter, $\beta$ is the non-adiabatic STT strength, $h$ is the reduced Planck constant, $\mu_0$ is the vacuum permeability, $e$ is the electron charge, $P$ is the polarization ratio of the electric current, and $H_{\text{eff}}$ is the effective field. The considered micromagnetic energy terms include the interlayer and intralayer Heisenberg exchange interaction energies, Dzyaloshinskii-Moriya interaction (DMI) energy, PMA energy, applied magnetic field energy, and dipole-dipole interaction (DDI) energy. The third and fourth terms on the right-hand side of Eq. (1) is related to the adiabatic and non-adiabatic STTs provided by the spin-polarized current $j$ in the racetrack, where $j$ is the applied current density.

The simulated racetrack is composed by two ferromagnetic layers with dimensions of $500 \times 50 \times 2$ nm$^3$, which are separated by a spacer of 1-nm-thick Ru layer to mimic a SyAF multilayer. The magnetic parameters used in our micromagnetic simulations are adopted from Refs. 6, 32, 39, 42, and 43 as follows: the saturation magnetization $M_S = 5.8 \times 10^5$ A m$^{-1}$; exchange stiffness $A_{ex} = 15 \times 10^{-12}$ J m$^{-1}$; relative AFM interlayer exchange coupling varying from $-1$ to $-10^{-12}$ J m$^{-1}$; the DMI constant equals $D = 3.5 \times 10^{-3}$ J m$^{-2}$; the PMA constant $K_0 = 0.8 \times 10^6$ J m$^{-3}$, the damping parameter $\alpha = 0.3$; the non-adiabatic STT parameter $\beta = 0.3$, and the spin polarization factor $P = 0.4$.

The images of magnetization configurations are obtained by using the MuVIEW software and the topological numbers are calculated based on the following definition

\[
Q = \frac{1}{4\pi} \int \mathbf{m} \cdot \left( \frac{\partial \mathbf{m}}{\partial x} \times \frac{\partial \mathbf{m}}{\partial y} \right) dx dy.
\]

In theory, the topological number $Q$ for a skyrmion is strictly equal to $\pm 1$ in the continuous model, however, due to the numerical discretization of the micromagnetic simulation process, we have $Q \approx \pm 1$ for a skyrmion in the micromagnetic system.

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Author Contributions
C.I.L.A coordinated the project. R.P.L. and C.I.L.A performed the simulation. C.I.L.A, R.P.L. and X.Z. prepared the manuscript with input from Y.Z., M.E. and X.L. All authors discussed the results and reviewed the manuscript.

Additional Information
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Competing Financial Interests
The authors declare no competing financial interests.