Magnetic skyrmion transport in racetracks: toward the realization of skyrmion racetrack memory

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Magnetic skyrmions offer promising potential for next-generation memory and logic devices due to their nanoscale size, stability, and efficient electrical manipulation. In this work, we demonstrate the three fundamental operations required for skyrmion racetrack memory: individual skyrmion generation, deletion, and current-driven transport. In a robust skyrmion hosting material, skyrmions are nucleated and annihilated via vertical voltage pulses applied through a GdOx layer that locally modulates magnetic states by forming conductive filaments. We further verify skyrmion deletion through negative pulses. By combining these capabilities with in-plane spin-orbit torque-induced motion, we realize a three-terminal device architecture capable of executing binary operations. As a proof of concept, we encode the bit sequence "1101," demonstrating complete racetrack memory functionality. These results pave the way for electrically programmable, skyrmion-based memory technologies.

***Index Terms*—Magnetic skyrmion, Racetrack memory, Spintronics**

I. Introduction

Since their first experimental observation [1, 2], magnetic skyrmions, topologically protected spin in real space, have attracted significant attention due to their distinct topological features, including the skyrmion Hall effect [3, 4], the topological Hall effect, and their robustness against defects [5]. Beyond their fundamental scientific interest, a wide range of skyrmions-based devices have been proposed, spanning from skyrmion racetrack memories [6] to neuromorphic computing units [7]. In this work, we introduce the key operation techniques to realize skyrmion racetrack memories. These include skyrmion generation at designated positions, electrically-driven skyrmion transport. Using this, we further present the proof-of-concept experiments of skyrmion racetrack memory devices.

II. Skyrmion Generation and deletion

As skyrmion hosting materials, we employ multilayer stacks of MgO (1 nm)/Ta (0.08 nm)/CoFeB (1.3 nm)/W (5 nm)/TaO_x (2 nm) deposited on Si/SiO_2 substrates, where the CoFeB layer is a ferromagnetic layer, the W layer serves as a source of both spin-orbit torque (SOT), and Dzyaloshinskii-Moriya Interaction (DMI), the MgO layer induces Perpendicular Magnetic Anisotropy (PMA), and the ultrathin Ta dusting layer is introduced to precisely modulate the strength of PMA because the PMA here originates from the interface between the CoFeB/MgO layers. At zero magnetic field, this system exhibits a half-filled stripe domain pattern with a width of 2.4 µm. However, applying a +z-axis magnetic field of 4.3 Oe breaks the symmetry along the z-axis, expanding the +z domains whereas the –z domains shrink, as described in Fig. 1c. Note that under a +z magnetic field of 4.3 Oe, the skyrmion state becomes the global ground state, whereas the stripe domain state transitions into a local energy minimum state. However, skyrmions are not spontaneously formed because external perturbation, such as thermal energy, is not sufficient to overcome the barrier between the stripe domain state, skyrmion state, and uniform state.

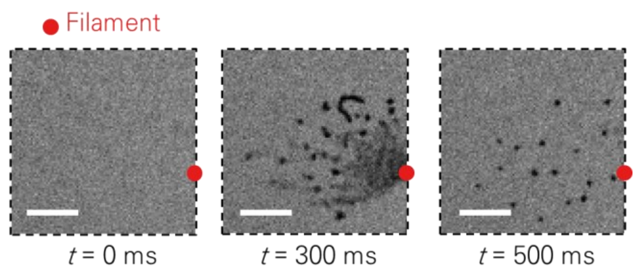

Fig. 1. Isolated skyrmion generation via vertical current injection.

Therefore, in order to generate an isolated skyrmion at a desired position, we adopt an alternative approach by introducing an additional source of external perturbations. A GdO_x (2 nm)/Pt (2 nm) layers are selectively deposited on the magnetic stacks using magnetron sputtering. Upon applying a sufficient voltage pulse across the GdO_x/Pt layers, dielectric breakdown occurs, resulting in the formation of a localized conductive filament. Subsequently, as shown in Fig. 1, the initial state is prepared as a uniformly magnetized configuration along the +z direction by applying a z-axis magnetic field of 4.3 Oe. When a voltage pulse (V_v) is applied, localized magnetization reversal is induced near the conductive filament (marked by the red dot in Fig. 1), resulting in the generation of several isolated skyrmions.

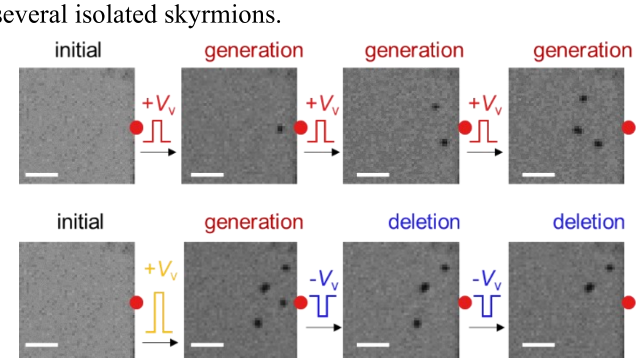

Fig. 2. Successive generation and deletion of isolated magnetic skyrmions

One isolated skyrmion can be also generated by applying an appropriately tuned V_v pulse of 1.0 V. This allows for the controlled accumulation of skyrmions through the sequential applications of a pulse train. To experimentally confirm this accumulation process, we began from a uniformly magnetized initial state (Fig. 2). The application of a single 1.0 V V_v pulse resulted in the formation of an individual skyrmion. Repeating the same pulse led to the creation of an additional skyrmion, and further pulses continued to nucleate skyrmions, each slightly displacing the previously generated ones due to SOT.

Conversely, applying a negative voltage V_v pulse drives and in-plane current toward the location of the conductive filament, effectively pulling in and annihilating nearby domain walls and skyrmions. This mechanism serves as a functional means of skyrmion deletion. For instance, when four skyrmions were generated using a 1.3 V V_v pulse, the subsequent application of -1.0 V removed one skyrmion. Repeated applications of -1.0 V V_v pulses continued to eliminate skyrmions one by one, eventually return to the initial state (Fig. 2).

III. Skyrmion transport in racetrack

A. Fert et al. [6] proposed introduced the concept of skyrmion racetrack memory, where digital information is represented by the presence or absence of magnetic skyrmions. In such a scheme, writing and erasing data require precise control over the generation and deletion of individual skyrmions, while data shifting corresponds to the controlled displacement of skyrmion positions. Building on our experimental demonstrations of skyrmion generation, deletion, and motion, we present a proof-of-concept implementation of all three essential operations within a three-terminal device structure that incorporates both vertical and in-plane current injection pathways.

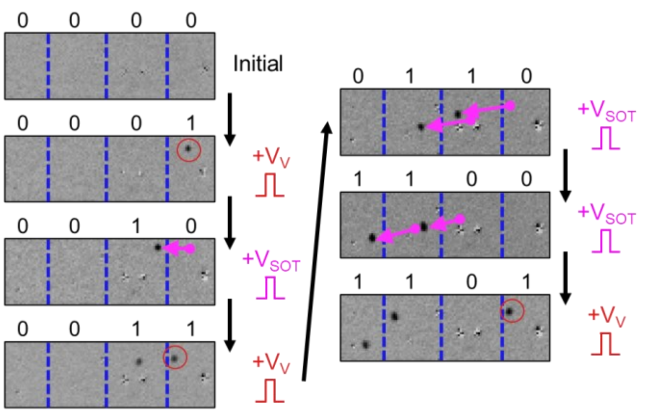

Fig. 3. Operation of the skyrmion racetrack memory.

As a demonstration, we encoded the binary number 1101, which corresponds to the decimal number 13. The process begins with a uniformly magnetized +z state, divided into four segments as indicated by blue dashed lines in Fig. 3. To write the first '1' in the rightmost bit position, a skyrmion is generated via a positive V_v pulse, resulting in the state (0001). A subsequent shift operation to the left is executed using a positive V_{SOT} pulse, after which another skyrmion is written to the rightmost bit, yielding (0011). Two additional shift operations are then applied, moving both skyrmions two bits to the left while preserving their relative spacing. Finally, a third skyrmion is generated in the rightmost bit, completing the target bit sequence (1101), equivalent to the binary representation of decimal 13 [8].

References

[1] U. K. Rößler, A. N. Bogdanov, and C. Pfleiderer, "Spontaneous skyrmion ground states in magnetic metals" *Nature, 442,* 797-801, 2006.

[2] S. Mühlbauer, B. Binz, F. Jonietz, C. Pfleiderer, A. Rosch, A. Neubauer, R. Georgii, and P. Böni, "Skyrmion Lattice in a Chiral Magnet" *Science*, 323, 915-919, 2009.

[3] U W. Jiang, X. Zhang, G. Yu, W. Zhang, X. Wang, M. Benjamin Jungfleisch, John E. Pearson, X. Cheng, O. Heinonen, K. L. Wang, Y. Zhou, A. Hoffmann, and Suzanne G. E. te Velthuis, "Direct observation of the skyrmion Hall effect" *Nat. Phys., 13,* 162-169, 2017.

[4] K. Litzius, I. Lemesh, B. Krüger, P. Bassirian, L. Caretta, K. Richter, F. Büttner, K. Sato, O. A. Tretiakov, J. Förster, R. M. Reeve, M. Weigand, I. Bykova, H. Stoll, G. Schütz, G. S. D. Beach, and M. Kläui, "Skyrmion Hall effect revealed by direct time-resolved X-ray microscopy" *Nat. Phys. 13,* 170-175, 2017.

[5] N. Nagaosa, and Y. Tokura, "Topological properties and dynamics of magnetic skyrmions" *Nat. Nanotech., 8,* 899-911, 2013.

[6] A. Fert, V. Cros, J. Sampaio, "Skyrmions on the track" *Nat. Nanotech, 8,* 152-156, 2013.

[7] K. M. Song, J.-S. Jeong, B. Pan, X. Zhang, J. Xia, S. Cha, T.-E. Park, K. Kim, S. Finizio, J. Raabe, J. Chang, Y. Zhou, W. Zhao, W. Kang, H. Ju, and S. Woo, "Skyrmion-based artificial synapses for neuromorphic computing" *Nat. Electron., 3,* 148-155, 2020.

[8] S. Yang, K.-W. Moon, T.-S. Ju, C. Kim, H.-J. Kim, J. Kim, B. X. Tran, J.-I. Hong, and C. Hwang, "Electrical Generation and Deletion of Magnetic Skyrmion-Bubbles via Vertical Current Injection" *Adv. Mater., 33,* 2104406, 2021.