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Stabilization and Dynamics of Skyrmions in Stepped Nanowires for Multistate Memory Devices

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Extended Abstract

Magnetic skyrmions are nanoscale spin configurations with a topologically protected vortex-like structure, exhibiting exceptional stability even at reduced dimensions. Their compact size and robustness make them strong candidates for next-generation spintronic applications, including high-density memory and neuromorphic systems. Owing to their resilience and responsiveness to various excitations—such as spin-transfer torque (STT), spin–orbit torque, and magnetic fields—skyrmions can be manipulated at remarkably low current densities, positioning them as ideal information carriers in ultra-efficient device architectures.

Nonetheless, one of the critical challenges in the practical deployment of skyrmion-based devices lies in achieving deterministic control over their trajectories within nanotracks. Under STT excitation, skyrmions deviate from linear paths due to the skyrmion Hall effect, often drifting toward the track edges [1] [23]. This lateral drift, combined with repulsive interactions from the boundaries, may distort the skyrmion structure or lead to its annihilation. These factors hinder precise spatial control and compromise the reliability of multibit memory devices, where accurate skyrmion positioning is paramount for data integrity.

To address these constraints, we introduce a geometrically engineered nanowire with periodic stepped confinements, designed to serve as pinning sites that guide skyrmion motion. The behavior of skyrmions within this architecture was examined via micromagnetic simulations based on the Landau–Lifshitz–Gilbert formalism. By fine-tuning pulse parameters—amplitude, width, and timing—a single skyrmion was systematically driven through discrete confinement zones along a 780-nm-long, 2-nm-thick nanotrack featuring multiple stepped regions [4]. This configuration facilitated the establishment of eight distinct, stable skyrmion positions, each corresponding to a separate memory state. The refined control over pulse delivery enabled the skyrmion to overcome localized potential barriers and repulsive edge forces, progressing sequentially from one state to another without deviation. Interestingly, transitions into upper confinements required only a single pulse, whereas transitions into lower confinements necessitated two pulses to counter the transverse displacement induced by the skyrmion Hall effect.

Further analysis involving two interacting skyrmions demonstrated that the combination of geometric constraints and inter-skyrmion repulsion effectively prevents simultaneous occupation of the same pinning site. The leading skyrmion naturally stabilizes in the first available confinement, while the trailing one is deflected into the next unoccupied region, preserving state exclusivity. This dynamic ensures that each confinement accommodates a single skyrmion, a prerequisite for maintaining distinct resistance levels and ensuring the fidelity of multistate memory encoding. The system inherently distributes skyrmions into spatially isolated states, enhancing robustness and mitigating the risks associated with skyrmion overlap or crowding.

In conclusion, this study presents a viable methodology for achieving controlled skyrmion stabilization within engineered nanowires, addressing long-standing limitations in skyrmion transport and placement. The proposed multi-confinement design offers a scalable path toward multistate spintronic memory, with high precision in skyrmion localization, resilience against annihilation, and compatibility with neuromorphic computing paradigms. This work lays essential groundwork for future skyrmion-based racetrack memory technologies and complex spintronic logic circuits.

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