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A multi-state memory device based on the Manipulation of a single skyrmion using spin-polarized current

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Towards a multistate skyrmionic device, Firstly, the motion of a single skyrmion under spin-transfer-torque (STT) is studied in the conventional and constricted wire the study reveals the possibility to pin, depin and annihilate skyrmion. Later, a stepped nano-track with bottom and top confinements has been proposed, to stabilize the skyrmion in each confinement. The adjustment of the current density magnitude and its duration enabled the displacement of the skyrmion at any position. More interestingly, it was observed that only one skyrmion can be stabilized in each confinement when a large number is displaced by current pulses. These results open the way for large-capacity memory devices and neuromorphic computing.

Index Terms—Ferromagnetic materials, Micromagnetics, Skyrmion, spin systems, spintronics.

I. INTRODUCTION

Magnetic skyrmion are particle-like magnetic configurations that attracted attention due to their small size, stable structure, easily moved, and provide a new route to denser information storage. Driven by the need for higher storage devices, there is a shift to control the magnetic skyrmion rather than magnetization and domain wall (DW). Intensive studies have been carried out, but the major challenge is device heating has been a serious issue because a large current density is necessary to overcome the pinning, and, therefore, the experiments usually have been done using a short pulse of electric current.

Skyrmions show inertia-driven drift shortly after the current pulse is removed as reported by Morshed et al. [1]. a stepped nanowire is proposed with a stepped barrier to control and stabilize skyrmions under a pulsed current. Later, a constricted wire is designed to stabilize the skyrmion at every site. Opening a path to a new concept of promising magnetic memories based on skyrmion motion in nano tracks, should help future studies to design new memories based on a very dense encoding of information.

II. THEORETICAL METHOD

Numerical solutions for Neel- skyrmion in constricted nanowire were performed using micromagnetic simulation Mumax3 [2] based on Landau-Lifshitz-Gilbert (LLG) to investigate the spin transfer-induced motion of skyrmions in magnetic tracks with the stepped region. The stepped region is added to the nanowire with the objective to act as a pinning site for stabilizing and controlling the motion of the skyrmions' position and the dimensions were varied. The intrinsic material parameters used in this work were fixed while the device dimension was changed. Following a previous study, the exchange stiffness constant A_{ex} , the damping constant α , the interfacial Dzyaloshinskii-Moriya strength D , the saturation magnetization and the perpendicular uniaxial anisotropy energy K_u were fixed to 15pJm^{-1} , 0.1 , 3.3mJm^{-2} , 500KA^{-1} and 0.8MJm^{-3} , respectively. The pulsed current is applied in the form of a rectangular pulse along the direction of the wire which flows to the left, so the electron would flow toward the right with a strength of the nonadiabatic STT fixed to 0.2 and the spin polarization P to 0.4 . Illustration of the nano-track is shown in fig. 1.

III. RESULTS AND DISCUSSIONS

A. Stabilizing magnetic skyrmion in constricted nanowires

The ability to exceed the edge is predicted through the competition between the force due to the edge generated by the geometrical structure and the driving force. If the current density is small as the skyrmion approaches the edge the velocity will decrease and then vanishes completely skyrmion, for intermediate current values the driving current overcomes the repulsive force without being annihilated, For even larger

values the skyrmion collides with the edge and is destroyed as shown in figure. 2. The threshold current density to overcome the edge is related to step size and the skyrmion size. The larger the step size (narrower passage) results in higher barrier energy which will lead to shrinking the size. The larger the size of the skyrmion, the harder for it to shrink and move to the second region resulting in pinning.

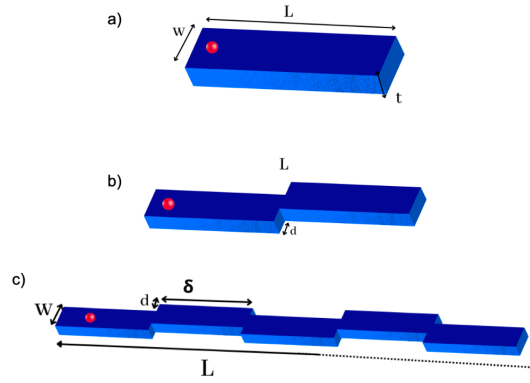


Fig. 1. (a), (b), and (c) are schematic drawings of the conventional, stepped nanowires and nano-track with multiple confinements. The length L and the width W were fixed to 300nm, and 75nm, respectively for (a) and (b), in (c) We consider a 2nm thick nano-track with a length of 780nm and a width of 80nm, stepped regions with a size of 3070nm².

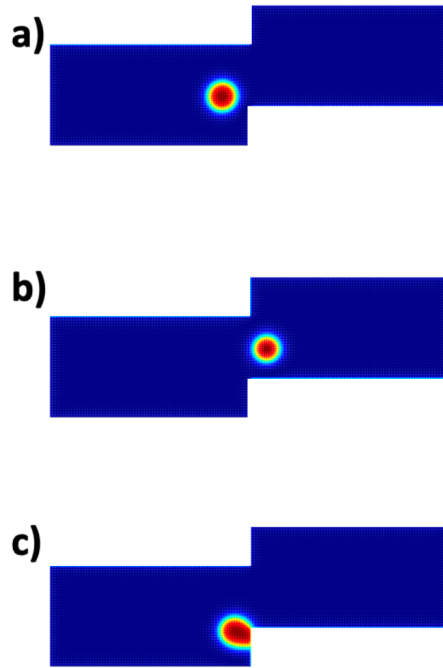


Fig. 2. snapshots of skyrmion within a stepped nanowire for (a) $J = 2.010^{11} \text{Am}^{-2}$ where it is pinned (b) $J = 2.510^{11} \text{Am}^{-2}$ where the skyrmion could overcome the stepped region and (c) $J = 7.010^{11} \text{Am}^{-2}$ where it was annihilated.

B. Stabilizing magnetic skyrmions in multi-constricted nanowires

In the second part of this study, the pinning and reliable depinning of the skyrmion from the pinning centers under current pulses to have a multistate memory device has been investigated. It can be seen from Figure3 that it is possible to achieve 8 states by pinning the skyrmion in the confinement regions where each region represents one bit, which corresponds to “0” if the region does not contain a skyrmion, and “1” if the region contains one skyrmion. It can be seen in4 that the skyrmion moves with a constant velocity when the current is applied as indicated by an almost straight line when the current stops it bounces back and stabilizes. Alternating the amplitude and number of pulses makes it possible to reach the required states.

Interestingly, the repulsive force from the edge causes the size of the skyrmion to shrink near the edges, if this force is too large in the case of a larger skyrmion or narrower channel or larger current density, the skyrmion will annihilate. It is possible to access any position by changing only the pulse width or/and current density within the nanowire without being pinned in specific confinement.

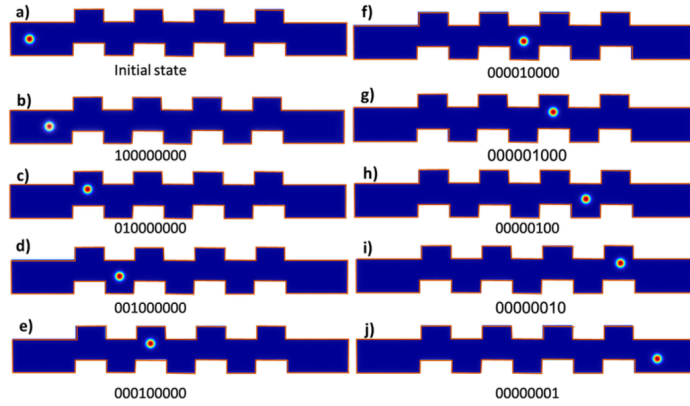


Fig. 3. snapshots of magnetic states, the length of the wire is $L = 780\text{nm}$, the width $w = 80\text{nm}$ and the thickness is 2nm . The color scale shows the out-of-plane component of magnetization.

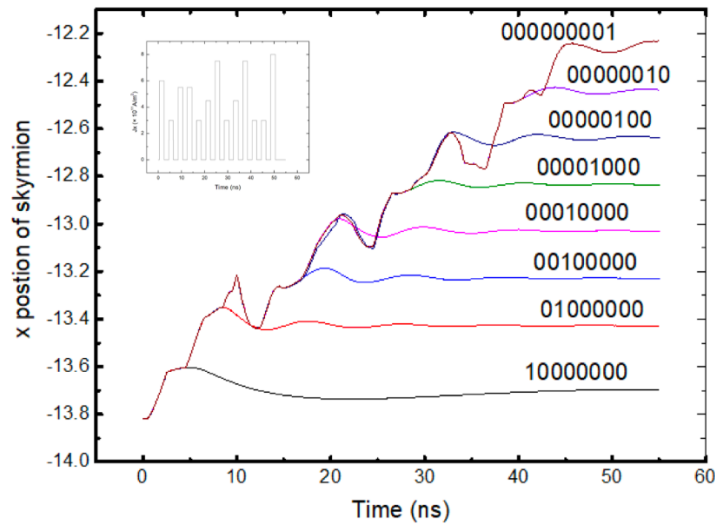


Fig. 4. skyrmion position at different current pulse values as function of the time. The current density magnitude is shown in the inset.

IV. CONCLUSION

In this study, the dynamics and stability of magnetic skyrmions within a nano-track with multiple confinements were investigated. the study reveals the possibility to pin and stabilize the skyrmion in each confinement. These results open the door for denser memory devices and neuromorphic computing.

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