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Research articles

Skyrmion motion driven by the gradient of voltage-controlled magnetic anisotropy

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ABSTRACT

Controllable manipulation of skyrmion motion is important for next-generation spintronics. Here, a gradient of voltage-controlled magnetic anistropy (VCMA) induced skyrmion motion in a Co/Pt nanotrack was reported using micromagnetic simulations. The results show that a magnetic skyrmion, driven by the gradient of VCMA, can move straightly along the nanotrack without deflection due to boundary effects. The velocity and diameter of the magnetic skyrmion increases in proportion to the gradient of VCMA, which are in agreement with the analytical model. Effects of notch on the VCMA gradient-induced skyrmion motion are also investigated. This work provides an effective approach to drive skyrmion motion, which can give guidance for next-generation spintronic devices.

1. Introduction

Magnetic skyrmions are topologically protected spin texture [1–3]. They have been experimentally discovered in bulk ferromagnetic materials lacking inversion symmetry, antiferromagnetic materials, artificial materials with magnetic vortexes embedding into an out-of-plane aligned spin environment, and non-spiral materials owing to the competing of exchange interaction with other strong magnetostatic interactions [1,3,4]. Investigations have been performed not only on observation of skyrmion crystal phase, but also on skyrmion dynamics, such as topological Hall effect, magnet-electric effect in a helimagnetic multiferroic and three spin-wave modes activated by microwave magnetic fields [5–9]. Furthermore, skymions possess profound applications for next-generation spintronics, such as racetrack memory, logic gates and microwave resource [1,10–14], due to their stable topology, nanometer size, insensitivity to edge roughness, and low driving current density ($\sim 10^6$ A m^{-2}, which is about 10^5 to 10^6 smaller than that required to drive magnetic domain walls) [1,11,14].

The ability to controllably manipulate magnetic skyrmions is of fundamental importance [1,9,12]. It is not only the precondition for next-generation spintronic devices, for example racetrack memory, but also important from a fundamental point [1,9,12]. Recently, current-induced motion of skyrmions have been extensively studied [1,8,14]. The low driving current density combined with extremely compact size would make skyrmion-based devices with an unprecedented combination of high information storage density, ultrafast information processing and low power consumption [1,8,14]. However, due to the skyrmion Hall effect (SkHE), skyrmions can't move in straight lines along the injected current without deflection, which gives a challenge for realistic applications in spintronics [15,16]. Alternative approaches to move magnetic skyrmions have recently been explored, for example, a magnetic field gradient, spin waves, and temperature gradient owing to spin Seebeck effect [1,17,18]. Despite the success of controllable manipulation of skyrmion motion, there are still challenges to drive skyrmion motion [1,19,20].

Voltage-controlled magnetic anisotropy, as a new approach to electronically manipulate skyrmions in a magnetic naonotrack, has been recently explored [19–23]. The principle of these systems is to electronically manipulate the perpendicular magnetic anisotropy (PMA) due to the charge accumulations [20]. Combined with an electronic field and an applied current, magnetic skyrmion transistor can be realized in a voltage-gated racetrack [19]. Furthermore, the electric field has an influence on current-induced skyrmion motion for racetrack memory [23] .Under certain current density, both the direction and velocity of skymion motion can be controllably manipulated by an VCMA [20]. More importantly, skyrmions can be guided along desired trajectories with a special-patterned electronic field [20]. Here, a VCMA gradient-induced skyrmion motion in a Co/Pt nanotrack is investigated using micromagnetic simulations and an analysis model is also derived. A magnetic skyrmion, with a VCMA gradient, can move straightly

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along the nanotrack without deflection due to boundary effects. The velocity, skyrmion size and skyrmion pining as a function of the gradient are also systematically investigated, which offers a promising route for the design of non-volatile memory and logic devices.

2. Model and simulations

Micromagnetic simulations have been performed using the object-oriented micromagnetic framework (OOMMF) [24], including the extension module of Dzyaloshinskii-Moriya interaction (DMI) without temperature effect (T = 0 K) [25]. The modified Lan dau–Lifshitz–Gilbert equation is written as:

$$\frac{d\mathbf{m}}{dt} = -|\gamma|\mathbf{m} \times \mathbf{H}_{\mathrm{eff}} + \alpha\left(\mathbf{m} \times \frac{d\mathbf{m}}{dt}\right) \quad (1)$$

where $\mathbf{m} = M/M_s$ is the normalized magnetization vector with M_s the saturation magnetization; γ is the gyromagnetic ratio which equals to 2.211×10^5 m/(A·s)); H_{eff} is the effective field; α is damping constant. The effective field H_{eff} is comprised of Heisenberg exchange, magnetic anisotropy, demagnetization, DMI and external magnetic field. The DMI energy density is expressed as:

$$\varepsilon_{\mathrm{DM}} = \mathcal{D}\left(m_z\frac{\partial m_x}{\partial x} - m_x\frac{\partial m_z}{\partial x} + m_z\frac{\partial m_y}{\partial y} - m_y\frac{\partial m_z}{\partial y}\right) \quad (2)$$

where m_x, m_y and m_z are the components of normalized magnetization and $\mathcal{D}$ is the continuous effective DMI parameter [25].

Simulation designs are demonstrated in Fig. 1. A film system, as shown in Fig. 1, was assumed to be a magnetic layer/insulator/electrode structure. The insulating layer decrease in film thickness from left to right. The VCMA can effectively modulate the anisotropy energy density, which is given by $\Delta PMA = |aE|$. a and E are the coefficient of electric field-controlled magnetic anisotropy and the applied electric field, respectively. For the film system, $a = (\Delta k \times t_{Co/Pt})/(\Delta V/t_{insulator})$, where Δk is the change in anisotropy energy density and ΔV is the applied voltage. $t_{Co/Pt}$ and $t_{insulator}$ are the respective thickness of Co/Pt and insulator layer. Thus, the gradient of $t_{insulator}$ results in the gradient in PMA. In the following simulation, we choose a baseline $K_u = 0.8$ MJ/m^3 and a maxmumin reduction of 10% in PMA for detailed evaluations. Hence, the magnetic anisotropy constant deceases linearly from the left edge in the strip [(the anisotropy, position) = ($K_u^0 = 8 \times 10^5$ J/m^3, $X_0 = 0$ nm)] to the right edge ($K_u^1 = 7.2 \times 10^5$ J/m$^3 \sim 8 \times 10^5$ J/m^3, $X_1 = 1000$ nm) [26]. The reduction rate is defined as $\triangle K_u = (K_u^0 - K_u^1)/(X_0 - X_1)$, and it can be modulated using the applied biased voltages or the gradient in the thickness of the insulating layer in experiments. Since the maximum reduction in PMA is 10%, $\triangle K_u$ are set to $-1.0 \sim -8.0 \times 10^{10}$ J/m^4 in this numbers simulations. The magnetic strip is in dimension of $2000 \times 40 \times 0.4$ nm^3.

Other typical materials parameters of a perpendicularly Co/Pt system are as fellows [26]: saturation magnetization $M_s = 5.8 \times 10^5$ A/m; exchange stiffness $A = 1.5 \times 10^{-11}$ J/m; DM interaction parameter is 3 mJ/m^2. The damping constant α is set to 0.01 [26]. The mesh cell is $1 \times 1 \times 0.4$ nm^3. A magnetic skyrmion was initially created at x = 1000 nm in the nanostrip by local injection of a spin-polarized current pulse with the DMI strength fixed at 3 mJ/m^2. A perpendicular spin-polarized current (1.0×10^{12} A/m^2) is injected into the nanostripe in a circle region with diameter of 20 nm at 0 ns. The perpendicular spin-polarized current is turned off at 0.4 ns and followed with 1 ns long relaxation of the nanostripe. A stable skyrmion is nucleated in the nanostripe.

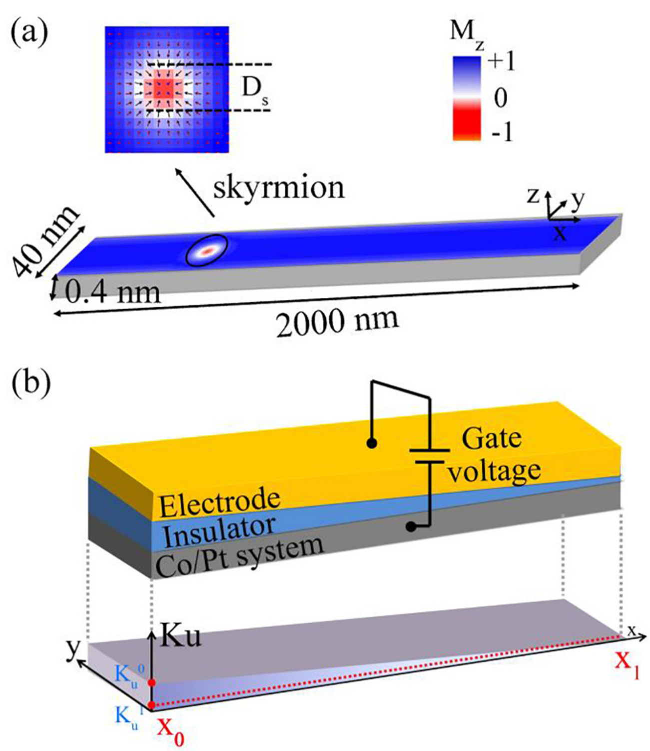

Fig. 1. The schematic of VCMA gradient-induced skyrmion motion in a magnetic nanotrack.

3. Results and discussions

Fig. 2 demonstrates representative snapshots of the positions of a magnetic skyrmion at the nanostrip in the condition of $\triangle K_u = 0$ and $\triangle K_u = -8.0 \times 10^{10}$ J/m^4, respectively. The magnetic skyrmion moves in direction of decreasing anisotropy along the magnetic nanotrack without deflection at $\triangle K_u = -8.0 \times 10^{10}$ J/m^4, whereas it completely motionless in the nanostrip at $\triangle K_u = 0$. Under $\triangle K_u = -8.0 \times 10^{10}$ J/m^4, the diameter of magnetic skyrmion increases

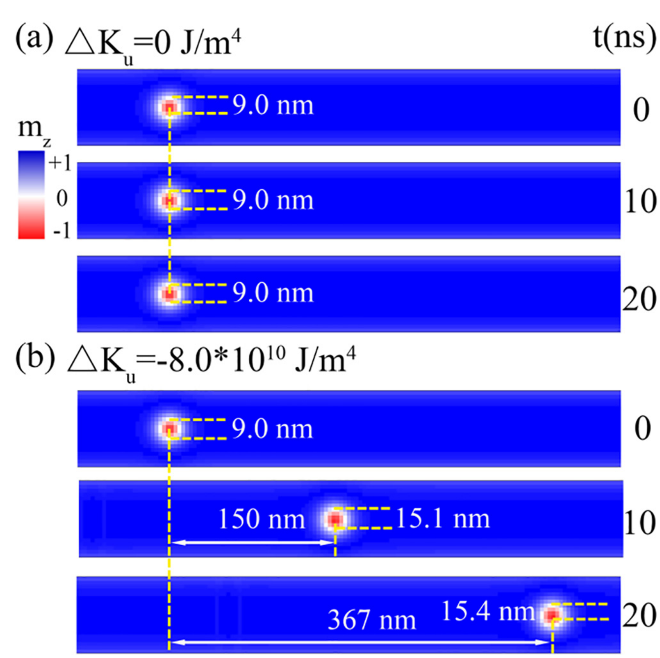

Fig. 2. Snapshots of skyrmion positions in the nanotrack with $\triangle K_u = 0$ J/m^4 and $\triangle K_u = -8.0 \times 10^{10}$ J/m^4.