Journal of Magnetism and Magnetic Materials 455 (2018) 19–24

Contents lists available at ScienceDirect

Journal of Magnetism and Magnetic Materials

journal homepage: www.elsevier.com/locate/jmmm

Research articles

Strain-controlled skyrmion creation and propagation in ferroelectric/ferromagnetic hybrid wires

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ARTICLE INFO

Article history:
Received 31 May 2017
Accepted 3 July 2017
Available online 3 July 2017

Keywords:
Skyrmion
Micromagnetic simulation
Magnetization reversal
Magneto-elastic effect

ABSTRACT

The control of magnetic skyrmion creation and pinning through strain is studied by micromagnetic simulations. A single stable skyrmion can be created by a vertical strain pulse on Pd/Fe/Ir hybrid structure on $Pb(Zr_{1-x}Ti_x)O_3$ nanowire with −1.8 V pulse voltage from 1.2 ns to 2.0 ns. Then the skyrmion is pinned by the vertical strain independent of the polarity during its propagation in the wire driven by the current. The proposed device integrates strain-controlled skyrmion creation and pinning in a single nanowire structure, which would open a new route for skyrmion-based memory and logic devices with ultra-low power consumption.

1. Introduction

Magnetic skyrmions are topologically protected spin textures, which are experimentally observed in both bulk non-centrosymmetric crystals and interfacial symmetry broken thin films [1,2]. Due to their small size, high stability and low current density required for motion, skyrmions exhibit great potential in high-density and low-power spintronic devices [3–6]. On the roadmap to future applications, the efficient creation, manipulation and detection of a single skyrmion in magnetic nanostructures is essential.

The creation and manipulation of skyrmions have been widely studied [7–9]. The skyrmion motion is normally driven by a low-density current and manipulated by electric fields or local defects [10–12]. Various methods for creating skyrmions have been proposed, like external magnetic fields [13,14], spin-polarized current [15,16], local heating [17], and electric fields [18,19]. However, all these methods suffer from either high-power consumption, high electric field or incompatibility with existing CMOS circuitry [20]. Thus, a low-energy creation and driving scheme is highly desired for practical applications. Here, we propose a strain-dependent control of skyrmion creation and pinning in a hybrid ferroelectric/ferromagnetic nanowire, in which the strain is applied by utilizing the inverse piezoelectric effect [21]. The proposed structure exhibits several advantages in terms of structural simplicity and low-power consumption, which provides a practical way for building future applications of skyrmion-based devices.

2. Model

Strain controlled magnetization reversal by manipulating magnetic anisotropy has been intensively studied in hybrid ferroelectric/ferromagnetic nanowires [22,23]. More recently, skyrmion creation by applying strain has also been studied by some of the authors through micromagnetic simulations. However, the work reported in Ref. [24] focused on transition from chiral domains to skyrmion in nanowires. Moreover, the strain is assumed to be uniform, which is oversimplified for heterojunction under investigation in this work. Here, the strain-controlled skyrmion creation and pinning are quantitatively studied with COMSOL® and OOMMF packages. The device structure of $Au/Pd/Fe/Ir/Pb(Zr_{1-x}Ti_x)O_3$ (PZT) nanowire, with 200 nm width and 7 μm length, is shown in Fig. 1. A magnetic disk with 400 nm diameter is connected to the nanowire for a single skyrmion creation. The bottom Au electrodes of 400 nm width and 200 nm thickness work as bit lines and the electrode located below the disk is used to create a single skyrmion, while the other one under the skyrmion track is used for pinning the skyrmion locally, which accomplishes a logic or a storage function. The top Au electrode works as a word line to realize an array extension.

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http://dx.doi.org/10.1016/j.jmmm.2017.07.008
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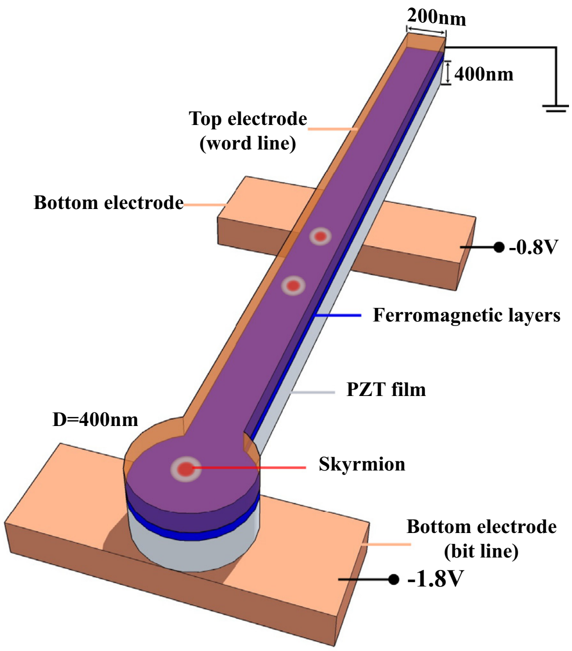

Fig. 1. Schematic of the simulated device structure. 200 nm wide Au/Pd/Fe/Ir/PZT-5H nanowire is connected to a disk with 400 nm in diameter for skyrmion creation, propagation and pinning. Thickness of PZT film is 400 nm and Fe layer is 2 nm. The top Au electrode is grounded, the bottom Au electrodes are applied with −1.8 V voltage for skyrmion creation and −0.8 V for skyrmion pinning, respectively.

Here, PZT-5H is chosen as the reference for our simulation, where the piezo-electric constant of $d_{33} = 620\,pC/N$ and dielectric constant is $e_{33} = 3200$ [25,26]. The magnetic parameters used in the simulation are based on the Pd/Fe/Ir films: the perpendicular magnetic anisotropy constant $K = 270\,kJ/m^3$, DMI constant $D = 0.7\,mJ//m^3$, saturation magnetization $M_s = 6 \times 10^5\,A/m$, exchange coefficient $A_{ex} = 1.12 \times 10^{-11}J/m$, Gilbert damping $\alpha = 0.05$ and Young's modulus $E_Y = 155\,GPa$ [27,28]. Modulation of anisotropy and DMI E_{DM} coefficient can be realized by interfacial modification [29,30]. As magnetostriction arises due to the spin-orbit coupling interaction between ferromagnet and impurity in ultra-thin regime, Fe/Pd interfacial spin-orbit coupling dominated magnetostriction can be considered as the same as FePd alloy. Therefore, in this case, the magnetostriction coefficient $\lambda = 9 \times 10^{-5}$ of the FePd alloy is $K \ll K_c$ used in the simulation [31,32].

The total energy in this system can be written as $E_{total} = E_{DM} + E_{ani} + E_{ex} + E_{ME}$, where E_{DM}, E_{ani}, E_{ex} and E_{ME} are Dzyaloshinskii–Moriya interaction (DMI) energy, anisotropy energy, exchange coupling energy and magneto-elastic energy, respectively. The magnetic anisotropy energy and the exchange coupling energy are the origin of ferromagnetic (FM) single domain state, while the DMI energy is the origin of helical magnetic structures [33,34]. Magnetic domain structure varies with the competition between, E_{demag}, E_{ani} and E_{ex}. There is another important factor known as critical effective anisotropy constant K_c [35], expressed as

$$K_c = \frac{\pi^2 D^2}{16 A_{ex}} \tag{1}$$

below which domain walls proliferate. This means that a single domain state is stable for samples with high K, for, polydomain state forms, and for $K \lneqq K_c$, the skyrmion state appears, which is stabilized by the competition of the exchange interaction, DMI and magnetic anisotropy. The skyrmion diameter is written as [35]

$$R_s \approx \sqrt{\frac{A_{ex}}{2K_{eff}\left(1 - \frac{D}{D_c}\right)}} \tag{2}$$

where D_c is critical DMI constant. For certain A_{ex} and D, skyrmions shrink as the effective anisotropy constant K_{eff} increases and disappears with further increase of K_{eff}.

Tuning the magnetic anisotropy through magneto-elastic effect could control the skyrmion state, including creation and pinning during its motion. The magneto-elastic anisotropy energy is written as [36,37]

$$k_{ME} = -\frac{3}{2}\lambda \cdot E_Y \cdot \varepsilon \tag{3}$$

where λ, E_Y and ε are magnetostriction coefficient, Young's modulus and applied strain, respectively. The DMI coefficient $D = \sqrt{3}D_{12}/at$ is inversely proportional to lattice constant a. However, the first-principle study has shown that the DMI constant would change no more than 1% with strain smaller than 0.1% [38], while the magnetic anisotropy energy could change more than 10% in high magneto-elastic and low magnetic anisotropy structures [39,40], which is one order of magnitude larger than the change of the DMI energy. Thus, only the strain-induced magneto-elastic anisotropy is considered and the strain-induced variati K on of DMI is disregarded in this work.

3. Results and discussions

3.1. Strain distribution under applied voltage

The phase diagram of Pd/Fe/Ir nanostructure in the skyrmion creation region is simulated by the OOMMF micromagnetic software, as shown in Fig. 2. The FM state is stable when K is larger (the red zone), polydomain state appears when D is larger (the blue zone), polydomain-FM and skyrmion-FM bi-stable states are in between (the green and yellow zones respectively). Note that the appearance of polydomain-FM bi-stable state is due to the size limitation of our design structure. In skyrmion-FM bi-stable state, an energy barrier exists between FM and skyrmion, because of which an external excitation is required to transform between these two

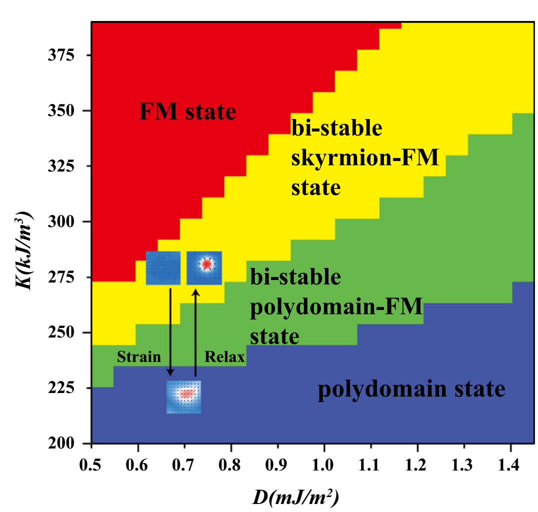

Fig. 2. Phase diagram of the magnetic states in Pd/Fe/Ir nanostructure. Depending on the given values of D and K, ferromagnetic state, bi-stable skyrmion-FM state, bi-stable polydomain-FM state and polydomain state are observed. Inserted instance demonstrates the process of skyrmion creation: A reversed domain is observed with a strain-induced K decrease and a single skyrmion formed by a following relaxation.