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Magnetic domain wall motion across a step of Dzyaloshinskii-Moriya interaction

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ABSTRACT

Magnetic domain wall motion is numerically studied in a nanowire with a Dzyaloshinskii-Moriya interaction (DMI) step at which DMI varies in real space. The spatially modulated DMI results in the formation of asymmetric domain wall energy landscape across the step, which affects the domain wall motion significantly. Utilizing this DMI step, we propose a domain wall memory device where the switching of up- and down-state is induced by a spin-orbit spin-transfer torque (SOT)-driven domain wall motion. This domain wall memory device is expected to have a high switching efficiency.

1. Introduction

The Dzyaloshinskii-Moriya interaction (DMI) is the antisymmetric component of exchange interaction, which favors chiral spin textures in magnetic systems [1,2]. Spin-orbit coupling combined with broken inversion symmetry gives rise to DMI that is present, for instance, at the interface of ferromagnet/heavy-metal bilayer systems [3–12]. Recently, this bilayer system has been studied intensively because it exhibits intriguing phenomena such as the interfacial DMI, spin Hall effect, and Rashba effect [13–15]. Spin-orbit spin-transfer torques (SOTs) originating from the spin Hall effect and Rashba effect enable fast current-induced magnetization switching without the second ferromagnetic layer [16–19] and efficient magnetic domain wall motion in cooperating with DMI [20–25]. Also, recent works found that interfacial DMI significantly modifies spin-wave properties [7,26,27], which provides additional functionalities for spin-wave devices [28–30].

A magnonic crystal is a magnetic metamaterial with spatially modulating magnetic properties [31–42]. Recently, we find that for a magnonic crystal with alternating DMI, which can be achieved by a local gating [43], a local modulation of the interface between ferromagnetic layer and heavy metal layer [44–46], or a local variation of the heavy metal thickness [47], a spin-wave can be amplified and the spin-wave bandgap is tunable either by an external magnetic field, an in-plane current, or a perpendicular electric gating voltage [48]. A recent study [49] found such spatially modulated DMI supplies a strong confinement effect for a domain wall. As a low threshold driving force for domain wall depinning is also an important characteristic for domain wall devices, domain wall motion in a magnetic system with spatially modulated DMI also needs to be analyzed.

In this paper, we investigate the magnetic field- and current-(SOT-) induced domain wall motion in a nanowire including a DMI step at which DMI constant spatially varies by using micromagnetic simulation. We found that an energy step or barrier is formed at the DMI step depending on the DMI constants of two neighboring regions across the step and controls whether the domain wall passes through the DMI step or not. The SOT-induced domain wall motion through a DMI step can be utilized in a domain wall memory device. For SOT-domain wall memory device, one of key issues is to enhance a switching efficiency [≡ energy barrier (E_b)/switching current (I_{th})] because there is a direct correlation between E_b and I_{th} [50]. We found that the domain wall device utilizing DMI step, proposed in this work, has an improved switching efficiency, which

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can be further enhanced by controlling DMI constants effectively.

2. Micromagnetic simulation

The Hamiltonian of DMI between atomic spins $\mathbf{S}_i$ and $\mathbf{S}_j$ is written as,

$$H_{DM,ij} = \mathbf{D}_{ij} \cdot (\mathbf{S}_i \times \mathbf{S}_j), \quad (1)$$

where $\mathbf{D}_{ij}$ is the DM vector, which is perpendicular to both the inversion asymmetry direction and the position vector $\mathbf{r}_{ij}$ between atomic spins $\mathbf{S}_i$ and $\mathbf{S}_j$. Thus, in the atomic chain shown in Fig. 1(a), DM vector is along y-axis because the asymmetry direction and the position vector are along z-axis and x-axis, respectively. Here, we assume the DMI constant changes from D_1 to D_2 between two atomic spins $\mathbf{S}_i$ and $\mathbf{S}_{i+1}$, which we call the DMI step. Given that DMI constants between $\mathbf{S}_{i-1}$ and $\mathbf{S}_i$ ($\mathbf{S}_{i+1}$ and $\mathbf{S}_{i+2}$) is D_1 (D_2), the DMI constant between $\mathbf{S}_i$ and $\mathbf{S}_{i+1}$ is $(D_1 + D_2)/2$. As a result, the effective DMI field acting on the spin at site i can be written as,

$$\mathbf{H}_{DM,i} = -\frac{\partial\left(H_{DM,(i-1)i} + H_{DM,i(i+1)}\right)}{\partial \mathbf{S}_i} = -\mathbf{D}_1 \times \mathbf{S}_{i-1} + \left(\frac{\mathbf{D}_1 + \mathbf{D}_2}{2}\right) \times \mathbf{S}_{i+1}. \quad (2)$$

The magnetization dynamics is described by the Landau-Lifshitz-Gilbert equation including SOT term as,

$$\frac{\partial \mathbf{m}}{\partial t} = -\gamma \mathbf{m} \times \mathbf{H}_{eff} + \alpha \mathbf{m} \times \frac{\partial \mathbf{m}}{\partial t} + \gamma\, c_j \mathbf{m} \times (\mathbf{m} \times \mathrm{y}), \quad (3)$$

where $\mathbf{m}$ is the unit vector along the magnetization, $\mathbf{H}_{eff}$ is the effective magnetic field including the external, exchange, perpendicular anisotropy, magnetostatic, and DMI fields, α is the damping constant, and c_j is the magnitude of damping-like SOT [$= (\hbar/2e)(\theta_{SH}J/M_S t)$], θ_{SH} is the effective spin Hall angle, J is the current density, M_S is the saturation magnetization, t is the thickness of ferromagnet. Here, we do not consider the conventional spin-transfer torque and field-like SOT for simplicity. We consider one-dimensional nanowire of 2000 nm × 100 nm × 2 nm (unit cell size = 2 nm × 100 nm × 2 nm) and the parameters used in the calculation are as follows: the exchange stiffness constant $A = 1 \times 10^{-6}$ erg/cm, the perpendicular anisotropy constant $K = 1 \times 10^7$ erg/cm^3, $\alpha = 0.1$, $\theta_{SH} = 0.3$, and $M_S = 1000$ emu/cm^3. As shown in Fig. 1(b), a domain wall is initially positioned in the region I ($D = D_1$) and is driven to the right [i.e., toward the region II ($D = D_2$)] by an external field or SOT. The DMI step is located at $x = 1000$ nm. The exact initial positions of domain wall in the region I are set 100 nm–350 nm distant from DM step and are denoted in the figure legends.

3. Result and discussion

In Fig. 2, we show field-driven domain wall motion across a DMI step. The combination of D_1 and D_2 can be classified into 4 cases: (i) $D_1D_2 \geq 0$ & $D_1 < D_2$, (ii) $D_1D_2 \geq 0$ & $D_1 > D_2$, (iii) $D_1D_2 < 0$ & $|D_1| = |D_2|$, and (iv) $D_1D_2 < 0$ & $|D_1| \neq |D_2|$. The time evolution of domain wall position is shown in Fig. 2(a)–(c) for the cases (i) - (iii). Domain wall motion for the case (iv) can be estimated based on cases (i) to (iii) which is described in detail below and it is not shown here. First, for case (i) shown in Fig. 2(a), where $D_1 = 0$ and $D_2 = 1$ erg/cm^2, a domain wall starts to move from region I to region II. In the region I, because the Walker breakdown field is about 52 Oe at $D = 0$ [$H_{WB} = |\alpha \sin\phi\,(H_d \cos\phi + (\pi/4\lambda)H_{DM})|_{max}$, where $\phi \equiv$ domain wall angle], the domain wall moves linearly with H_{ext} below the H_{WB} ($H_{ext} = 30$ Oe) and moves back and forth above the H_{WB} ($H_{ext} = 60$ and 90 Oe). In this case, the domain wall smoothly passes through DMI step at all external fields. This is because the domain wall energy (E_{DW}) in the region I ($D_1 = 0$) is higher than that in the region II ($D_2 = 1$ erg/cm^2) as shown in Fig. 2(d), where the energy difference is given in the unit of k_BT ($T = 300$ K). This energy step can be described from the equation of the domain wall energy density written in,

$$\sigma_{DW} = 4\sqrt{AK} - \pi|D|, \quad (4)$$

where $E_{DW} = \sigma_{DW} \times$ (cross-section area of ferromagnet) [51]. The difference of domain wall energy density is $\pi|\Delta D|$ where ΔD is the difference of DMI constants between two regions. One finds that, from this equation, the domain wall energy density at $D = 0$ is higher than that at $D = 1$ erg/cm^2. In the region II, a domain wall moves linearly with H_{ext} for all external fields because Walker field is about 395 Oe for $D = 1$ erg/cm^2.

For cases (ii) and (iii) shown in Fig. 2(b) and (c), respectively, domain wall is blocked at a DMI step at low external fields ($H_{ext} = 200$, 600 Oe) whereas it passes through a DMI step at a high field ($H_{ext} = 900$ Oe). This is caused by the energy step or barrier formed at DMI step as shown in Fig. 2(e) and (f), respectively. For case (ii), it shows the energy step due to the higher energy in the region II ($D_2 = 0$). On the other hand, for case (iii), the domain wall energy is the same for two regions ($|D_1| = |D_2| = 1$ erg/cm^2) but the energy barrier is formed at the DMI step. At the center of DMI step, because the average value of D_1 and D_2 is 0, the corresponding domain wall energy is higher than those of region I and region II. Thus, the height of the energy barrier is related to the absolute value of $|D_1|$ ($= |D_2|$). This energy barrier is related to the force rotating domain wall angle between two regions because the opposite sign of DMI constant induces opposite magnetic chirality.

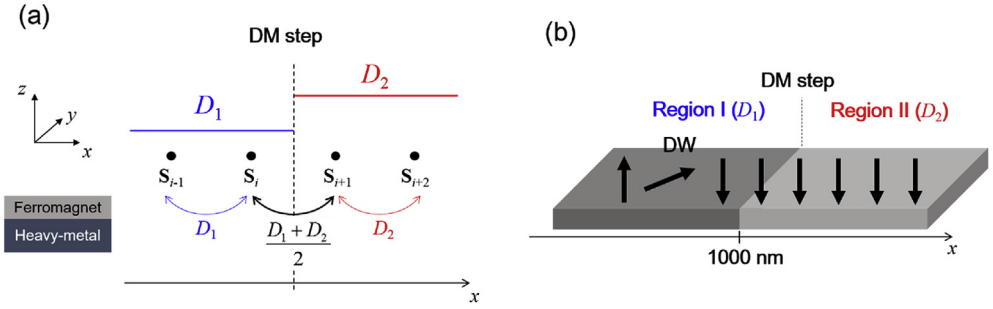

Fig. 1. (a) A schematic illustration of one-dimensional chain of atomic spins in ferromagnetic layer where DMI constant abruptly changes from D_1 to D_2 between $\mathbf{S}_i$ and $\mathbf{S}_{i+1}$, which is called DMI step. DMI constant between $\mathbf{S}_i$ and $\mathbf{S}_{i+1}$ is given as the average value of D_1 and D_2. (b) A nanowire used in our calculation. A domain wall is initially positioned in the region I (D_1) and the DMI step is located at $x = 1000$ nm.