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Fast current-induced motion of a transverse domain wall induced by interfacial Dzyaloshinskii–Moriya interaction

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ABSTRACT

Based on a theoretical study, we show that the interfacial Dzyaloshinskii–Moriya interaction results in very efficient current-induced manipulation of a transverse domain wall in magnetic nanowires. The efficient domain wall motion is caused by combined effects of the domain wall distortion induced by the interfacial Dzyaloshinskii–Moriya interaction and the damping-like spin–orbit spin transfer torque. We find that with reasonable parameters, the domain wall velocity reaches a few hundreds m/s at the current density of 10^7 A/cm^2, which has never been achieved before. Our result will be beneficial for low-power operation of domain wall devices.

1. Introduction

Recently, ferromagnet/heavy metal bilayers attract considerable attention because they allow us to investigate various spin–orbit coupling effects combined with spin transport and magnetization dynamics. The intriguing spin–orbit coupling effects are caused by the fact that the system has both spin–orbit and exchange interactions in the presence of the inversion symmetry breaking at the interface of ferromagnet/heavy metal. A representative example is the so-called spin–orbit spin transfer torque (SOT) [1–6] that enables very fast current-induced magnetization switching even without the second ferromagnetic layer [7–10]. The dominant mechanism responsible for SOT is under debate [11–19], i.e., bulk spin Hall effect in heavy metal layer or interface spin–orbit coupling effect at the interface of ferromagnet/heavy metal.

Another interesting magnetic property, Dzyaloshinskii–Moriya interaction (DMI), emerges when all of spin–orbit coupling, exchange interaction, and inversion asymmetry are present. The DMI is the antisymmetric component of the exchange interaction [20,21], which favors non-collinear magnetic textures. The bulk DMI in centrosymmetry-broken B20 structures has been extensively studied [22–25]. Recently, the interfacial DMI present at the ferromagnet/heavy metal interface attracts considerable interest [26–32]. The interfacial DMI assists an efficient control of magnetic domain walls [29–32] and modifies spin wave properties significantly [33,34]. Measurements of the interfacial DMI based on anisotropic domain wall expansion [35] and the wavevector-dependent shift of spin wave frequency [36] show that it occurs in principle at all magnetic interfaces and is particularly strong at the ferromagnet/heavy metal interface, i.e., the magnitude of interfacial DMI ~ 0.5 erg/cm^2.

Effects of the interfacial DMI on the domain wall motion in perpendicularly magnetized nanowires have been extensively studied [29–32]. Recently, Kravchuk [37] reported a theoretical study on the effect of the bulk DMI on transverse domain wall motion in nanowires with in-plane magnetization. However, the effect of the interfacial DMI on transverse domain wall motion has not been studied yet. In this work, we investigate the effect of the interfacial DMI on static and dynamic properties of a transverse domain wall. We find that the equilibrium domain wall profile deviates from both Walker profile and one distorted by the bulk DMI [37]. As we show below, this interfacial DMI-induced distortion of a transverse domain wall enhances current-induced domain wall velocity significantly.

2. Equilibrium profile of a transverse domain wall

Fig. 1 shows schematics of the model system where W and t_F are

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the width and thickness of nanowire, respectively ($W \gg t_F$). With the unit vector along the magnetization $\widehat{\mathbf{m}} = (\cos\theta,\ \cos\varphi\sin\theta,\ \sin\varphi\sin\theta)$ where θ is the polar angle from x-axis and φ is the azimuthal angle from y-axis, the reduced energy ε is given as

$$\varepsilon = E/K_d = \kappa\left(\theta'^2 + \sin^2\theta\varphi'^2\right) + \left(\kappa + \sin^2\varphi\right)\sin^2\theta + \chi(\sin\varphi\theta' + \cos\theta\sin\theta\cos\varphi\varphi'), \quad (1)$$

where E is the energy, K_d is the hard-axis anisotropy, $\kappa = K/K_d$, K is the easy-axis anisotropy, $\chi = \delta/\lambda$, $\lambda = \sqrt{A/K}$ is the domain wall width, $\delta = D/K_d$, A is the exchange stiffness constant, D is the interfacial DMI energy, $O' = dO/d\xi$, and $\xi = x/\lambda$. Based on the Euler–Lagrange equation, the equilibrium profile of a transverse domain wall is determined by following coupled differential equations:

$$-\sin 2\theta\left(\kappa + \sin^2\varphi\right) + 2\chi\cos\varphi\sin^2\theta\varphi' - \kappa\sin 2\theta\varphi'^2 + 2\kappa\theta'' = 0, \quad (2)$$

$$\sin\theta\theta'(\chi\cos\varphi\sin\theta - 2\kappa\cos\theta\varphi') + \sin^2\theta(\cos\varphi\sin\varphi - \kappa\varphi'') = 0. \quad (3)$$

For $D = 0$, one finds that the solution of Eqs. (2) and (3) with the boundary condition of $\theta(x = -\infty) = 0$ and $\theta(x = \infty) = \pi$ is the Walker profile [38], i.e., $\theta(x) = 2\tan^{-1}(e^{x/\lambda})$ and $\varphi(x) = 0$. For nonzero D, we solve Eqs. (2) and (3) perturbatively assuming $\kappa \ll 1$ and $\chi \ll 1$. These assumptions are usually valid for nanowires with in-plane magnetization. For instance, typical values of A, K, K_d, and D are ~10^{-6} erg/cm, ~10^5 erg/cm^3, ~10^7 erg/cm^3, and ~0.5 erg/cm^2, respectively, which give κ ~0.01 and χ ~0.016. The resultant $\theta(x)$ and $\varphi(x)$ are given by

$$\theta(x) \equiv 2\tan^{-1}\left(\exp\frac{x-q}{\lambda}\right), \quad (4)$$

$$\varphi(x) \equiv \varphi_0 - \chi\,\mathrm{sec}\,h\frac{(x-q)}{\lambda}, \quad (5)$$

where q is the domain wall center position and φ_0 is the domain wall tilt angle. In comparison to the case of $D = 0$ (i.e., $\chi = 0$), therefore, $\varphi(x)$ becomes spatial-dependent whereas $\theta(x)$ does not change with D within the perturbative approach. We note that $\varphi(x)$ for the interfacial DMI is different from $\varphi(x)$ for the bulk DMI [37] because of the different symmetry. We also note that this interfacial DMI-induced domain wall distortion appears only for a transverse domain wall, not for a perpendicular domain wall, because of the symmetry. Fig. 2 shows the equilibrium profile of $\varphi(x)$ for various values of D. One can find that the domain wall distortion appears in cases with non-zero D and numerically calculated ones (symbols) are in good agreement with the theoretically predicted ones (lines).

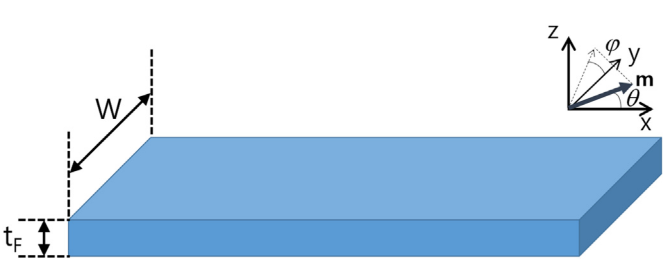

Fig. 1. Schematic coordinate system.

3. Domain wall dynamics

The domain wall dynamics in the presence of an in-plane current is described by the Landau–Lifshitz–Gilbert equation including SOT, adiabatic spin transfer torque, and non-adiabatic spin transfer torque, given as

$$\frac{\partial\mathbf{m}}{\partial t} = -\gamma\mathbf{m}\times\mathbf{H}_{eff} + \alpha\mathbf{m}\times\frac{\partial\mathbf{m}}{\partial t} + b_J\frac{\partial\mathbf{m}}{\partial x} - \beta b_J\left(\mathbf{m}\times\frac{\partial\mathbf{m}}{\partial x}\right) + \gamma c_J\mathbf{m}\times(\mathbf{m}\times\mathbf{y}), \quad (6)$$

where γ is the gyromagnetic ratio, $\mathbf{H}_{eff}$ is the effective magnetic fields including the exchange, the magnetostatic, the magnetocrystalline anisotropy, and the DMI fields, α is the damping constant, b_J is the spin current velocity, β is the non-adiabaticity, and c_J describes the magnitude of damping-like SOT (we neglect field-like SOT for simplicity). We note that at the current density of 10^8 A/cm^2, typical magnitudes of b_J and c_J are about 50 m/s for the spin polarization of 0.7 [39] and 500 Oe for the spin Hall angle of 0.33 [40] and t_F of 2 nm, respectively.

By using Eqs. (3) and (4), and the procedure developed by Thiele [41], we derive the equations of motion for the two collective coordinates (q, the domain wall center position and φ, the domain wall tilt angle) of a transverse domain wall in the rigid wall approximation where the domain wall width λ does not vary during the domain wall motion. This rigid domain wall approximation is valid for our study because the domain wall width varies with φ but the out-of-plane demagnetization effect is strong enough to make φ small.

$$\alpha\frac{\dot{q}}{\lambda} + \dot{\phi}_0 = -\beta\frac{b_J}{\lambda} + \gamma c_J\left(\frac{\pi}{2}\sin\phi_0 - \frac{4}{3}\chi\cos\phi_0\right), \quad (7)$$

$$\frac{\dot{q}}{\lambda} - \alpha\dot{\phi}_0 = -\frac{b_J}{\lambda} + \gamma\frac{D}{\lambda M_S}\left(\frac{\pi}{2}\cos\phi_0 + \frac{4}{3}\chi\sin\phi_0\right) + \gamma\frac{K_d}{M_S}\left(\sin 2\phi_0 - \frac{\pi}{2}\chi\cos 2\phi_0\right), \quad (8)$$

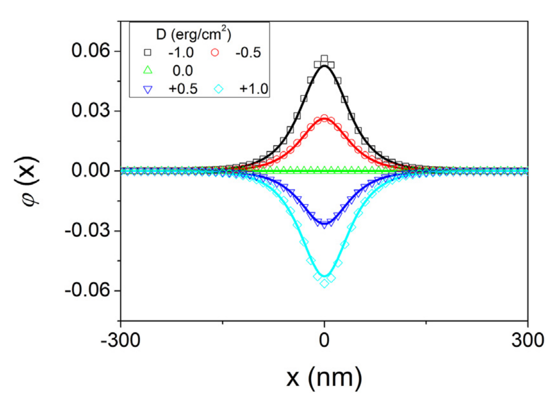

Fig. 2. Equilibrium profile of the z-component of the magnetization ($= \sin(\varphi(x))$) where $\varphi_0 = 0$, $K_d = 6\times10^6$ erg/cm^3, $K = 10^5$ erg/cm^3, and $A = 10^{-6}$ erg/cm (lines = Eq. (5) and symbols = simulation results).