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

Seo-Won Lee[1*], Byong-Guk Park[2] and Kyung-Jin Lee[1,3]
[1]Department of Materials & Engineering, Korea University, Seoul 136-713, Korea
[2]Materials Science and Engineering and KI for Nanocentury, KAIST, Daejeon 305-701, Korea
[2]KU-KIST Graduate School of Converging Science and Technology, Korea University, Seoul 136-713, Korea

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. A representative example is the spin-orbit spin transfer torque (SOT) [1] that enables very fast current-induced magnetization switching even without the second ferromagnetic layer [2]. Another interesting magnetic property is the Dzyaloshinskii-Moriya interaction (DMI), emerging when all of spin-orbit coupling, exchange interaction, and inversion asymmetry are present. The DMI is the antisymmetric component of the exchange interaction [3,4], which favors non-collinear magnetic textures. Effects of the interfacial DMI on the domain wall motion in perpendicularly magnetized nanowires have been extensively studied [5]. 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.

Based on the Euler-Lagrange equation, the equilibrium profile of a transverse domain wall is determined as,

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

$$\varphi(x) \equiv \varphi_0 - \chi \sec h\frac{(x-q)}{\lambda}, \tag{2}$$

where $\hat{\mathbf{m}} = (\cos\theta, \cos\varphi\sin\theta, \sin\varphi\sin\theta)$, θ is the polar angle from x-axis and φ is the azimuthal angle from y-axis, q is the domain wall center, φ_0 is the domain wall tilt angle, λ is the domain wall width, $\chi = \delta/\lambda$, $\delta = D/K_d$, and K_d is the hard-axis anisotropy energy density. From above equations, one can find that the domain wall distortion appears in cases with finite D. We found that the numerically calculated ones are in good agreement with the theoretically predicted ones.

By using the procedure developed by Thiele [6], we derive the equations of motion for the two collective coordinates of a transverse domain wall as following.

$$\alpha\frac{\dot{q}}{\lambda} + \dot{\varphi}_0 = -\beta\frac{b_J}{\lambda} + \gamma c_J\left(\frac{\pi}{2}\sin\varphi_0 - \frac{4}{3}\chi\cos\varphi_0\right), \tag{3}$$

$$\frac{\dot{q}}{\lambda} - \alpha\dot{\varphi}_0 = -\frac{b_J}{\lambda} + \gamma\frac{D}{\lambda M_S}\left(\frac{\pi}{2}\cos\varphi_0 + \frac{4}{3}\chi\sin\varphi_0\right) + \gamma\frac{K_d}{M_S}\left(\sin 2\varphi_0 - \frac{\pi}{2}\chi\cos 2\varphi_0\right), \tag{4}$$

where $\dot{O} = dO/dt$, γ is the gyromagnetic ratio, α is the damping constant, β is the nonadiabaticity, b_J is the magnitude of spin-transfer torque, c_J is the magnitude of SOT and M_S is the saturation magnetization. Using the small angle approximation, we obtain the domain wall velocity v_{DW} at the steady state, given as

$$v_{DW} = \frac{-b_J(\pi c_J - 2\beta H_d) + (8/3)\gamma\chi\lambda c_J H_d}{\pi c_J - 2\alpha H_d}, \tag{5}$$

where $H_d = 2K_d/M_S$.

We perform semi two-dimensional micromagnetic simulation for confirming a validity of Eq. (5). As shown in the figure 1, when $D = 0$, v_{DW} is small, but it increases rapidly with D. With reasonable material parameters, the v_{DW} reaches 400 m/s at the current density of 9×10^6 A/cm^2 which has never been achieved for a transverse domain wall without DMI [7]. This high v_{DW} can be explained by a DMI-induced domain wall distortion. It generates non-zero SOT in the z-direction, which tilts the domain wall and enhances the domain wall motion.

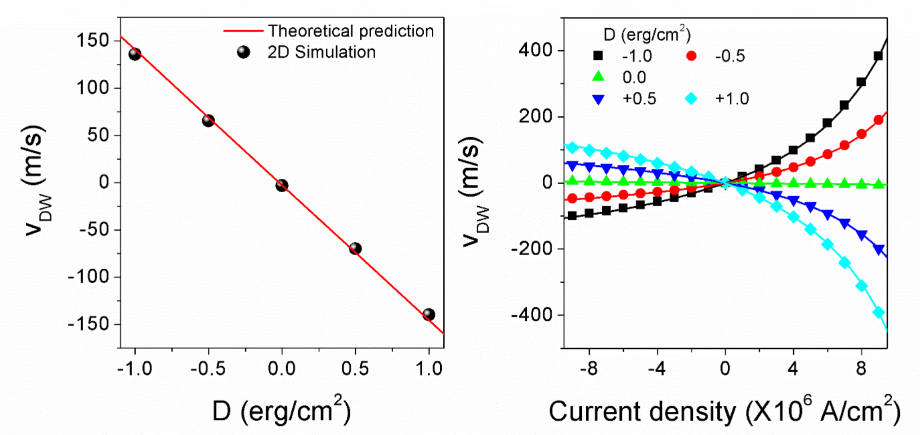

Fig. 1. (a) Effect of the interfacial DMI (D) on the domain wall velocity for 1-D micromagnetic simulation results (dots) and theoretical prediction (line). (b) v_{DW} as a function of the current density at various DMI values.

References

[1] K. Obata, and G. Tatara, Phys. Rev. B 77, 214429 (2008).
[2] I. M. Miron et al., Nature (London) 476, 189 (2011).
[3] I. E. Dzialoshinskii, Sov. Phys. JETP 5, 1259 (1957).
[4] T. Moriya, Phys. Rev. 120, 91 (1960).
[5] S. Emori, U. Bauer, S.-M. Ahn, E. Martinez, and G. S. D. Beach, Nat. Mater. 12, 611 (2013).
[6] A. A. Thiele, Phys. Rev. Lett. 30, 230 (1973).
[7] M. Hayashi et al., Phys. Rev. Lett. 96, 197207 (2006).