Influence of Depinning Environment on Critical Depinning Current Density for Current-induced Domain Wall Motion

Soo-Man Seo*, Hyun-Woo Lee[1], Woojin Kim[2], Taek-Dong Lee[2], Dong-Hyun Kim[3], Sug-Bong Choe[4] and Kyung-Jin Lee

Department of Materials Science and Engineering, Korea University

[1]Department of Physics, Pohang University of Science and Technology

[2]Department of Materials Science and Engineering, KAIST

[3]Department of Physics and Institute for Basic Research, Chungbuk National University

[4]Department of Physics and Astronomy, Seoul National University

*kj_lee@korea.ac.kr

Current-induced domain wall motion (CIDWM) has attracted a considerable interest because of its fundamental physics and potential for the application of storage [1] and logic devices [2]. The adiabatic and non-adiabatic spin torque terms have been proposed to describe the CIDWM. Despite lots of studies, there is a controversy over the so-called β term which measures the relative magnitude of the non-adiabatic torque with respect to the adiabatic torque [3]. From the viewpoint of application, equi-spaced mechanical notches can be used to precisely control the position of DW in a nanostrip. Therefore, it is important to investigate the depinning current density of DW from a notch.

In this work, we investigate the depinning current density in CIDWM and its dependence on the β term by means of micromagnetic modeling and theory of the collective coordinate approach. According to the initial position of the DW, we consider two kinds environments of the DW depinning. One is "static" depinning case, which the DW is initially placed at a notch, and the other is "dynamics" depinning case, which the DW is initially placed far from a notch. By comparing the J_{St} and J_{Dy}, it is possible to get a clue for resolving the controversy over the β term.

In order to perform the modeling study, we use the modified Landau-Lifshitz-Gilbert equation taking into account the spin torque terms (Eq. (1));

$$\frac{\partial \mathbf{M}}{\partial t} = -\gamma \mathbf{M}\times\mathbf{H}_{eff} + \frac{\alpha}{M_s}\mathbf{M}\times\frac{\partial \mathbf{M}}{\partial t} - \frac{b_J}{M_s^2}\mathbf{M}\times(\mathbf{M}\times\nabla\mathbf{M}) - \frac{c_J}{M_s}(\mathbf{M}\times\nabla\mathbf{M}), \tag{1}$$

where $\mathbf{H}_{\mathrm{eff}}$ is the effective magnetic field consisting of the anisotropy, exchange, magnetostatic, and current-induced Oersted fields. The model parameter is selected for the Permalloy widely used for CIDWM experiments. The $b_J(=Pj_e\mu_B/eM_s)$ and $c_J(=\beta\cdot b_J)$ present the magnitude of the adiabatic and non-adiabatic spin torque, respectively. In homogeneous current distribution due to a presence of the notch in the nanostrip is calculated by solving the Laplace’s equation. The model system is shown in Fig. 1(a). The dimension of nanostrip is 1000 × 75 × 10 (length(l) × width(w) × thickness(t)) nm3 divided into 2.5 × 2.5 × 10 nm^3 cells. The shape of a notch is a triangle. The width(d) of nanostrip at the center of notch is 50nm. According to the winding direction of the DW, the clockwise transverse wall (CW-TW) and anti-clockwise transverse wall (ACW-TW) are considered. As shown in Fig. 1(b), the total energy of the system as a function of the DW position, is different for CW-TW and ACW-TW. The distinction length (d_2) indicates a distance between initial position of the DW and the notch. The "dyancmis" and "static" cases correspond to d_2 = 200nm and d_2 = 0, respectively.

Fig. 1(c) and (d) show the critical depinning current density (J_{CD}) as a function of the contribution of the non-adiabatic spin torque (denoted as β/α), where J_{St} and J_{Dy} correspond to J_{CD} of "static" and "dyanamic" cases, respectively. For the case of ACW-TW (CW-TW), J_{St} and J_{Dy} slightly increase for β=0~2α(4α), but their difference is small. For β≥4α (β≥6α) of ACW-TW (CW-TW), J_{St} and J_{Dy} are discriminative. On the other hands, in these particular ranges of the β, moving TW under the “Dynamic environment” gains an additional kinetic energy before reaching the notch. To quantitatively estimate the difference between J_{Dy} to J_{St} with respect to β terms, we calculate the ratio between J_{Dy} and J_{St}, being Δ(%) = (J_{St}-J_{Dy})/J_{St}×100. In inset of Fig. 1(c) and (d), we show that Δ(%) increases as increasing β. Of particular, we find that Δ(%) is dramatically changed at β = 4α(6α) for the ACW-TW (CW-TW), respectively, and its increase is up to 40%. We observed that for the case of ACW-TW, J_{St} depends on the sign of the current. For β>0, (+)J_{St} is larger than (－)J_{St}, and their difference is about 10%. Note that energylandscape of ACW-TW shows double minima within the potential well (Fig. 1(b)). In our model, we initially placed ACW-TW at the left minima of the potential well. As a result, for je<0, the minor barrier plays a role of reducing the total energy barrier. At the abrupt changing point of β>2α for ACW-TW, the ratio of (+)J_{St} and (－)J_{St} increases up to 30%. By contrast, the CW-TW has a single potential well, so that CW-TW is initially placed at the center of the notch. Therefore, we observed that J_{St} is independent to the sign of the current.

The critical depinning current density depends on the chirality and initial position of DW. By comparing the J_{St} and J_{Dy}, it is possible to get a clue about the non-adiabatic contribution.

Reference

[1] S. S. P. Parkin, U.S. Patent No. 6,834,005 (2004).

[2] D. A. Allwood et al, Science **309**,1688(2005).

[3] G. Tatara and H. Kohno, Phys. Rev. Lett. 92, 086601 (2004); S. E. Barnes et al, Phys. Rev. Lett. 95, 107204 (2005); Y. Tserkovnyak et al, Phys. Rev. B 74, 144405 (2006).

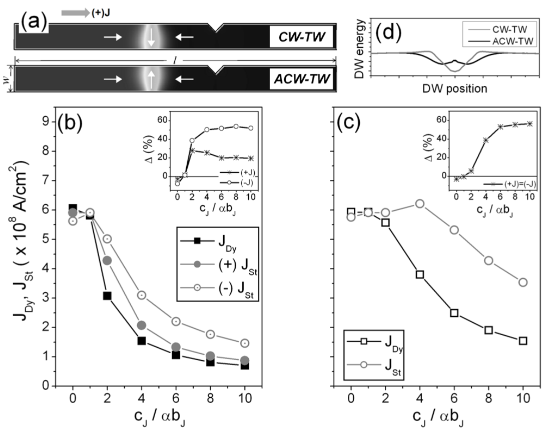

Fig. 1. (a) depicts geometry of the nanostrip and initial equilibrium state of the DW. (b) and (c) show the critical depinning current density as a function of a value of βterms, correspond to the ACW-TW and CW-TW, respectively. Inset of (b) and (c) show Δ(%) defined as Δ(%)=(J_{St}-J_{Dy})/J_{St}×100. (d) shows DW energy landscape of which is plotted as DW energy versus position of the DW.