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Kinetic and Static Domain-Wall Pinning at Notches on Ferromagnetic Nanowires

Sung-Min Ahn[1], Dong-Hyun Kim[2], and Sug-Bong Choe[1]

[1]Center for Subwavelength Optics and School of Physics and Astronomy, Seoul National University,
Seoul 151-742, Republic of Korea
[2]Department of Physics and Institute for Basic Research, Chungbuk National University, Cheongju 361-763, South Korea

We investigate the domain wall (DW) pinning and depinning processes at notches of ferromagnetic nanowires by means of micromagnetic calculation. Two distinct pinning mechanisms are examined—the kinetic pinning for a moving DW to be trapped at a notch and the static depinning for a trapped DW to move from the notch. Interestingly, the kinetic pinning field is revealed to be noticeably smaller than the static depinning field. The DW energy landscapes around the notch visualize that the kinetic DW motion bypasses the lowest energy state, from which the static depinning field is determined. This phenomenon is basically equivalent to the kinetic and static friction processes in classical mechanics.

***Index Terms*—Ferromagnetic nanowire, domain wall, notch, pinning, Permalloy.**

I. INTRODUCTION

RECENTLY, several novel architectures based on ferromagnetic nanowires have been proposed for promising applications with DW motion to magnetic memory and logic devices [1], [2]. For implementing these DW-mediated devices, it is essential to control the DW position and structure. Artificial geometric constraints have been proposed to control the DW position [3], [4] and propagation direction [5], [6] in nanowires by changing the local energy landscape and the pinning force. There have been a number of studies about DW pinning with artificial constrictions [7]–[11]. Most of the studies have focused on the depinning process for trapped DWs to move from notches. However, as an opposite case, the pinning process for moving DWs to be trapped at the notches states is not well understood yet. In this study, we investigate the pinning mechanism of initially moving DWs, called as the kinetic pinning, in comparison with the static depinning mechanism from initially pinned states. The kinetic and static pinning processes exhibit distinct pinning strength, as an analogous to the kinetic and static friction in classical mechanics.

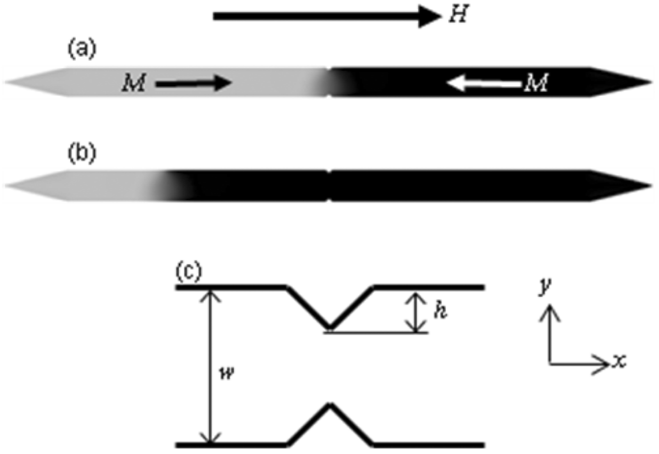

Fig. 1. Nanowire structure and the initial magnetization states for (a) static and (b) kinetic depinning processes. The arrows indicate the planar direction of the magnetization and magnetic field, respectively. The grey contrast corresponds to the +x component of the magnetization. The detailed notch structure is sketched in (c).

II. MICROMAGNETIC CALCULATION

For this study, nanowire structures with symmetric double notches are designed for micromagnetic calculation. The symmetric double notches are known to exhibit a unique static depinning field irrespective to the DW polarity and propagation direction [12], unlikely to the single or asymmetric notches with several distinct depinning strengths [13]–[15]. The nanowire length is 20 times the wire width as shown in Figs. 1(a)–(b). The double notches with the depth h are placed at the center of the wire in the form of the right-angle equilateral triangle as shown in Fig. 1(c). The magnetic field from the wire ends is artificially removed by preliminary calculation of the magnetostatic field at the saturated state. Soft-magnetic Permalloy is chosen for the nanowire material, which has been popularly used in these experiments [8]–[20]. The saturation magnetization M_S was given by 8.6×10^5 A/m and the exchange stiffness A_X was given by 1.3×10^{-11} J/m.

Two different initial conditions are adopted for the static and kinetic pinning processes, respectively. For the static case, a static DW is initially located at the notch as illustrated in Fig. 1(a). On the contrary, the kinetic case has the initial state that a DW at the left side of the notch moves toward the notch under an external magnetic field as shown in Fig. 1(b). The arrows in the figure indicate the direction of magnetization and magnetic field, respectively. The transverse DW [21] rather than the vortex DW is considered, since the former appears in thinner and narrower nanowires for the practical device application [22]. The micromagnetic calculation is performed by OOMMF [23].

For the given initial conditions, an external magnetic field H along +x direction is applied with increment of 0.1 mT. The

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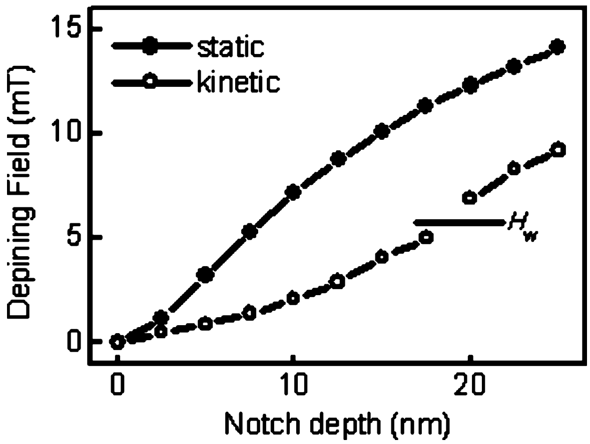

Fig. 2. The static and kinetic depinning fields with respect to the notch depth. The Walker breakdown field is indicated by H_W.

final DW state either pinned or depinned is checked after attaining the equilibrium state for each magnetic field. The internal maximum torque less than $2 \times 10^{-4}\mathrm{M}_S^2$ is employed as the criterion of the equilibrium. We denote the static and kinetic depinning fields as the minimum field for depinning (or passing) over the notch. Both the depinning fields are obtained with varying the notch depth for 100-nm-wide and 5-nm-thick nanowires. The Gilbert damping parameter is set to 0.02. The cell size is chosen to be 2.5 nm, sufficiently smaller than the exchange length (~5.3 nm).

III. RESULTS AND DISCUSSION

The static and kinetic depinning fields are revealed to be noticeably different with each other. Fig. 2 shows the depinning fields with respect to the notch depth. The solid circles show the static depinning field and the open circles show the kinetic depinning field. Both the depinning fields increase with increasing the notch depth. It is ascribed to the finite size effect of the notch in comparison with the DW width [12], followed by the saturation to a value for sufficiently large notches. However, it is interesting to note that the kinetic depinning field is much smaller than the static depinning field. The kinetic depinning field is less than one third of the static depinning field for small notches. A kink is observed in the kinetic depinning field, which is ascribed to the Walker breakdown. For a magnetic field larger than the Walker breakdown field, the DW structure is periodically transformed between the transverse and vortex wall, followed by a reduction of the DW speed due to the additional energy consumption for DW transformation [24]. The Walker breakdown thus induces a kink of the kinetic depinning field for large notches. This phenomenon depends on moving domain wall structures [25].

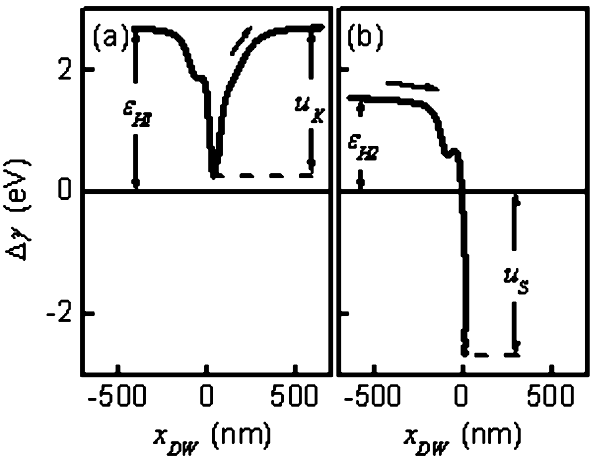

Fig. 3. The DW energy landscape with respect to the DW position, under an external magnetic field (a) 0.3 mT and (b) 0.1 mT for a 2.5-nm-deep notch. ε_{H1} and ε_{H2} indicate the kinetic DW energy excited by the external magnetic field, respectively. The kinetic and static pinning strengths are denoted by u_K and u_S, respectively.

To understand the origin of the difference between the two depinning mechanisms, the DW energy landscapes around the notches are examined. Fig. 3 illustrates the DW energy landscape with respect to the DW position x_{DW} from a notch that creates an attractive pinning potential well [26]. The DW position is calculated by $x_{\mathrm{DW}} = \int_V x|M_Y(\vec{r})|d\vec{r}/M_S$, within a presumption of a delta-function-like profile of M_Y around the DW. The integration is performed over the wire volume V. The ordinate axis is scaled with $\Delta\gamma$, which is the energy difference $\gamma_H - \gamma_0$ between the kinetic DW energy γ_H under an external field H and the static DW energy γ_0 under zero field bias. In the plot, we show the DW energy difference for (a) 0.3 mT and (b) 0.1 mT, for a 2.5-nm-deep notch. For the former case under 0.3-mT field bias, the DW initially comes from the left side with an excited DW energy ε_{H1}. Approaching to the notch the DW energy is reduced due to the interaction with the notch. The maximum energy drop denoted by u_K corresponds to the kinetic pinning strength of the notch. The DW finally passes over the notch because $\varepsilon_{H1} > u_K$. On the other hand, the latter case with 0.1 mT meets the condition $\varepsilon_{H2} < u_K$ and thus, the DW has to be trapped at the notch. Once the DW is trapped, the energy is further dissipated in time to finally reach the lowest energy u_S. Note that u_S corresponds to the static pinning strength i.e., the ground energy of the pinned DW at the notch, which is consequently related with the strength of the static depinning field. Therefore, one can conclude that the kinetic and static depinning fields are individually governed by completely different physical parameters, u_K and u_S, respectively, even for the same notch.

It is worthwhile to note that the lowest energy state can be attained only after energy dissipation with time and thus, the kinetic DW has no chance to experience the lowest energy state but experiences an incomplete and smaller pinning strength. It explains the reason why the kinetic depinning field is smaller than the static depinning field. It is equivalent to the distinction between the static and kinetic friction processes in classical mechanics.

IV. CONCLUSION

Two distinct depinning processes, either static or kinetic, are investigated. The kinetic depinning field is revealed to be noticeably smaller than the static depinning field. By examining the energy landscape around the notches, the kinetic depinning process has a smaller pinning strength than the static depinning process, due to the kinetic bypassing over the lowest energy state.

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