Depinning Field at Notches of Ferromagnetic Nanowires With Perpendicular Magnetic Anisotropy

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In this paper, we experimentally characterize the domain-wall depinning mechanism at notches of ferromagnetic nanowires with perpendicular magnetic anisotropy. A time-resolved magneto–optical Kerr effect detection reveals that the depinning time is exponentially proportional to the strength of external magnetic field. From an analysis based on Néel–Brown theory, the depinning field and the activation volume are quantitatively determined for several notches with different gap distances. Interestingly, both the depinning field and the activation volume are proportional to the inverse of the gap distance. This is explained by the sizeable extrinsic effect from geometric constrictions in contrast to the intrinsic properties of the films.

***Index Terms*—Activation volume, depinning field, gap distance, notch, perpendicular magnetic anisotropy.**

I. Introduction

CONTROLLABILITY of domain walls in ferromagnetic nanowires has triggered various prospective applications of the next generation of memory and logic devices [1], [2]. In these devices, the data are stored in the form of magnetic domains which are divided by the domain walls. Thus, precise control of the domain walls in magnetic nanostructures is a key issue in all related applications. Geometric constrictions such as notches have been widely investigated for the precise control of domain-wall position. Up to now, most studies have focused on Permalloy nanowires with in-plane magnetic anisotropy [3]–[5]. Only recently, structures with perpendicular magnetic anisotropy (PMA) have drawn great attention due to their less stable domains induced at higher storage density [6]. In this paper, we present the experimental characterization of the depinning mechanism at the notches of PMA nanowires. The dependence of the depinning field on the notch geometry is analyzed in terms of extrinsic effects and compared to the intrinsic pinning field in continuous thin films.

II. Experimental Procedure and Results

For this study, SiO_2/Ta(5 nm)/Pt(2.5 nm)/$Co_{90}Fe_{10}$(0.3 nm)/Pt(1 nm) film was prepared by direct current (dc)-magnetron sputtering in ultrahigh vacuum environment. The film exhibits a squared hysteresis loop with a strong PMA as depicted in Fig. 1(a). The saturation magnetization M_S and the coercivity H_C are measured to be 1330 emu/cm^3 and 56 Oe, respectively, by use of an alternating gradient magnetometer (AGM). A conventional magneto–optical Kerr effect (MOKE) microscope visualizes a clear domain-wall motion in the film as shown by the inset of Fig. 1(a). The gray contrast corresponds to the different domain images taken after applying successive magnetic field pulses. The formation of the clear circular domains manifests the high quality of the film with less natural pinning sites. The nanowire structures with several different notches were then realized on the film by electron–beam lithography and ion milling. Fig. 1(b) shows the secondary electron microscopy (SEM) images for the notches with different gap distance, 1) 210, 2) 305, 3) 420, and 4) 500 nm on the 570-nm-wide nanowire. The opening angle of the notches was fixed to be 90° to avoid the possible effect from different angles. The magnetic properties of the patterned structure were confirmed to be almost unchanged from the film.

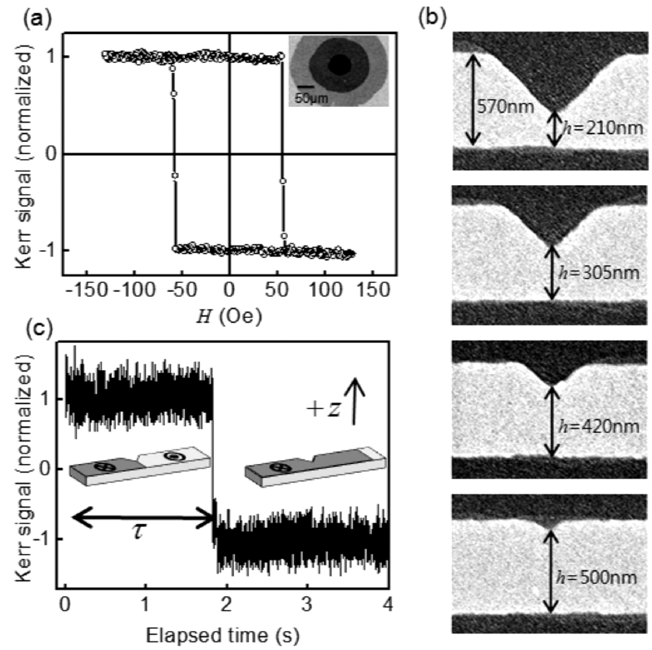

Fig. 1. (a) Out-of-plane hysteresis loop of the film. The inset shows the typical domain images. The gray contrast corresponds to the different domain images after applying successive magnetic pulses. (b) The secondary electron microscopy images of the notches with different gap distance as denoted in the figure. (c) MOKE signal detection during domain-wall depinning process. The depinning time is defined as an elapsed time between the application of the pulsed magnetic field and the MOKE signal drop.

The domain-wall depinning time was measured by scanning MOKE detection capable of 1-ms time resolution with 500-nm

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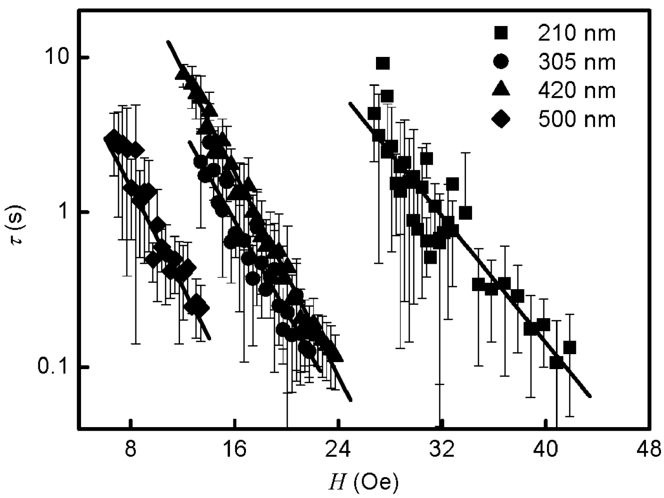

Fig. 2. Depinning time with respect to the strength of the magnetic field for several notches with different gap distances as denoted in the figure. Each data point is averaged by five measurements and the error bar indicates the standard deviation. The solid line shows the best fit with (1).

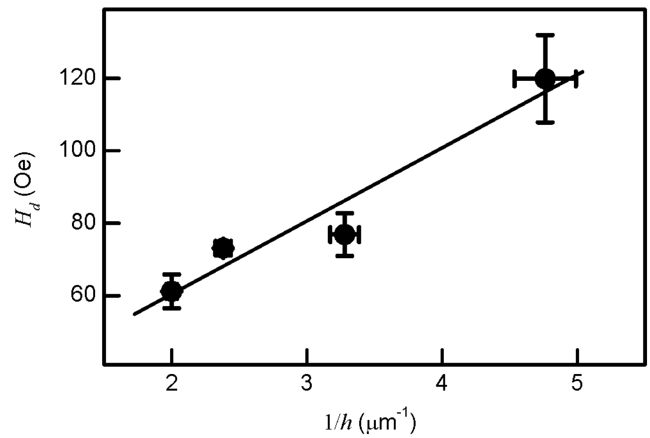

Fig. 3. Depinning field with respect to the inverse of gap distance. The solid lines exhibit the best linear fit to the data.

spot size [7]. The sample was first saturated to the $+z$-direction under a sufficiently high magnetic field, followed by domain-wall formation at notch by thermomagnetic writing under a small magnetic field in $-z$-direction. The domain-wall depinning time after applying magnetic field in $-z$-direction was then measured at a position, 2 μm away from notch. Fig. 1(c) depicts the typical MOKE signal measurement—an abrupt drop of the MOKE signal is detected when a domain wall passes through the laser spot [7]. The depinning time is measured by the time between the application of the external field pulse and the MOKE signal drop.

III. Theoretical Model and Discussion

The domain-wall depinning time is plotted in Fig. 2 for the notches with different gap distances as indicated in the figure. It is clear from the figure that the depinning time exhibits an exponential dependence with respect to the strength of the applied magnetic field H. This exponential dependence is characteristic to thermally activated magnetization processes and can be explained by the Néel–Brown formula as given by [8]–[10]

$$\tau(H) = \tau_0 \exp\left[\frac{M_S V_A}{k_B T}(H_d - H)\right] \tag{1}$$

where τ_0 is the inverse of the attempt frequency, V_A is the activation volume, $k_B T$ is the thermal fluctuation energy, and H_d is the depinning field at 0 K. From the best fit with this equation, one can determine the values of both the activation volume V_A and the depinning field H_d, by assuming $\tau_0 \sim 1$ ns and using the experimental values of M_S and T.

Fig. 3 shows the dependence of the depinning field H_d with respect to the inverse of the gap distance at the notches. The depinning field H_d is defined as the minimum field needed for domain-wall depinning at 0 K. However, the thermal fluctuations at finite temperature activate the domain-wall energy to enable depinning at a magnetic field lower than H_d. The depinning field H_d is thus determined by extrapolating the exponential dependence on the condition $\tau(H_d) = \tau_0$, at which the numerator in (1) vanishes irrespective of the temperature. It is seen in the figure that the depinning field H_d exhibits linear dependence on the inverse of the gap distance h. The $1/h$ dependence is ascribed to the extrinsic pinning effect in contrast to the intrinsic pinning effect. The intrinsic pinning is originated from the interaction with the grain boundaries and thus, assumed to be ubiquitous with a constant intrinsic pinning field $H_d^{\rm int}$ over the whole sample. On the other hand, the extrinsic pinning is governed by the geometric constriction, and thus, certainly dependent on the notch geometry.

The extrinsic pinning strength at notches has been predicted by an analytic theory based on the domain-wall energy and the Zeeman energy [11]. From the theory, the optimal domain-wall configuration is predicted to form a circular arc connecting between the notch and the nanowire boundary. The radius of the circular arc is determined by the counterbalance between the domain-wall energy and the Zeeman energy. The domain-wall energy prefers shorter domain-wall length whereas the Zeeman energy prefers longer domain-wall length for larger reversed area. The extrinsic depinning field $H_d^{\rm ext}$ is then given by $H_d^{\rm ext} = \sigma_W \sin\theta / \{2M_S(h + 1/2 l_W \sin\theta)\}$, where σ_W is the domain-wall energy density per unit area, θ is the angle of the notch slope, and l_W is the domain-wall width. The typical domain-wall width of the Bloch wall configuration is about a few tens of nanometers, which is far smaller than the gap distance h in our experiments. It can be thus simplified to $H_d^{\rm ext} \cong \sigma_W \sin\theta / 2hM_S$ within our measurement accuracy.

The depinning field is known to be the sum of the intrinsic depinning field and the extrinsic depinning field [6]. Therefore, the depinning field is finally written as

$$H_d = H_d^{\rm int} + \left(\frac{\sigma_W \sin\theta}{2M_S}\right)\frac{1}{h}. \tag{2}$$

Equation (2) explains the experimental $1/h$ dependence of the depinning field. From the best fit to Fig. 3, the intrinsic depinning field $H_d^{\rm int}$ is estimated to be about 20.0 Oe and the domain-wall energy density σ_W is estimated to be about 7.6 $\pm$ 1.4 mJ/m^3. The intrinsic depinning field is a little bit smaller than the previous results [12], which is possibly ascribed to less intrinsic defects or impurities in our film as evidenced by the

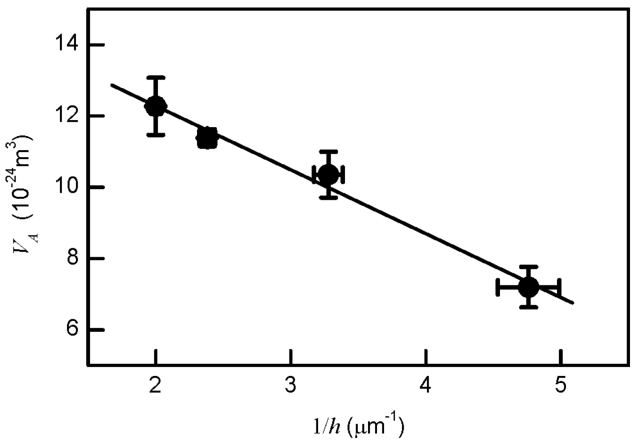

Fig. 4. Activation volume with respect to the inverse of gap distance. The solid lines exhibit the best linear fit to the data.

clear circular domain formation. The domain-wall energy density is within the range of the typical Bloch wall energy density.

Another intriguing governing parameter in thermal activation process is the activation volume. The activation volume V_A is the characteristic volume acting as a single domain particle as well as the minimum size of domains in the thermally activated regime of domain-wall propagation. There have been a number of studies to characterize the activation volume with respect to the film thickness, layer structure, reversal phase, and the strength of applied magnetic field [13], [14]. However, most of the studies so far have focused on continuous films, which are primarily related to the intrinsic depinning effect. Only a few studies have dealt with the geometric effect in nanostructures such as the self-assembled cylindrical Co nanowires [15]. Therefore, the extrinsic effect on the activation volume is not clear yet.

The activation volume in our experiment is revealed to be sensitive to the geometric constraints. Fig. 4 shows the activation volume with respect to the inverse of the gap distance. The activation volume decreases from (12.2 $\pm$ 0.8) $\times$ 10^{-24} m^3 to (7.2 $\pm$ 0.6) $\times$ 10^{-24} m^3 with reducing the gap distance from 500 to 210 nm. A linear dependence on the inverse of the gap distance demonstrates a direct influence of the geometric constraints. For quantitative comparison with the gap distance, we introduce the activation length d_A, defined as the effective diameter of the activation volume, i.e., $V_A = \pi d_A^2 t_f/4$, where t_f denotes the film thickness. The activation length is estimated to be about 170–230 nm, which is almost comparable to the gap distance. Therefore, it is natural to imagine that the partitioning of the activation volume near the narrow gap is inevitably influenced by the geometric constrictions.

IV. Conclusion

We investigated the thermally activated domain-wall depinning process at notches of ferromagnetic Pt/CoFe/Pt nanowire with perpendicular magnetic anisotropy. The depinning field is inversely proportional to the gap distance due to the extrinsic pinning effect from the notch geometry. The activation volume also exhibits an extrinsic effect from the notch, rather than a constant intrinsic volume.

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