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Domain reversal behavior in perpendicular magnetic nanothin films ☆

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Abstract

We report domain reversal behavior in perpendicular ferromagnetic nanothin films investigated by means of a novel magneto-optical microscope magnetometer, capable of grabbing domain reversal patterns in real time under an applied field as well as simultaneous measurements of 8000 local hysteresis loops with 400-nm special resolution. Three contrasting domain reversal behaviors are found to exist: wall-motion dominant, dendritic-growth dominant, and nucleation dominant reversal. Quantitative analysis reveals that the contrasting reversal behavior is mainly caused by a sensitive change in wall-motion speed and that the reversal ratio of wall-motion speed over nucleation rate is a governing parameter for the contrasting domain reversal dynamics. The activation volumes of the wall-motion and nucleation processes are found generally unequal, and the inequality is closely related with the domain dynamics. The domain reversal pattern is truly coincident with submicron-scale local coercivity variation and local switching time of domain evolution is exponentially dependent on local coercivity governed by a thermal activation relaxation process. The observed domain reversal behavior could be well predicted by a Monte Carlo simulation of a micromagnetic model based on the uniaxial magnetic anisotropy of nanothin films.

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Keywords: Domain dynamics; Activation volume; Local magnetic properties; Magnetic microscope; Co/Pd multilayer

1. Introduction

Domain reversal dynamics in ferromagnetic thin films continues to be a fundamental issue in magnetism, largely motivated by experimental observation of the contrasting magnetization reversal dynamics between wall-motion dominant and nucleation dominant processes exhibited in similar samples of many systems [1–7]. Interest has rapidly grown by the recent technological progress in high-density magnetic information storage and memory. Much effort has been devoted to investigate contrasting domain reversal dynamics in a number of systems and recently, understanding on domain configuration has been greatly progressed.

In this article, we have investigated the magnetization reversal dynamics of ferromagnetic Co/Pd multilayer films and the origin of its contrasting magnetization reversal behavior. Wall-motion speed and nucleation rate have been quantitatively determined based on time-resolved domain evolution patterns, observed by a magneto-optical microscope magnetometer (MOMM) capable of grabbing domain reversal patterns in real time under applying a magnetic field, as well as, simultaneous probing local magnetic properties with 400-nm spatial resolution [8–11]. From the field dependence of the wall-motion speed and nucleation rate, we have measured activation volumes of the wall-motion and nucleation processes within the context of a thermally activated relaxation process. To understand the experimental finding, domain reversal dynamics has been theoretically predicted by using a micromagnetic simulation.

2. Experiments

The MOMM system, which is basically a polarizing optical microscope detectable magnetic contrast via the

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magneto-optical Kerr effect, can visualize the perpendicular component of the magnetization via the polar Kerr effect with a normal incident of illumination light [8–11]. The system is equipped with an electromagnet controlled by a personal computer to apply an external magnetic field to a sample in the range of ±3.5 kOe. An advanced charge-coupled device (CCD) camera system equipped with a signal intensifier is attached to the microscope to store the magnetic images into a computer with a video rate. The images are composed of the light intensity distribution measured by a CCD array of 100×80 pixels, where a unit pixel corresponds to an area of 0.4×0.4 μm^2 at the film surface. Storing the domain images during the magnetization reversal, it is possible to obtain an array of the hysteresis loops for every corresponding CCD pixel while sweeping an applied magnetic field. It should be stressed here that the magnetization viscosity curves can be obtained from every corresponding CCD pixel and thus, one can obtain the spatially-resolved hysteresis characteristics with a submicrometer spatial resolution.

A number of (t_{Co}-Co/11-Å Pd)$_n$ samples with varying either the Co-sublayer thickness t_{Co} or the number of repeats n were prepared on glass substrates by alternatively exposing two e-beam sources of Co and Pd under a base pressure of 2.0×10^{-7} Torr at the ambient temperature [5]. Low-angle X-ray diffraction studies using CuKα radiation revealed that all samples had distinct peaks indicating an existence of the multilayer structure. High-angle X-ray diffraction studies showed that the samples grew along the [1 1 1] cubic orientation. All samples in this study had perpendicular magnetic anisotropy and showed square Kerr hysteresis loops.

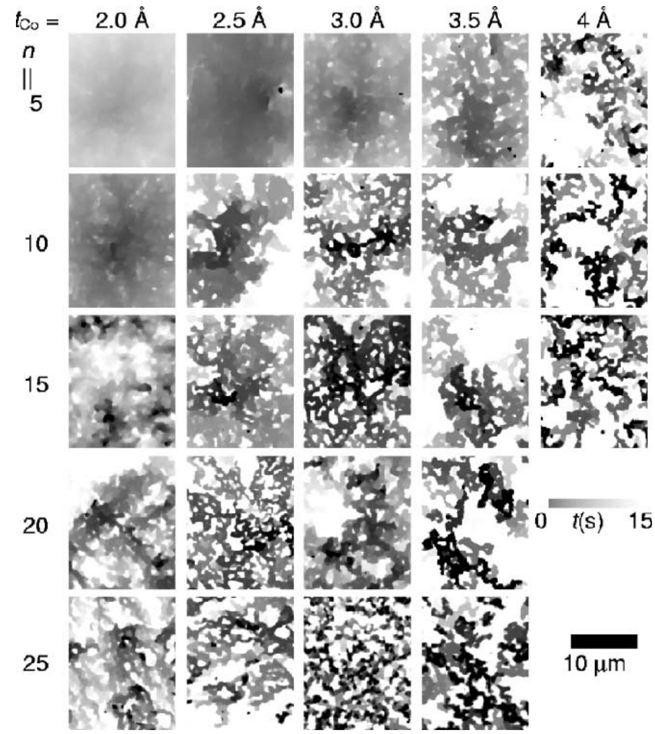

Fig. 1. Typical magnetic domain evolution pattern of the (t_{Co}-Co/11-Å Pd)$_n$ samples. Each box is aligned in column with t_{Co} and in row with n. The gray color filled in the images corresponds the local switching time of the corresponding regions as given by the palette at the bottom right corner.

3. Contrasting magnetization reversal dynamics

Contrasting magnetization reversal behaviors were observed by time-resolved domain observation. Domain reversal behavior has been found to change contrastingly from wall-motion dominant to nucleation dominant either with increasing the Co-sublayer thickness t_{Co} or with increasing the number of repeat n. In Fig. 1, we show typical domain reversal patterns of the (t_{Co}-Co/11-Å Pd)$_n$ samples during domain reversal under a reversed applied field. The gray color filled in the images corresponds to the local switching time as given by the palette at the bottom right corner. It is quite interesting to note that the domain reversal pattern in this serial samples shows a quite contrasting behavior.

To better understand the contrasting reversal behaviors of those samples, the wall-motion speed and the nucleation rate of each sample were determined using the quantitative analysis technique recently developed by Choe and Shin, based on the time-dependent domain reversal patterns [7,10]. In the analysis, the wall-motion speed V and the nucleation probability R are explicitly given by the time-resolved measurement of the reversed domain area and the domain boundary length. The wall-motion speed was found to decrease sensitively with either increasing the Co-sublayer thickness or increasing the number of repeats, while the nucleation speed is insensitive to the multilayer structure. Thus, one might conclude that the contrasting reversal behavior in this system is caused by the sensitive change in the wall-motion speed.

Based on the values of the wall-motion speed V and the nucleation rate R, we found that the reversal ratio V/R is a governing parameter for the contrasting domain reversal dynamics [7]. The reversal ratio is sensitively decreased with either increasing the Co-sublayer thickness or increasing the number of repeats. By comparison with the domain reversal patterns shown in Fig. 1, we notice here that the reversal ratio V/R is an important parameter to characterize different spin reversal process: a larger value of V/R yields more wall-motion dominant process, while a smaller value of V/R does more nucleation dominant process. It should be pointed out that even though the wall-motion speed and the nucleation rate are very sensitive to the strength of an applied field, the reversal ratio is quite independent of an applied field.

4. Unequal activation volumes

The activation volume, characterizing the unit volume acting as a single-domain particle as well as limiting the minimum size of domains, is a crucial parameter in both of the wall-motion and nucleation processes [12,13]. To determine the activation volumes, we have determined the wall-motion speed V and nucleation rate R of the Co/Pd multilayers from the time-resolved domain patterns during the magnetization reversal under various strengths of an applied field [10]. Interestingly, both the reversal parameters are exponentially dependent on the strength of the reversing applied field. The exponential dependency strongly evidences that both the reversal processes are governed by the thermally activated relaxation in the range of a reversing applied field in this study. By fitting the dependencies based on a thermal activation model, one can determine the activation volume of each process. In Table 1, we summarize the activation volumes of the wall-motion and nucleation processes.

Table 1
Experimental magnetic properties, activation volumes, and reversal ratio of Co/Pd multilayers

n	t_{Co} (Å)	M_S (emu/cm^3)	H_C (kOe)	V_W (10^{-18} cm^3)	V_N (10^{-18} cm^3)	V/R
5	2.0	250	0.4	7.4 ± 0.1	7.8 ± 0.3	3.4 ± 1.8
10	2.0	265	1.1	4.3 ± 0.1	4.8 ± 0.2	2.4 ± 1.1
15	2.0	270	1.7	3.4 ± 0.1	3.5 ± 0.2	1.5 ± 0.3
20	2.0	290	2.1	3.3 ± 0.1	3.1 ± 0.1	0.5 ± 0.1
25	2.0	310	2.2	3.0 ± 0.1	2.7 ± 0.1	0.4 ± 0.1
10	2.5	370	1.0	4.8 ± 0.2	5.0 ± 0.3	2.1 ± 1.2
10	3.0	400	0.7	6.4 ± 0.2	6.3 ± 0.4	0.9 ± 0.4
10	3.5	460	0.4	10.7 ± 0.6	9.4 ± 0.2	0.4 ± 0.1

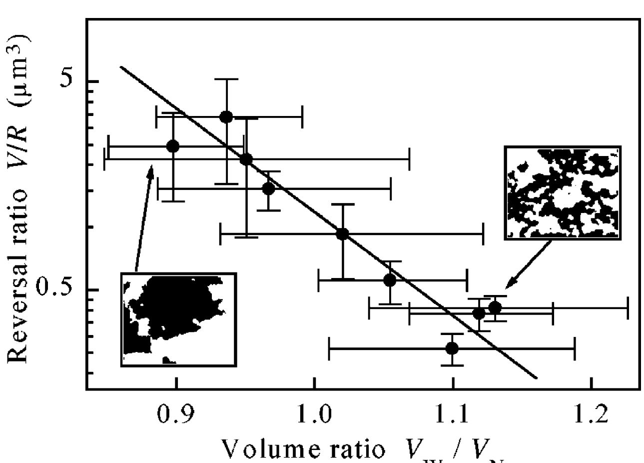

Fig. 2. The correlation between the reversal ratio of the wall-motion speed V over the nucleation rate R and the volume ratio of the wall-motion activation volume V_W over the nucleation activation volume V_N. The domain images in the insets illustrate the typical domain reversal patterns of wall-motion dominant process for a large V/R and nucleation dominant one for a small V/R, respectively.

Most interestingly, the activation volumes of the wall-motion and nucleation processes are noticeably different with each other and the difference between the activation volumes is systematically changed in accordance with the variation of the multilayered structure [10]. We find that the difference in the activation volumes is closely related with the contrasting domain reversal dynamics. In Fig. 2, we plot the reversal ratio V/R versus the activation volume ratio V_W/V_N: one see a clear correlation between the two ratios, which evidences that the activation volume ratio relates closely with the magnetization reversal modes. It could be explained since a smaller activation volume results in easier reversal than a larger one since the activation energy is proportional to the activation volume.

5. Local magnetic variation

To testify the effect of the local magnetic variation in ferromagnetic thin films, we have examined the domain reversal behavior among the Co/Pd multilayer samples with varying the number of repeats, where the macroscopic magnetic properties of these samples were confirmed to be basically same. However, the domain reversal behavior was found to change sensitively from wall-motion dominant to nucleation dominant with increasing the number of repeats. To understand this phenomenon, we have investigated the local magnetic variation via probing the local coercivity distribution using the MOMM system [8]. We generated the coercivity distribution map from the local hysteresis loops by mapping the corresponding grays for each coercivity H_C onto the two-dimensional XY plane as shown in Fig. 3(a). The figure vividly shows the spatial fluctuation of the local coercivity on the submicrometer scale; the local areas having the lowest coercivity, indicated by black, are nucleation sites in the magnetization reversal process.

The local dynamic behavior during magnetization reversal under a constant magnetic field was also investigated by means of the MOMM system [8]. The sample was first saturated by applying an initializing field larger than the coercivity and then, the magnetization reversal was triggered by applying a reversing field smaller than the coercivity. The magnetization viscosity curves [14,15] were monitored for every CCD pixels and then, the switching time τ was simultaneously determined from each corresponding CCD pixel. Therefore, using the MOMM we can also generate the spatial distribution map of the local switching time on the submicrometer scale from the viscosity curve measurement as shown in Fig. 3(b), where the magnitude of the switching time was indicated by filling the corresponding grays on each pixel according to the gray palette at the bottom of the figure.

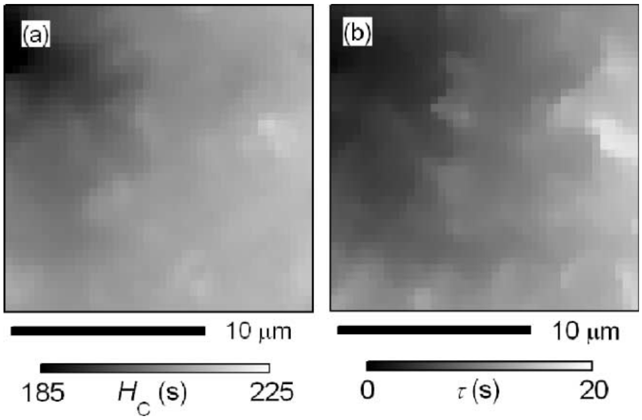

Fig. 3. (a) Distribution map of the local coercivity generated from the simultaneous probing of the local hysteresis loops on each corresponding local region of 400×400 nm^2 of a (2.5-Å Co/11-Å Pd)$_5$ sample. (b) Distribution map of the local switching time generated from the simultaneous probing of the local viscosity curves.

It is very interesting to note that the reversal pattern in Fig. 3(b) coincides with the local coercivity distribution for the corresponding sample area shown in Fig. 3(a). The reversal mechanism under the local coercivity variation could be analyzed by adopting the thermally activated relaxation process. By considering the local coercivity distribution $H_C(x,y)$, the switching time $\tau(x,y)$ is given by a spatially nonuniform function as follows:

$$\tau(x,y) = \tau_0 \exp(M_S V_A (H_C(x,y) - h)/k_B T). \quad (1)$$

The correlation between τ and H_C was indeed probed by a quantitative analysis technique using the MOMM system [8]. For a quantitative analysis of the correlation, we have measured the number of pixels $N(H_C, t)$ obtained by counting the pixels having the corresponding values of $H_C(x,y)$ and $\tau(x,y)$ measured at the same (x,y)th pixel in the map. From the correlation analysis, we clearly see that the local switching time is truly correlated with the coercivity distribution. The correlation could be well fitted by Eq. (1), which provides the strong evidence that the magnetization reversal in ferromagnetic thin films could be described by a thermally activated reversal process based on the local coercivity variation on the submicrometer scale [8–10].

6. Micromagnetic simulations

To understand the observed reversal behaviors in Co/Pd multilayers, a theoretical study has been carried out by Monte Carlo simulation adopting a simple uniaxial anisotropy model [5]. In this model, the film is considered to be composed of nano-sized identical single domain cells of volume on hexagonal lattices lying in *XY* plane with periodic boundary condition. Each cell has the saturation magnetization, the uniaxial anisotropy, and the exchange stiffness. Then, the magnetic energy of a cell can be given by a function of the magnetization direction of the cell. The magnetic energy has two minimum with an energy barrier in between. The energy barrier, the difference in energy between the initial value and the maximum, is then analytically calculated by a function of the initial states and the magnetic properties. Thus, one can evaluate the reversal probability within the context of a thermally activated reversal process. Using the Monte Carlo algorithm, each cell is determined to be reversed by comparing the probability with a random value ranging $[0, 1]$.

The magnetization reversal was found to be contrastingly dependent on the saturation magnetization, the domain-wall energy, and the local irregularity; a more detailed discussion is reported elsewhere [16]. Here, we report the effect of the domain-wall energy on the magnetization reversal dynamics. The magnetization reversal dynamics is expected to be sensitive to the domain-wall energy, since the magnetization reversal behavior is determined by the counterbalance between the nucleation process and the domain-wall motion process. In Fig. 4, we present the simulated domain evolution patterns of ferromagnetic thin films having different domain-wall energy *w* of (a) 0.5, (b) 0.7, and (c) 0.9 erg/cm^2, respectively. From the figures, one can vividly observe the contrasting domain reversal behaviors among the samples. A nucleation dominant reversal is vividly observed as shown in Fig. 4(a). In this sample, the nucleation occurs at a number of places, but the nucleated domains grow only marginally in size. On the other hand, a wall-motion dominant reversal is clearly seen from Fig. 4(c). The nucleation hardly occurs in this sample. But once nucleated, the domain expands gradually in size at all domain boundaries by wall-motion process and approaches to a large regular domain. Gradual change from the nucleation dominated behavior to the wall-motion dominated behavior is clearly observed in Fig. 4(a)–(c). These contrasting behaviors

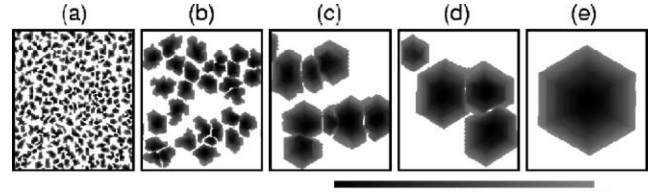

Fig. 4. Simulated domain evolution patterns of samples having different domain-wall energy of (a) 0.5, (b) 0.7, and (c) 0.9 erg/cm^2, respectively. All the samples have the same magnetostatic energy of 219 emu/cm^3, the anisotropy constant of 5×10^6 erg/cm^3, the cell size and the film thickness of 20 nm, the temperature of 300 K, and the 256×256 cells.

could be understood from the different dependency of the energy barriers between the nucleation and wall-motion processes: the nucleation process needs considerable energy to form domain-walls on all cell boundary, while the wall-motion process reversing a cell adjacent to already reversed cell needs less energy due to fewer new walls. Thus, the nucleation process hardly takes place with increasing the domain-wall energy, and the wall-motion process having relatively low energy barrier becomes dominant in the magnetization reversal dynamics.

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