Journal of Magnetics 8(3), 108-112 (2003)

Time-resolved Observation of Field-dependent Magnetization Reversal Behavior in Co/Pd Multilayer Film

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(Received 6 August 2003)

We report the experimental finding that there exists a transition of magnetization reversal process with varying the applied field in Co/Pd multilayer. We have measured the wall-motion speed V and the nucleation rate R during magnetization reversal via time-resolved direct domain observation, where the magnetization reversal process of Co/Pd multilayer is found to take a transition from thermal activation process to viscous process at the critical field of about 1.87 H_C (coercivity). In the thermal activation regime, we find that the field dependences of two activation volumes for the wall-motion process and the nucleation process are different with each other, which reveals that the wall-motion and nucleation experience completely different interactions. In the viscous regime, we find that the wall-mobility is much smaller than a typical value for the sandwiched Co films, which implies that the Co/Pd interfaces in multilayer substantially contribute to the dynamic dissipation.

Key words : magnetization reversal behavior, thermal activation, viscous, multilayer

1. Introduction

Co/Pd multilayer system is considered as one of the most promising candidates for the next-generation high-density magnetic and magneto-optical recording media due to their novel magnetic and magneto-optical properties [1-4]. Magnetization reversal study in this system continues to be an important issue in achieving high performance of magnetic or magneto-optical recording as well as in exploring fundamental understanding of domain dynamics [5, 6]. It is well-known that magnetization reversal process in ferromagnetic thin films takes a transition from thermal activation process to viscous process around the critical field H_{crit} that characterizes the wall-pinning force of a film. The thermal activation process takes place by switching the activation volumes via thermal activation energy overcoming the energy barrier, whereas the viscous process is related to energy dissipation through spin precession damping [7-12].

Most of the earlier magnetization reversal studies have been concentrated on the thermal activation process where an applied field was smaller than the coercivity H_C and no many works have studied in a wide range of an applied field which revealed the transition behavior in magnetization reversal, except a few studies on TbFeCo alloy [7], sandwiched Co [8, 10], Co/Cu [11], and CoCrTa alloy films [12]. In this work, we have investigated magnetization reversal processes of Co/Pd multilayer film in the applied field range of 0.47~2.74 H_C. For this study, we have measured both the wall-motion speed and the nucleation rate from time-resolved domain observation, whereas the previous studies only measured the wall-motion speed. It should be pointed out that the measurements of both the wall-motion speed and the nucleation rate are desirable for an in-depth study of magnetization reversal, since magnetization reversal occurs via two fundamental processes of wall-motion and nucleation [13-15]. In this letter, we report the transition from thermal activation process to viscous process in magnetization reversal of Co/Pd multilayer.

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2. Experiment

The sample in this study was Co/Pd multilayer of (2.5-Å Co/11-Å Pd)$_5$ having Co-sublayer thickness of 2.5 Å, Pt-sublayer thickness of 11 Å, and number of repeats of 5, where both wall-motion and nucleation behaviors are

expected during magnetization reversal [13]. The layer thickness was carefully controlled within a 4% accuracy. Low-angle x-ray diffraction studies using Cu $K\alpha$ radiation revealed that this sample had distinct peaks indicating an existence of the multilayer structure. The sample was prepared on glass substrate by alternatively exposing two e-beam sources of Co and Pd under a base pressure of 2.0 $\times 10^{-7}$ Torr at an ambient temperature. A magneto-optical kerr effect hysteresis loop measurement with the field sweeping rate of 30 Oe/s revealed that the sample had perpendicular magnetic anisotropy with the coercivity H_C of 234.2 Oe. Magnetization reversal behavior was investigated using a magneto-optical Kerr effect microscope system capable of grabbing time-resolved domain evolution patterns with 10 frames/s under a constant field in the range of 0.47~2.74 H_C [13, 14]. An electromagnet was used to generate the field in the range of 0.47~0.72 H_C, while a small coil connected to a pulse generator circuit was used due to short reversal time at higher field range of 0.69~2.74 H_C.

3. Result and Discussion

Figure 1 shows typical domain patterns at 60% magnetization reversal under an applied field H of (a) 0.72 H_C, (b) 1.29 H_C, and (c) 2.32 H_C, respectively. From the direct observation of domain evolution patterns, one can see that both wall-motion and nucleation are involved in magnetization reversal behavior, which enables us to simultaneously measure both the wall-motion speed V and the nucleation rate R. To quantitatively understand magnetization reversal behavior, V and R of the sample were measured from the time-dependent domain evolution patterns at a given applied field using the model described in Ref. 16. From this model, V and R are explicitly given as follows:

$$\left.\begin{aligned} V&=(a'-r_0 l'/2)/(l-\pi r_0) \\ R&=(ll'/2\pi-a')(l-\pi r_0)r_0(s-a) \end{aligned}\right\}, \quad (1)$$

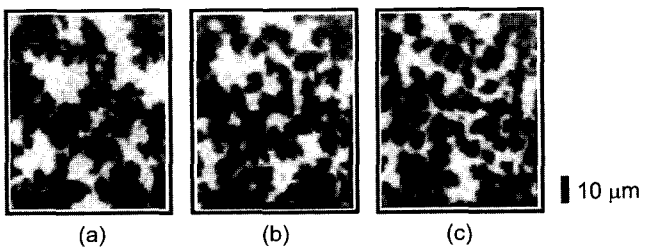

Fig. 1. Typical domain patterns at 60% magnetization reversal under an applied field H of (a) 0.72 H_C, (b) 1.29 H_C, and (c) 2.32 H_C, respectively.

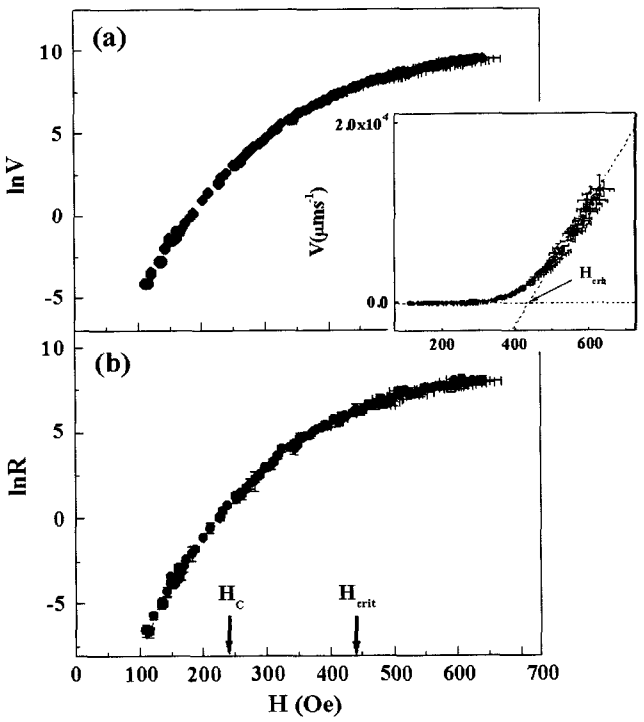

Fig. 2. (a) Wall-motion speed V as a function of an applied field H (V in μms^{-1}). The dashed line in the inset is the linear fit of the high field part (H > 490 Oe) and the arrow marks its intersection with the line V(H) = 0. This is the definition of the critical field H_{crit}. (b) Nucleation rate R as a function of an applied field H (R in $\mu m^{-2}s^{-1}$).

where a is the reversed domain area and l is the domain boundary length. The a' (l') denotes the first derivative of a (l) with respect to time. The characteristic radius r_0 of nucleation is set to 200 nm corresponding to the unit pixel size of observation.

Figure 2(a) shows the wall-motion speed V as a function of an applied field H. It can be seen that V depends exponentially on H in the low field regime (H < H_C). This exponential dependency strongly evidences that the wall-motion is governed by thermal activation process. However, with increasing H the slope of lnV decreases in the mid field regime (H_C < H < H_{crit}) and then, V depends linearly on H in the high field regime (H > H_{crit}) as clearly seen in the inset of Fig. 2(a). This result vividly demonstrates that a transition in the wall-motion from thermal activation process to viscous process gradually occurs around the critical field H_{crit} with increasing an applied field [8]. Here, the critical field H_{crit} is estimated to be 438 Oe (1.87 H_C) by linear extrapolation from the high-field dependency in Fig. 2(a) to V = 0 as suggested in Ref. 10. Generally, the critical field H_{crit} is known to clearly separate two regions at room temperature, the thermal activation regime and the

viscous regime [10]. This transition can be also witnessed from careful examination of domain wall structure with increasing H. Note that the domain wall structure becomes less jagged with increasing H as demonstrated in Fig. 1. The jagged shape is a characteristic of thermal activation process: a domain wall is strongly influenced by the random distributed pinning sites [8, 9]. On the other hand, the less jagged one is understood by a viscous process, where the domain wall structure is made to be circular and smooth by the weak influence of a domain wall on the pinning sites and the relative dominance of wall energy term tending to keep the wall lines straight [8-10].

Figure 2(b) shows the nucleation rate R as a function of an applied field H. Unlike the wall-motion, the nucleation occurs only by thermal activation process, even above the critical field H_{crit}, since the nucleation is a random switching of magnetization statistically governed by the probability [6, 15]. It means that the semi-log plot of the nucleation rate, lnR, in Fig. 2(b) directly represents the activation energy of the nucleation according to an Arrhenius law, from which we can see that the activation energy of the nucleation is nonlinearly dependent on an applied field H. In the case of the wall-motion, the same trend is also seen in its thermal activation regime before the transition ($H < H_{crit}$), as shown in Fig. 2(a). These results reveal that the energy barriers of the wall-motion and nucleation in the thermal activation regime are nonlinearly dependent on an applied field, consistent with the recent theoretical predictions based on Kirby's model [17-19]. Generally, the exact field dependences of two energy barriers in real films are difficult to analyze due to the complicated situations such as energy barrier distribution and interaction effects [20-22].

For further understanding about the energy barriers in the thermal activation regime, we have determined the activation volumes using the Gaunt's definitions given as follows [22, 23]:

$$\left.\begin{aligned} V_W(H) &= -\frac{1}{M_S}\frac{dE_M}{dH} = \frac{k_B T}{M_S}\frac{d\ln V}{dH} \\ V_N(H) &= -\frac{1}{M_S}\frac{dE_W}{dH} = \frac{k_B T}{M_S}\frac{d\ln R}{dH} \end{aligned}\right\}, \qquad (2)$$

where M_S is the saturation magnetization, E_W and E_N are the energy barriers of the wall-motion and the nucleation processes, respectively. Here, it should be pointed out that the activation volume is a good tool to understand the energy barriers in real films having the complicated interactions. Figure 3 shows the wall-motion activation volume V_W and the nucleation activation volume V_N as a function of an applied field H, where two activation volumes are determined only in the field range of 0.47~1.62 H_C to avoid the viscous regime since the above equations are only valid in a thermal activation regime. It can be clearly seen that with increasing an applied field H both activation volumes decrease, but they show the different values. This result implies that the field dependences of two energy barriers are different with each other. Thus, one could conjecture that two processes experience completely different interactions. This difference is understood by the fact that wall-motion and nucleation are fundamentally different processes: the wall-motion takes place by switching magnetization at boundary of an existing domain, while the nucleation process is carried out via random switching of isolated domains [13-15].

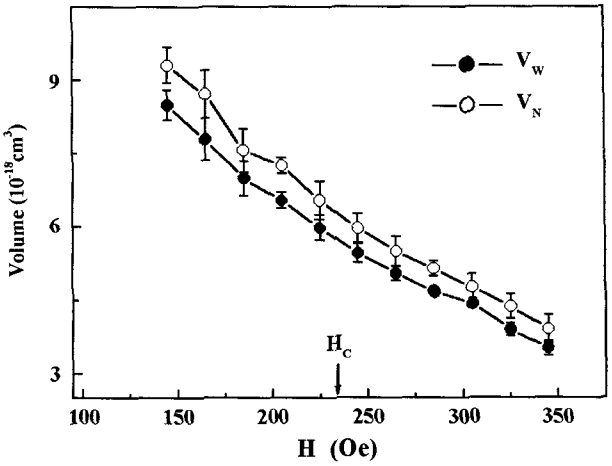

Fig. 3. Wall-motion activation volume V_W and nucleation activation volume V_N with respect to H in a thermal activation regime.

The viscous process in magnetization reversal of ferromagnetic thin films could be characterized by the function $V = \mu(H-H_0)$, where μ is the wall-mobility and H_0 is the quantity related to the coercivity. The viscous process is known to be limited by a spin precession damping: as the domain wall moves, the spins within the wall precess which leads to energy dissipation through spin precession damping. Thus, the domain wall experiences a velocity-dependent retarding force [8, 24, 25]. In such a case, H_0 corresponds to the critical field H_{crit} characterizing the wall-pinning force of a film, which is also called the propagation field H_P [8, 10]. In the present sample, we obtain $\mu \approx 0.063$ cm·s^{-1}·Oe^{-1} and $H_{crit} \approx 1.87\ H_C$ from the linear fit in the high-field regime in the inset of Fig. 2. In this sample, the viscous process is well expected, considering that the critical field H_{crit} is larger than those found in other systems (1.20~1.50 H_C) [8, 12]. Interestingly, the wall-mobility observed in our Co/Pd multilayer sample is two orders of magnitude smaller, compared to a typical

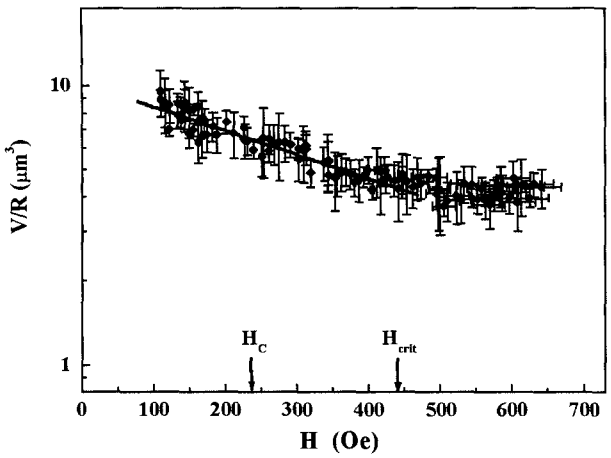

Fig. 4. Reversal ratio V/R as a function of an applied field H (V/R in μm^3).

value reported for the sandwiched Co films [8]. Because many defects are expected to exist at Co/Pd interfaces of a multilayer structure, this small wall-mobility is believed to ascribe to the presence of many pinning sites at Co/Pd interfaces, which causes substantial dynamic dissipation.

Figure 4 shows the reversal ratio V/R as a function of an applied field H. The reversal ratio V/R is known to be an important parameter to characterize magnetization reversal behavior, since the contrasting reversal behavior occurs from the counterbalance between the wall-motion and nucleation according to the Fatuzzo's theory [26]. It is interesting to note from the figure that with increasing an applied field V/R decreases almost exponentially in the thermal activation regime and then, it remains nearly constant in the viscous regime. The exponential decrease of V/R in the thermal activation regime is understood by the inequality in the activation volumes, i.e., $V_W(H) < V_N(H)$, directly relating with $dE_W/dH > dE_N/dH$. This results in the exponential decrease of V/R with increasing H, since ln(V/R) in a thermal activation regime indicates the difference between E_W and E_N according to an Arrhenius law. The deviation from the experimental behavior of V/R in the viscous regime is believed to be due to the viscous process of the wall-motion. In the viscous regime the wall-motion no longer dynamically experiences the energy barrier, while the nucleation still experiences its energy barrier. Therefore, the wall-motion becomes more dominant around the transition with increasing H in the viscous regime. These results are consistent with the domain evolution patterns observed under various applied fields shown in Fig. 1: the reversal behavior gradually changes form wall-motion dominant to nucleation-dominant with increasing H in the thermal activation regime as in seen Fig. 1(a) and (b). Then, the reversal pattern hardly changes in the viscous regime as a typical example shown in Fig. 1(c).

4. Summary

We have investigated magnetization reversal behavior of Co/Pd multilayer via the measurement of the wall-motion speed and the nucleation rate from the time-dependent domain reversal patterns observed by time-resolved magneto-optic microscope. We find that the wall-motion experiences the transition from the thermal activation process to the viscous process at the critical field of about 1.87 H_C, while the nucleation is dominated only by the thermal activation process. Interestingly, the activation energies of the wall-motion and nucleation in the thermal activation regime are found to be nonlinearly dependent on an applied field, consistent with the recent theoretical predictions based on Kirby's model. From the activation volumes with H, we find that the field dependences of two activation energies are different with each other, which reveals that the wall-motion and nucleation experience completely different interactions. We also witness that the wall mobility in the viscous regime of the Co/Pd multilayer is much reduced, which might be ascribed to substantial dynamic dissipation occurred at the Co/Pd interface.

This work was supported through the Creative Research Initiatives Project of Korean Ministry of Science and Technology. We thank A. Perumal for helpful discussion.

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