Thermally activated magnetization reversal behavior of uniaxial ferromagnetic thin films in the microsecond to second time regime

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We investigate the thermally activated magnetization reversal of Co/Pd multilayers with uniaxial perpendicular anisotropy using a magneto-optical Kerr effect microscope capable of direct domain observation in a wide time range of microsecond to second. It is found that the energy barrier in the thermally activated process is nonlinearly dependent on the applied field, irrespective of the difference in the domain evolution processes of wall motion, dendrite growth, and nucleation. These results are well explained by a theoretical model considering a ferromagnetic thin film with uniaxial perpendicular anisotropy. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2712054]

I. INTRODUCTION

Magnetization reversal dynamics in ferromagnetic thin films continues to be a challenging issue in magnetism as well as in spintronic device applications.[1,2] Recently, there has been a tremendous interest in understanding magnetization reversal dynamics due to the development of the magnetic imaging techniques, capable of direct observation of the domain evolution patterns.[3,4] It is well known that magnetization reversal in ferromagnetic thin films is governed by a thermally activated process when an applied field is smaller than a critical field at which the energy barrier can be overcome.[5–8] In a thermally activated process, three contrasting domain evolution processes such as wall motion, dendrite growth, and nucleation are involved, depending on the competition between the domain wall energy and the dipolar energy.[9,10]

Most of the previous studies have concentrated on a thermally activated process only in the fields smaller than the coercivity, where the reversal time is over a time regime of millisecond to second, due to the limited time resolution of the magnetic imaging techniques.[11–13] In the short field range, the energy barrier in the thermally activated process could be approximated as the linear dependence on the applied field. On the other hand, the theoretical analytic form of the energy barrier is described by the nonlinear dependence on the applied field.[10,14,15] To clarify whether the energy barrier has a nonlinear dependence, the magnetization reversal dynamics must be investigated in a wide field range smaller than the critical field, where the thermally activated process is governed.

To date, magnetization reversal studies in the wide field range have focused only on the transition from a thermally activated process to a viscous process at the critical field rather than on understanding of the thermally activated process.[6–8] Although Lemerle *et al.*[16] have conducted an in-depth research of the thermally activated process, their study only addressed the case of wall motion. In this paper, we present an in-depth study of the thermally activated process of uniaxial ferromagnetic thin films in a wide field range smaller than the critical field, where the reversal time is over a time regime of microsecond to second. For this study, Co/Pd multilayers were chosen as they exhibit three typical domain evolution processes, wall motion, dendrite growth, and nucleation, depending on the Co sublayer thickness.[9]

II. EXPERIMENTAL PROCEDURE

The $(t_{Co}\text{-Co}/11\ \text{Å Pd})_{10}$ samples with Co-sublayer thicknesses of $t_{Co}=2$, 3, and 4 Å were prepared on glass substrates by alternatively exposing the samples to two e-beam sources of Co and Pd under a base pressure of 2.0×10^{-7} Torr at an ambient temperature. The thickness calibration and the existence of a multilayer structure were determined by low-angle x-ray diffraction studies using Cu $K\alpha$ radiation. A magneto-optical Kerr effect hysteresis loop measurement with a field sweeping rate of 30 Oe/s revealed that the three samples had perpendicular magnetic anisotropy with coercivities H_c of 609, 498, and 203 Oe, respectively. The Co/Pd multilayers were found to exhibit an increased saturation magnetization and a decreased anisotropy constant as t_{Co} is increased in this thickness region (2–4 Å).[17] The value of the saturation magnetization, M_s, measured using a vibrating sample magnetometer (VSM), increases from 266 to 462 emu/cm^3 as t_{Co} is increased from 2 to 4 Å.

The magnetization reversal behavior was investigated by means of a magneto-optical microscope magnetometer (MOMM) capable of grabbing time-resolved domain evolution patterns under a constant applied field. Details of the MOMM have been described elsewhere.[4] The magnetization reversal was triggered by applying a magnetic field in a field range of $0.41-1.40H_c$ to an initially saturated sample. An electromagnet was used to apply low magnetic fields corre-

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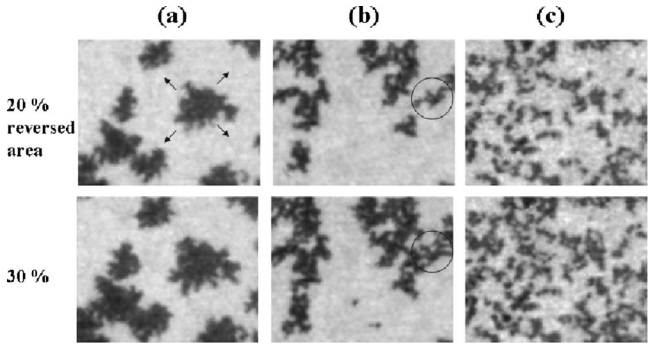

FIG. 1. Typical time-dependent domain patterns under a constant applied field in $(t_{Co}$-Co/11 Å Pd$)_{10}$ samples with t_{Co}=(a) 2, (b) 3, and (c) 4 Å, observed on the sample area of 80×64 μm^2 by means of the MOMM.

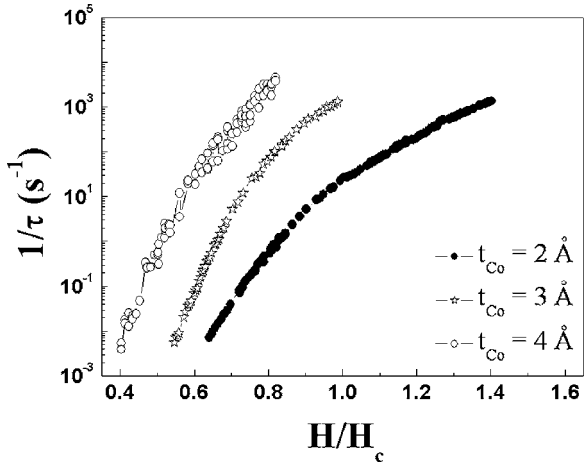

FIG. 2. The inverse of the half reversal time $1/\tau$ with respect to an applied field in $(t_{Co}$-Co/11 Å Pd$)_{10}$ samples with t_{Co}=2, 3, and 4 Å, respectively, where H_c corresponds to the coercivity of each sample.

sponding to a long time range (10 ms$<t<$1000 s), while a small coil connected to a pulse generator circuit was used to apply high fields for a short time duration (10 μs$<t<$100 ms).

III. RESULT AND DISCUSSION

In Fig. 1, we demonstrate typical time-dependent domain patterns under a constant applied field in $(t_{Co}$-Co/11 Å Pd$)_{10}$ samples with t_{Co}=(a) 2, (b) 3, and (c) 4 Å, observed on a sample area of 80×64 μm^2 by means of the MOMM. It can be clearly seen that as t_{Co} increases the domain reversal behavior changes from wall-motion dominant to dendrite-growth dominant behavior, followed by nucleation dominant behavior. The wall motion in the (2 Å Co/11 Å Pd$)_{10}$ sample takes place by switching the domain at the boundary of a few existing domains, whereas the dendrite growth in the (3 Å Co/11 Å Pd$)_{10}$ sample switches the domain at the ends of the stripe domains. On the other hand, the nucleation in the (4 Å Co/11 Å Pd$)_{10}$ sample results in the creation of isolated domains. This contrasting change in the domain evolution process can be explained by the increase in the relative magnitude of the dipolar energy to the domain wall energy, as shown in the simulated domain reversal phase diagram given in Ref. 10, which is mainly ascribed to the increase in M_s with an increase in t_{Co}. This characteristic of the Co/Pd multilayer system allows us to conduct an in-depth study of the thermally activated process in three typical domain evolution processes, i.e., wall motion, dendrite growth, and nucleation.

To characterize the thermally activated process in each domain evolution process, the field dependence of the half reversal time τ has been determined from the time-resolved domain evolution patterns during the magnetization reversal under different applied fields, where τ is the time needed to reverse half of the observed area of the sample. In Fig. 2, we plot the inverse of the half reversal time $1/\tau$ with respect to the applied field in $(t_{Co}$-Co/11 Å Pd$)_{10}$ samples with t_{Co}=2, 3, and 4 Å, respectively. The applied field was normalized by the coercivity H_c of each sample. It is clearly seen that the value of $1/\tau$ in each sample depends exponentially on the applied field, for values lower than the critical field ($\sim 1.87H_c$).[6] This reveals that all reversal behaviors are governed by the thermally activated process. Generally, the critical field is known as the applied field at which the magnetization reversal behavior exhibits a transition from the thermally activated process to the viscous process with an increase of the applied field. Also, it should be noted that the energy barrier of the half reversal time τ in the thermally activated process is closely related with $-k_BT\ln(1/\tau)$ according to the Arrhenius law.[18] Interestingly enough, it is found that the energy barrier of the thermally activated process is nonlinearly dependent on the applied field, irrespective of the difference in the domain evolution process. These results have not been reported in the previous studies. The nonlinear field dependence of the energy barrier could be obtained by using a MOMM capable of the direct domain observation in a wide time range of microsecond to second.

The nonlinear field dependence of the energy barrier can be understood by the theoretical predictions based on the model of Kirby *et al.* considering a ferromagnetic thin film system with perpendicular magnetic anisotropy.[14] The model describes a ferromagnetic thin film consisting of identical single domain cells with the critical volume V_c on a hexagonal lattice with periodic boundary conditions. Here, the critical volume V_c corresponds to the volume between pinning sites in which individual atomic moments are strongly correlated by the exchange interaction. Each domain cell has a saturation magnetization M_s and a uniaxial perpendicular magnetic anisotropy K_u, and its boundary has a wall energy density σ_w. Hence, the energy barrier E_b of a domain cell to reversal under the applied field H is estimated by the following simplified equation:

$$E_b = K_u V_c[1-(h+m\hat{h}+\zeta w)]^2, \tag{1}$$

where $m=2\pi M_s^2/K_u$, $w=\sigma_w/t_cK_u$, and $h=M_sH/2K_u$ are the ratios of the dipolar energy, the domain wall energy, and the Zeeman energy to the anisotropy energy, respectively. ζ is the fraction ratio of the newly formed wall length and $\hat{h}$ is the ratio of the demagnetizing field to its saturation value. Three typical domain evolution processes such as wall motion, dendrite growth, and nucleation can be characterized by the situation parameters of ζ and $\hat{h}$, as described in Ref. 10.

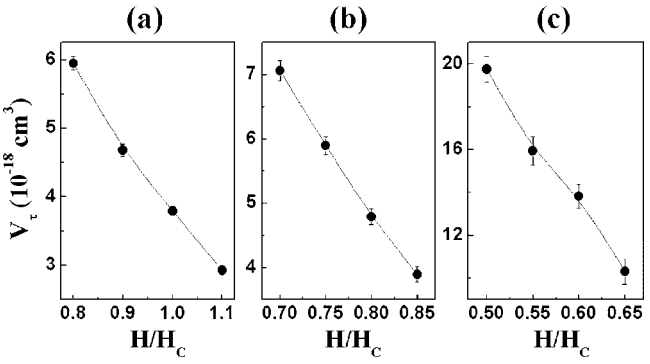

FIG. 3. The activation volume V_τ with respect to an applied field in $(t_{Co}$-Co/11 Å Pd$)_{10}$ samples with t_{Co}=(a) 2, (b) 3, and (c) 4 Å.

As expected by Eq. (1), the energy barriers of the three domain evolution processes are nonlinearly dependent on the applied field, which provides the origin of the nonlinear field dependence of the energy barriers, as observed above.

Most strikingly, it is found that the activation volume varies with the strength of the applied field. The activation volume is a crucial parameter in terms of attaining a better understanding of the thermally activated process, because it is determined from the field dependence of the energy barrier. In addition, it corresponds to the unit volume acting as a single domain during the magnetization reversal. The activation volume V_τ was determined from the field dependence of the half reversal time τ on the basis of Gaunt's definition,[15,19] given as follows:

$$V_\tau(H) = -\frac{1}{M_s}\frac{dE_\tau}{dH} = -\frac{k_B T}{M_s}\frac{d\ln\tau}{dH}, \tag{2}$$

where E_τ corresponds to the energy barrier of the half reversal time. Figure 3 shows the activation volume V_τ with respect to the applied field in $(t_{Co}$-Co/11 Å Pd$)_{10}$ samples with t_{Co}=(a) 2, (b) 3, and (c) 4 Å. In Fig. 3, it is clearly seen that V_τ in each sample no longer has a constant value and decreases with respect to the applied field, which has not been reported before. To date, the activation volume in the magnetization reversal has been considered as a constant value on the applied field. As expected from Eq. (2), the field dependence of the activation volume can be ascribed to the nonlinear field dependence of the energy barrier in the thermally activated process.

IV. SUMMARY

The magnetization reversal behavior of Co/Pd multilayers was investigated by using a MOMM capable of direct domain observation in a wide time range of microsecond to second. From this delicate experiment, we find that the energy barrier in the thermally activated process is nonlinearly dependent on the applied field irrespective of the difference in the domain evolution process. The nonlinear field dependence of the energy barriers is well explained by the theoretical model of Kirby *et al.* considering a ferromagnetic film with uniaxial perpendicular anisotropy. Lastly, it is found that the activation volume varies with the strength of the applied field, which is ascribed to the nonlinear field dependence of the energy barrier.

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