Dependences of the activation volumes on Ar sputtering pressure in Co/Pt multilayers prepared by dc magnetron sputtering

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We investigated the wall-motion and nucleation activation volumes of Co/Pt multilayer films prepared by dc magnetron sputtering under various Ar sputtering pressures. Delicate analysis of time-resolved domain evolution patterns reveals that the nucleation activation volume is generally smaller than the wall-motion activation volume in all the samples, which is consistent with the nucleation-dominant magnetization reversal behavior observed in this system. Interestingly, the activation volume is found to decrease with increasing Ar pressure, despite a decreasing trend in saturation magnetization. Decreasing grain size with increasing Ar pressure, smaller than the typical size of a Co single domain, is believed to be the origin of the unexpected observation. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1435405]

The Co/Pt multilayer system has been one of the most promising materials for perpendicular magnetic recording and magneto-optical recording media due to its characteristic properties of a large perpendicular magnetic anisotropy and a large Kerr rotation angle at a short wavelength.[1–4] To achieve high-performance magnetic information technologies, it is essential to understand domain reversal dynamics because information is stored in the form of magnetic domains and magnetization reversal behavior is closely related to the size, irregularity, and stability of the written domain.[5,6] Magnetization reversal behavior is generally explained by a thermally activated process, where the reversal process occurs by switching the activation volumes of the wall-motion and nucleation processes via thermal activation energy overcoming the energy barrier. Therefore, the key to understanding the thermally activated process is the activation volume, which is the effective unit volume of the coherent rotation acting as a single-domain particle or the volume swept between pinning sites by a single jump of the domain wall. In the information storage technologies, the activation volume is closely related to the theoretical limit of maximum achievable storage density, media noise, and thermal stability.[7,8]

Considerable effort has been made in recent years to measure the activation volumes. Street[9] and Wohlfarth[10] proposed that the activation volume could be estimated from the magnetic viscosity measurement using a concept of fluctuation field, where the fluctuation field is an effective field caused by thermal energy. Bruno[11] and Raquet[12] determined the activation volume based on their magnetization reversal dynamics model for sweeping rate dependence of the coercivity in Au/Co/Au films. Labrune[13] suggested that the wall-motion activation volume and the nucleation activation volume in rare-earth transition-metal films could be obtained from the field dependence of the nucleation rate and the domain-wall speed, respectively. Kirilyuk[14] directly measured the wall-motion activation volume and the nucleation activation volume of Au/Co/Au films from the field dependence of the wall-motion speed and the nucleation rate, based on domain evolution patterns generated by pulsed magnetic field. Based on these experimental results, both the wall-motion and the nucleation activation volumes have been considered to be same.[13,14] However, there is no clear physical reason why this should be the case. In this study, we have measured the wall-motion activation volume, the nucleation activation volume, and the effective activation volume from the magnetic-field dependence of the wall-motion speed, the nucleation rate, and the half-reversal time, respectively. We report that the activation volumes are generally unequal in Co/Pt multilayers prepared by dc magnetron sputtering under various Ar pressures and they are sensitively dependent on Ar pressure.

In this study, Co/Pt multilayers were prepared on glass substrates by dc magnetron sputtering with changing the Ar pressure P_{Ar} from 2 to 7.5 mTorr, with maintaining a constant Co-sublayer thickness of 4 Å, Pt-sublayer thickness of 11 Å, and number of repeats of 10. All samples have perpendicular magnetic anisotropy and show square Kerr hysteresis loops.

The magnetization reversal process has been observed using a magneto-optical Kerr effect microscope system capable of grabbing time-resolved domain patterns under various strengths of an applied magnetic field.[6,15] Figure 1 shows the typical domain evolution patterns of $(4\ \text{Å Co}/11\ \text{Å Pt})_{10}$ samples at a Ar pressures (a) 2, (b) 5, and (c) 7.5 mTorr, respectively, where the gray color corresponds to the switching time at the corresponding region. Dendritic growth, formed by the nucleation process is clearly observed in all the samples.[6,16] It can be understood that Co/Pt multilayers in this study have a large saturation magnetization M_S, and thus the domain splits into narrow stripes to minimize the demagnetization energy.[17]

To better understand the reversal behavior, the wall-motion speed and nucleation rate of each sample were quantitatively determined from the time-dependent domain reversal patterns based on a domain reversal model.[17] In this

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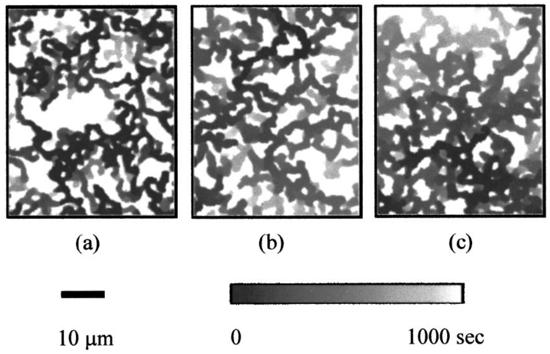

FIG. 1. Domain reversal patterns of (4-Å Co/11-Å Pt)$_{10}$ samples prepared at Ar sputtering pressures of (a) 2, (b) 5, and (c) 7.5 mTorr, respectively. The gray level in the pallet bar at the bottom of the figure corresponds to the switching time.

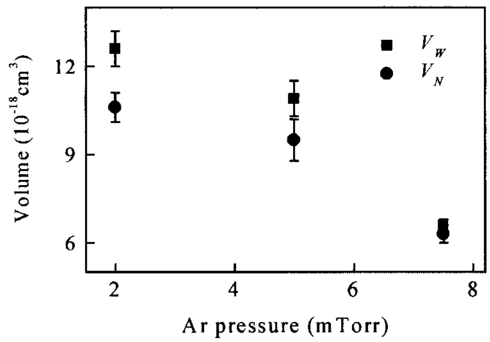

FIG. 2. Wall-motion activation volume V_W and nucleation activation volume V_N of (4-Å Co/11-Å Pt)$_{10}$ samples with respect to sputtering Ar pressure P_{Ar}.

method, the domain expands at all domain boundaries by the wall-motion process, and simultaneously, new domains are formed by the nucleation process during the magnetization reversal from the initially saturated state. From the model, wall-motion speed V and nucleation rate R are explicitly given by

$$V=(a'-r_0 l'/2)/(l-\pi r_0),$$
$$R=(ll'/2\pi-a')/(l-\pi r_0)r_0(s-a), \quad (1)$$

where a is the reversed domain area and l is the domain boundary length. The a' and l' denote the first derivatives of a and l, respectively. In this model, we assumed that all domain boundaries move with the same speed and nucleated domains are circular. Details of the model has been described elsewhere.[18] In the present study, total area s under examination is $40\times 32\ \mu\mathrm{m}^2$ and the characteristic radius r_0 of nucleation is set to 100 nm, corresponding to the unit pixel size of observation. The reversed domain area $a(t)$ and the domain boundary length $l(t)$ of each image were simultaneously determined from the black-and-white cell distribution counting and the edge finding, respectively. Then, wall-motion speed V and nucleation rate R can be simultaneously determined using Eq. (1) once the reversed domain area $a(t)$ and the domain boundary length $l(t)$ are measured. We have determined V and R of the Co/Pt multilayers from the time-resolved domain patterns during the magnetization reversal under various strengths of an applied field. We also determined half-reversal time τ, which is the time needed to reverse a half of the area of a sample under magnetization reversal. It was clearly seen that V, R, and τ were exponentially dependent on the strength of the reversing applied field. The exponential dependences could be well explained by a thermally activated relaxation model. In the model, wall-motion speed V, nucleation rate R, and half-reversal time τ are given by

$$V(H)=V_0 \exp\left(-\frac{(K_U V_W - M_S V_W H)}{k_B T}\right),$$
$$R(H)=R_0 \exp\left(-\frac{(K_U V_N - M_S V_N H)}{k_B T}\right), \quad (2)$$
$$\tau(H)=\tau_0 \exp\left(\frac{K_U V_A - M_S V_A H}{k_B T}\right),$$

where M_S is the saturation magnetization and V_W, V_N, and V_A are the wall-motion activation volume, the nucleation activation volume, and the effective activation volume, respectively.[5,13] Each activation volume was determined from Eqs. (2) using the measured values of the saturation magnetization and anisotropy energy K_U of each sample. This model describes the field dependence of the isolated single-domain particles within a first-order approximation, where the particles are assumed to have first-order uniaxial anisotropy and to coherently rotate under a reversing applied field. In this study, we adopted this model to determine the activation volumes, because the model provides clear physical insight into magnetization reversal. However, due to the interactions in real films, the determined activation volume is not equivalent to the physical volume itself. We designate the volume as an effective volume which includes interaction effects. Though it is hard to understand an *ab initio* relation between the two volumes with including the interaction effects, we believe that the effective volume rather than the physical volume is more responsible for magnetization reversal dynamics. In Table I, we summarize the measured values of V_W, V_N, and V_A of the samples prepared at different Ar sputtering pressures, together with their saturation magnetization. Interestingly, the wall-motion activation volume and the nucleation activation volume were found to be generally unequal with each other. Figure 2 shows the wall-motion and the nucleation activation volumes of the Co/Pt multilayer samples as a function of Ar sputtering pressure. As seen in

TABLE I. Saturation magnetization M_S, effective activation volume V_A, wall-motion activation volume V_W, nucleation activation volume V_N, reversal ratio V/R, and grain size d in Co/Pt multilayers.

P_{Ar} (mTorr)	M_S (emu/cc)	V_A (10^{-18} cm^3)	V_W (10^{-18} cm^3)	V_N (10^{-18} cm^3)	V/R (μm^3)	d (nm)
2	709	10.7±0.7	12.6±0.6	10.6±0.5	0.21	11.9±1.5
5	676	9.7±0.5	10.9±0.6	9.5±0.7	0.35	10.8±1.2
7.5	616	6.4±0.3	6.6±0.2	6.3±0.3	0.47	8.3±1.1

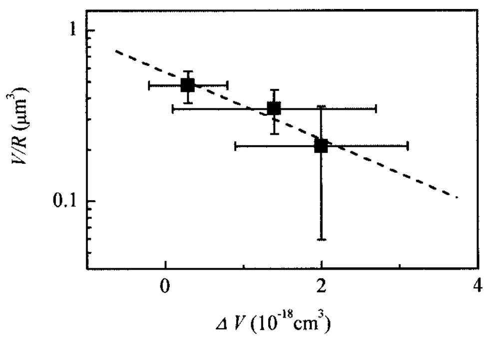

FIG. 3. Reversal ratio V/R of (4-Å Co/11-Å Pt)$_{10}$ samples with respect to the difference between the wall-motion activation volume and nucleation activation volume ΔV.

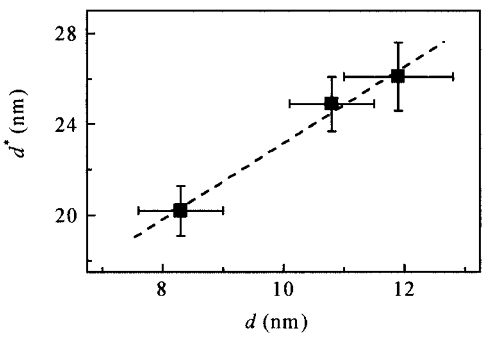

FIG. 4. Dependence of effective activation size d^* on grain size d of Co/Pt multilayers.

Fig. 2, both activation volumes decrease in the same trend with increasing Ar sputtering pressure. However, it should be pointed out that the nucleation activation volume is noticeably smaller than the wall-motion activation volume beyond the measurement accuracy, and the difference in the two activation volumes decreases with increasing Ar sputtering pressure.

The inequality in the activation volumes is found to have a crucial effect on the magnetization reversal dynamics. In Fig. 3, we plot reversal ratio V/R with respect to the difference of the activation volumes $\Delta V\,(=V_W-V_N)$. Reversal ratio V/R is known to be an important parameter to characterize the magnetization reversal behavior, since the contrasting reversal behavior occurs from the counterbalance between the wall-motion and the nucleation processes: a wall-motion dominant reversal is observed for a sample having a large V/R, whereas a nucleation dominant reversal appears in a sample having a small V/R.[19] All the samples in this study exhibit that $V/R<1\ \mu m^3$, which is consistent with the direct domain observation of the nucleation-dominant reversal behavior. Figure 3 shows a clear correlation between the difference of activation volumes and magnetization reversal behavior. This correlation is ascribed to the fact that the reversal mode is determined by the counterbalance between wall-motion activation volume and nucleation activation volume and the activation energy barrier is proportional to the activation volume. Thus, we conclude that a process having a smaller activation volume is more dominant in magnetization reversal.[20]

Interestingly, the activation volume is found to decrease with increasing Ar sputtering pressure although the saturation magnetization is revealed to increase as seen from Table I. This can be understood by the explanation that magnetization reversal behavior changes with respect to sample preparation conditions via the change in the film morphology such as grain structures. However, the influence of the grain structure on magnetization reversal behavior has not been clearly understood yet. To investigate the influence of the grain structure on magnetization reversal behavior, we measured the grain size from the surface morphology image using an atomic-force microscope. The grain size in diameter decreased from 12 to 8 nm with increasing the Ar sputtering pressure, as listed in Table I. This decrement might be ascribed to the increment of void area in a coarser film prepared in a higher Ar sputtering pressure. To quantitatively understand the correlation between magnetization reversal behavior and grain size, we plot the effective activation size d^* with respect to grain size d, as shown in Fig. 4, where d^* is defined as the diameter of a cylindrical body equivalent to the effective activation volume. Figure 4 shows a clear linear dependence of the effective activation size on the grain size. Note that these sizes are smaller than a typical value of Co single-domain size:[21] thus, the grain size plays a major role in limiting the activation volume. One can, therefore, expect that the activation volume decreases with increasing Ar pressure, because of decreasing grain size of the sample with increasing Ar pressure.

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