Journal of Magnetism and Magnetic Materials 240 (2002) 308–310

journal of magnetism and magnetic materials

www.elsevier.com/locate/jmmm

Activation volumes of wall-motion and nucleation processes in Co-based ferromagnetic multilayer films

Sug-Bong Choe*, Yoon-Chul Cho, Hyuk-Jae Jang, Sung-Chul Shin

Department of Physics and Center for Nanospinics of Spintronic Materials, Korea Advanced Institute of Science and Technology, Taejon 305-701, South Korea

Abstract

Activation volumes of the wall-motion and nucleation processes in Co-based multilayer films were characterized from time-resolved domain evolution patterns. These activation volumes were both sensitive to the multilayer structure as well as the film preparation condition. The two activation volumes were generally unequal with each other and the inequality directly influenced on magnetization reversal behavior. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Domain dynamics; Thermal activation; Activation volume

Magnetization reversal dynamics in ferromagnetic thin films continues to be an important issue in magnetism [1–3]. A number of experimental and theoretical studies have demonstrated that magnetization reversal dynamics takes place by successive switching of the activation volumes assisted by thermal activation energy overcoming the switching energy barrier [4–8]. The activation volume is a key parameter in this phenomenon, which characterizes the basic volume acting as a single particle as well as limits the minimum size of a stable magnetic volume in technological applications. The activation volume has been estimated from the field dependence of the reversal time and it has been reported that the activation volume is in the range from 10^{-19} to $10^{-16}\,cm^3$ for a number of ferromagnetic thin films, and sensitively depends on the composition, layered structure, and morphology of the films [4–8].

Recently, exploration of magnetization reversal dynamics has greatly advanced, largely motivated by direct observation of domain evolution patterns using magnetic imaging techniques, as well as by experimental observation of contrasting reversal modes in similar samples of many systems [2–5]. It has been revealed that the magnetization in ferromagnetic thin films reverses via two fundamental processes: (1) wall-motion of existing domains and (2) nucleation of new domains at random positions independent of existing domains. Much effort has been devoted to measure the activation volumes of the wall-motion and nucleation processes in a number of systems [1,5,6,8]. Based on the experimental evidence that the activation volumes are not substantially different, most theoretical studies so far have assumed that the activation volumes of wall-motion and nucleation processes are identical [9,10]. However, there is no clear physical reason that this should be the case and the correlation between the activation volumes remains still unclear. The present study was undertaken to characterize the correlation between the activation volumes for wall-motion and nucleation processes in ferromagnetic thin films.

For this study, a number of Co/Pd and Co/Pt multilayer films were prepared on glass substrates either by e-beam evaporation or Ar sputtering, with changing the multilayer structure and the Ar sputtering pressure. The layer thickness was carefully controlled within a 4% accuracy. Low-angle X-ray diffraction studies using Cu K_α radiation revealed that all samples had distinct peaks indicating the existence of the multilayer structure. High-angle X-ray diffraction studies showed that the samples grew along the [1 1 1] cubic orientation.

*Corresponding author: Tel.: +82-42-869-2591; fax: +82-42-869-2510.

E-mail address: sugbong@hitel.net (S.-B. Choe).

PII: S0304-8853(01)00786-7

The activation volumes of the wall-motion and the nucleation processes of the samples have been measured by adopting a domain analysis model. Details of the model have been described elsewhere [11]. Briefly, the model of magnetization reversal is proposed by using the time-resolved domain evolution patterns based on circular domains. In the model, domains expand at all domain boundaries with wall-motion process and simultaneously new domains are formed at a nucleation process during magnetization reversal from the initially saturated state. Considering the changes in reversed domain area a and domain boundary length l in time, the wall-motion speed V and the nucleation rate R are explicitly given by

$$V = (a' - r_0 l'/2)/(l - \pi r_0),$$

$$R = (ll'/2\pi - a')/(l - \pi r_0) r_0 (s - a), \tag{1}$$

where r_0 is the characteristic radius of nucleation, s is the total area under examination, and a' and l' denote the time derivation of the reversed domain area and the domain boundary length, respectively.

Then, the wall-motion speed V and the nucleation rate R of a sample could be determined by measuring the reversed domain area a and domain boundary length l in Eq. (1). Magnetization reversal from a saturated state was triggered by applying a reversing magnetic field and simultaneously, time-resolved domain images of 128 frames were grabbed by a MOKE microscope system in real time at 10 frames/s with a spatial resolution of 400 nm. The image, composed of 200×160 pixels with a unit pixel size of $200 \times 200\,\text{nm}^2$, was initially obtained in 256 gray levels and then, intensified by noise filtering and black-and-white image extraction processes. The a and l of each image were determined by counting black and white cells and by use of an edge-determining algorithm, respectively.

The activation volumes of the wall-motion and the nucleation processes were determined from the field dependence of the wall-motion speed and the nucleation rate, respectively. We measured the wall-motion speed and nucleation rate under various strengths of a reversing applied field smaller than the coercivity. All the samples exhibited that both the reversal parameters are exponentially dependent on the strength of a reversing applied field. The exponential dependency strongly evidences that both reversal processes are thermally activated in this field range and can be explained by

$$V(H) = V_0 \exp\left[-(E_\mathrm{W} - 2HM_\mathrm{S}V_\mathrm{W})/k_\mathrm{B}T\right],$$

$$R(H) = R_0 \exp\left[-(E_\mathrm{N} - 2HM_\mathrm{S}V_\mathrm{N})/k_\mathrm{B}T\right], \tag{2}$$

where M_S is the saturation magnetization, E_W and E_N are the energy barriers, and V_W and V_N are the activation volumes of the wall-motion and nucleation processes, respectively. Fitting the experimental data with Eq. (2) and using the measured values of the saturation magnetization of each sample, we determined the two activation volumes of the Co-based multilayer films.

Fig. 1 exhibits the activation volumes of the wall-motion and nucleation processes for (a) the e-beam evaporated (2-Å Co/11-Å Pd)$_n$ samples with varying the number of repeats n, (b) the e-beam evaporated (t_Co-Co/11-Å Pd)$_{10}$ samples with varying the Co-sublayer thickness t_Co, and (c) the sputtered (4-Å Co/11-Å Pt)$_{10}$ samples prepared under various Ar-sputtering pressures, respectively. It is clear from the figure that both the activation volumes change in the same manner with changing either the multilayer structure or the Ar-sputtering pressure, which implies that both processes are influenced in the same manner by the structural and/

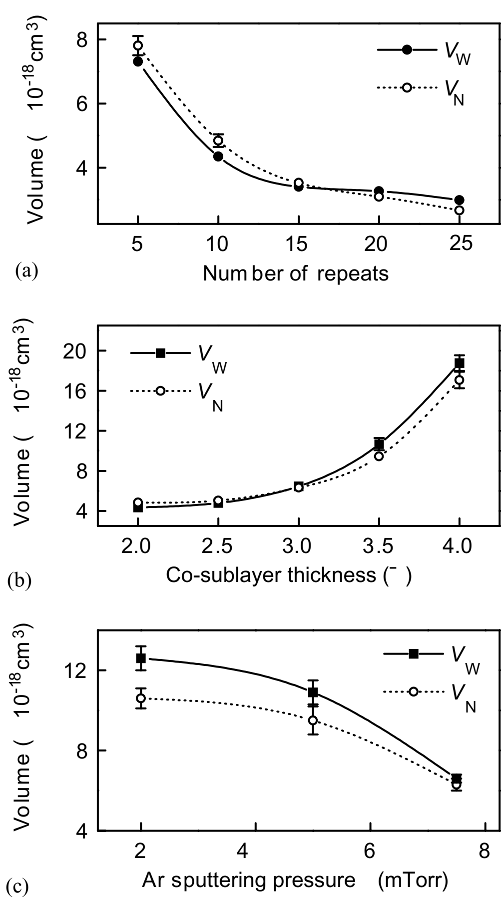

Fig. 1. The wall-motion activation volume V_W and the nucleation activation volume V_N of (a) the (2-Å Co/11-Å Pd)$_n$ samples with respect to the number of repeats n, (b) the (t_Co-Co/11-Å Pd)$_{10}$ samples with respect to the Co-sublayer thickness t_Co, and (c) the (4-Å Co/11-Å Pt)$_{10}$ samples prepared under various Ar-sputtering pressure. The lines are guide for eye and the error bars indicate the chi-square values of linear fitting.

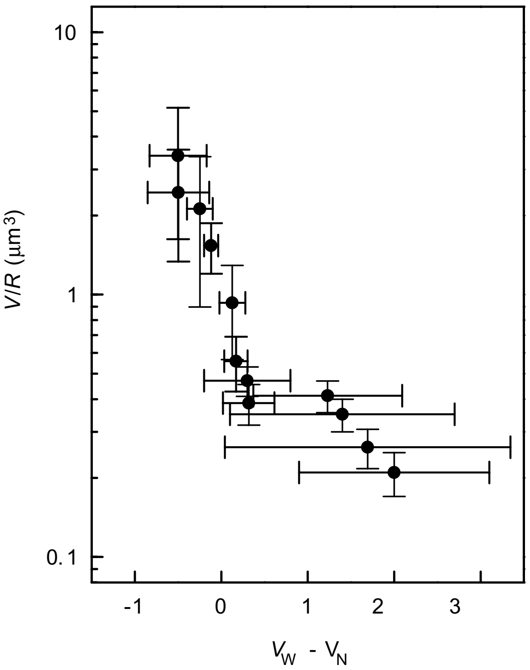

Fig. 2. The correlation between the reversal ratio of the wall-motion speed V over the nucleation rate R and the inequality $V_W - V_N$.

or magnetic properties. The most striking feature of Fig. 1 is the fact that the activation volumes of the wall-motion and nucleation processes are different from each other beyond the measurement accuracy and that the inequality systematically changes in accordance with the variation of the multilayer structure and the sputtering pressure.

We found that the inequality had a crucial influence on magnetization reversal behavior. In Fig. 2, we plot the reversal ratio V/R versus the inequality $V_W - V_N$, where the reversal ratio was measured under a reversing field of the coercivity for each sample. The reversal ratio indicates the difference between the activation energies of the two reversal processes [2,8], and characterizes the contrasting reversal modes: wall-motion dominant reversal for a larger ratio, while nucleation dominant one for a smaller ratio. The figure shows a clear correlation between the inequality and the magnetization reversal behavior. The correlation is ascribed to the fact that the reversal mode is determined by the counterbalance between the wall-motion and nucleation processes of each activation volume and the reversal energy barrier is proportional to the activation volume. We thus conclude that a process having smaller activation volume is dominant in magnetization reversal process.

This work was supported by the Creative Research Initiatives Project of the Ministry of Science and Technology of Korea.

References

[1] B. Raquet, R. Mamy, J.C. Ousset, Phys. Rev. B 54 (1996) 4128.
[2] J. Ferré, J.P. Jamet, P. Meyer, Phys. Stat. Sol. A 175 (1999) 213.
[3] S.-B. Choe, S.-C. Shin, Phys. Rev. B 57 (1998) 1085.
[4] J.X. Shen, R.D. Kirby, Z.S. Shan, D.J. Sellmyer, T. Suzuki, J. Appl. Phys. 73 (1993) 6418.
[5] J. Pommier, P. Meyer, G. Pénissard, J. Ferré, P. Bruno, D. Renard, Phys. Rev. Lett. 65 (1990) 2054.
[6] S.-B. Choe, S.-C. Shin, Phys. Rev. B 86 (2001) 532.
[7] W. Wernsdorfer, E.B. Orozco, K. Hasselbach, A. Benoit, B. Barbara, N. Demoncy, A. Loiseau, H. Pascard, D. Mailly, Phys. Rev. Lett. 78 (1997) 1791.
[8] A. Kirilyuk, J. Ferré, V. Grolier, J.P. Jamet, D. Renard, J. Magn. Magn. Mater. 171 (1997) 45.
[9] A. Lyberatos, J. Earl, R.W. Chantrell, Phys. Rev. B 53 (1996) 5493.
[10] R.D. Kirby, J.X. Shen, R.J. Hardy, D.J. Sellmyer, Phys. Rev. B 49 (1994) 10810.
[11] S.-B. Choe, S.-C. Shin, Appl. Phys. Lett. 70 (1997) 3612.