phys. stat. sol. (b) **241**, No. 7, 1669 – 1672 (2004) / **DOI** 10.1002/pssb.200304608

Fractal analysis of time-resolved magnetic domain patterns in Co/Pd multilayer with varying number of repeats

Dong-Hyun Kim[*, 1], **Yoon-Chul Cho**[1], **Sug-Bong Choe**[2], and **Sung-Chul Shin**[1]

[1] Department of Physics and Center for Nanospinics of Spintronic Materials,
Korea Advanced Institute of Science and Technology, 373-1 Guseong-dong, Yuseong-gu, Daejeon, Korea
[2] Advanced Light Sources, Lawrence Berkeley National Laboratory, Berkeley, CA94720, USA

Received 23 October 2003, revised 21 February 2004, accepted 25 March 2004

PACS 05.40.–a, 75.70.Cn, 75.70.Kw

We investigate the fractal behavior of magnetic domain together with analysis of dynamic reversal behavior in Co/Pd multilayer films prepared with different number of repeats *n*. We utilize a novel magneto-optical microscope magnetometer technique to visualize the time-resolved domain evolution patterns in these films. Quantitative analysis of the time-resolved domain evolution patterns allows us to determine the fractal dimension D_f and the reversal ratio V/R depending on *n*, where V/R represents the counterbalance between the wall-motion speed V and the nucleation rate R. As *n* increases, domain shape becomes more ragged and complex and thus, D_f increases. Interestingly enough, the change in D_f clearly seems to be coupled to the change in V/R with varying *n*, which implies that the correlation between D_f and V/R is mediated via the distributed defects.

1 Introduction Understanding the shape of magnetic domain and domain dynamics during magnetization reversal in ferromagnetic nanothin films continues to be an intriguing issue in magnetism, greatly motivated by recent technological interest for upcoming magnetoelectric technology such as spintronics and quantum computing as well as for ultrahigh density magnetic and magneto-optical recording [1, 2]. To meet the technological interest, it is so vital to understand domain properties, since the magnetic information is stored and controlled via the formation and the reversal of the domain. The size, irregularity, and stability of the written domain will affect the performance of the real magnetic devices. Recently, it has been reported that the detailed shape and the reversal behavior of the magnetic domain is closely correlated with varying the Co sublayer thickness in Co/Pd multilayers [3], where the fractal dimension D_f characterizing the shape of the domain has been found to be inversely related to the reversal parameter V/R representing the counterbalance between the wall-motion speed V and the nucleation rate R of magnetic domain [4]. However, systematic investigation on the correlation between the shape and the reversal behavior of magnetic domain in the real ferromagnetic films are still lacking.

Domain properties in the real films cannot be fully explained without considering the defect distributed in the film. Numerous efforts have been devoted to correlate the defect to the domain properties. It has been known that distributed defect may leads the motion of domain wall to be glassy creeping dominated by defect [5] or to be propagating with a deroughened shape competing with defect [6]. In this sense, it is not surprising to notice that there have been wide varieties of results reporting different and, in some cases, controversial domain properties depending on detailed fabrication conditions even among similar samples [7 – 10]. Recently, domain dynamics has been investigated based on thermally activated

---

[*] Corresponding author: e-mail: d.h.kim@kaist.ac.kr, Phone: +82 42 869 8164, Fax: +82 42 869 8100

relaxation model in Co/Pt multilayer films sputtered with variation of Ar sputtering pressure [11], where it has been revealed that dynamic properties of domain is truly affected by distributed defects such as grain boundary. However, no in-depth quantitative study has been addressed on the correlation between the domain-wall shape and the reversal behavior under the influence of the defects. In the present work, we report the quantitative analysis of correlation between the fractality and the reversal behavior of the domain with varying the number of repeats of the Co/Pd multilayer and thus, with varying the areal defect density of the sample.

2 Experimental For the purpose of our study, Co/Pd multilayer (4-Å Co/11-Å Pd)$_n$ has been prepared with varying only the number of repeats n from 5 to 15 with fixing all other parameters so that the number of interfaces and thus, the number of defects in the sample increases with being roughly proportional to n. Co/Pd multilayer system has been chosen, since this system has been one of the most promising materials for perpendicular magnetic recording and magneto-optical recording media due to a large perpendicular magnetic anisotropy and a large Kerr rotation angle at a short wavelength. We expect a wide range of magnetization reversal behavior in this system from the wall-motion dominant one to the nucleation dominant one. Samples were prepared on glass substrates by dc-magnetron sputtering under 2.0×10^{-7} Torr base pressure and 5 mTorr Ar sputtering pressure. Low-angle X-ray diffraction studies revealed that all samples had distinct peaks indicating an existence of the multilayer structure. We utilize a novel magneto-optical microscope magnetometer (MOMM) technique to directly visualize the time-resolved domain evolution patterns in these multilayers. Details of MOMM are described elsewhere [12]. The magnetization was triggered by applying a magnetic field in the field range of 70–90% of the coercivity to an initially saturated sample.

3 Results The domain evolution patterns of (4-Å Co/11-Å Pd)$_n$ with n = 5, 10, and 15, observed via MOMM under a constant applied field, are demonstrated in Fig. 1. It is clear that irregularity and roughness of domain wall patterns appear to increase as n increases, which is expected from the increase of defects proportional to the number of interfaces in the multilayers. From Fig. 1, one can also notice that that not only the geometry of domain patterns but also the reversal process is changed with increase of n. We witness that domain reversal process changes from a wall-motion dominant process to a nucleation dominant one with the increase of n.

The shape of domain has been quantitatively analyzed via fractal dimension D_f, which can be determined through the perimeter-area scaling relation of the domain patterns [13]. The perimeter and the area can be determined from image processing of grabbed images, such as contrast-enhancing, background subtraction, noise-filtering, and black-and-white image extraction processes. We find that D_f increases

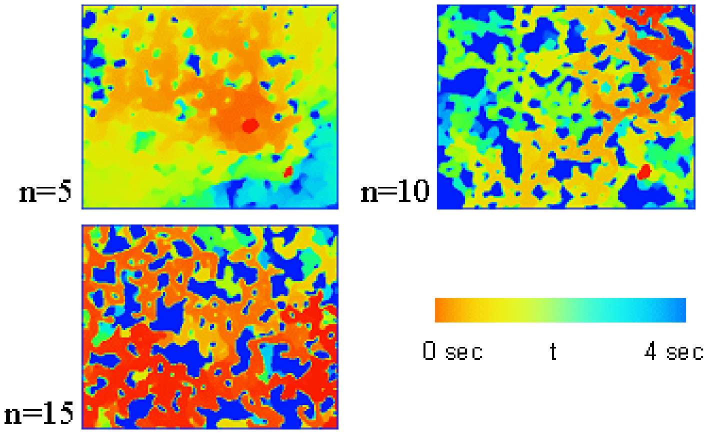
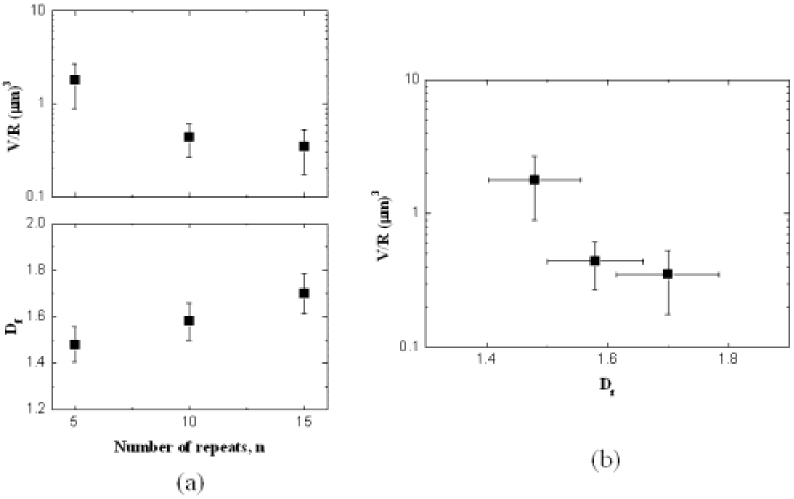


Fig. 1 (online colour at: www.interscience.wiley.com) Domain evolution patterns of (4-Å Co/11-Å Pd)$_n$ samples prepared with varying n to be 5, 10, and 15. The observed area is 40×32 μm^2 and the color represents the elapsed time from 0 to 10 seconds in the process of domain evolution.



(a)

(b)

Fig. 2 (a) Fractal dimension D_f of (4-Å Co/11-Å Pd)$_n$ and reversal ratio *V*/*R* with respect to number of repeats *n*. (b) Correlation between the fractal dimension D_f vs the reversal ratio V/R.

from 1.45 ± 0.07 to 1.70 ± 0.08 with increase of *n*, as shown in Fig. 2(a). It should be noted that D_f of each sample is truly coincident with the degree of jaggedness of the corresponding domain evolution patterns of Fig. 1. The increase of D_f directly proves the role of defects in shaping the domain wall during magnetization reversal. As the number of defects increases, the propagating wall will have a more chance to be pinned, forming a roughned domain wall through the distributed defects.

The reversal behavior has been quantitatively analyzed using reversal ratio *V*/*R*, which can be determined from the observed time-resolved domain evolution patterns. The wall-motion speed *V* and the nucleation rate *R* can be independently determined from the area and the perimeter of time-resolved domain evolution patterns. The details of the analysis method are described in Ref. [14]. The *V*/*R* of each sample decreases from 1.80 ± 0.78 to 0.35 ± 0.16, as shown in Fig. 2(a). Note that the reversal behavior of corresponding sample changes from the wall-motion dominant process to the nucleation dominant one, as the *V*/*R* decreases, which can be directly witnessed from the corresponding domain evolution patterns in Fig. 1. The decrease of *V*/*R* can be explainable with the consideration of the increased number of defects. The increased number of defects provides more chance for nucleation of domain at each defect site and thus, *R* increases. Moreover, the defects distributed in the sample act as barriers during propagation of the domain wall and thus, the wall motion is damped and *V* decreases as n increases.

4 Discussion To examine the correlation between D_f and *V*/*R*, we plot *V*/*R* vs. D_f in Fig. 2(b). Interestingly enough, an inverse relation between *V*/*R* and D_f is demonstrated. It should be reminded that there has been a recent report by Kim et al. on the inverse correlation in Co/Pd multilayer system having different Co sublayer thickness [3], where the inverse relation is explained using macroscopic parameter such as saturation magnetization M_s and anisotropy constant K_u. However, in the present study, the multilayer samples are prepared only by varying the number of repeats with keeping other preparation conditions identical for each sample. Thus, it is expected that the overall sample properties will not be significantly different with each other and the number of defects originated from the interfaces is mainly varied. Note that the Co sublayer thickness of the multilayers investigated in this study is 4 Å, which corresponds to 2 Co atomic layers. Thus, it is reasonable to expect the main source of the defects is interfaces in this system.

It has been known that *V*/*R* can be approximated as ~exp ($E_W - E_N$) based on thermally activated relaxation model [3], where E_N and E_W represent the nucleation and the wall-motion activation energy. The relation between D_f and log (*V*/*R*) can be expressed as $D_f \sim (E_W - E_N) + C$, where *C* is a constant related with Barkhausen volume or minimum size of activated domain [15]. With this assumption, the increased number of defects can be considered to make the E_N lower and the E_W higher, since the defect can be an initial site for domain nucleation as well as a damping barrier for wall propagation. Our experimental result directly proves that the correlation between D_f and V/R can be mediated via the effect of microscopic defects distributed over the sample.

5 Conclusions In conclusion, we have investigated the fractal dimension D_f and the reversal ratio V/R of magnetic domain in Co/Pd multilayers having different number of repeats n. The time-resolved domain evolution patterns are directly visualized, where D_f and V/R are determined depending on n. The change in D_f clearly seems to be coupled to the change in V/R with varying n, where it has been revealed that the inverse correlation between D_f and V/R exists and it is mediated via the distributed defects in the sample.

Acknowledgement This work was supported through the Creative Research Initiatives Project of the Korean Ministry of Science and Technology.

References

[1] P. Grünberg, Phys. Today **54**, 31 (2001).
[2] D. A. Allwood, Gang Xiong, M. D. Cooke, C. C. Faulkner, D. Atkinson, N. Vernier, and R. P. Cowburn, Science **296**, 2003 (2002).
[3] D.-H. Kim, Y.-C. Cho, S.-B. Choe, and S.-C. Shin, Appl. Phys. Lett. **82**, 3698 (2003).
[4] S.-B. Choe and S.-C. Shin, J. Appl. Phys. **87**, 5076 (2000).
[5] S. Lemerle, J. Ferré, C. Chappert, V. Mathet, T. Giamarchi, and P. Le Doussal, Phys. Rev. Lett. **80**, 849 (1998).
[6] T. Shibauchi, L. Krusin-Elbaum, V. M. Vinokur, B. Argyle, D. Weller, and B. D. Terris, Phys. Rev. Lett. **87**, 2672 (2001).
[7] M. S. Miller, F. E. Stageberg, Y. M. Chow, K. Rook, and L. A. Heuer, J. Appl. Phys. **75**, 5779 (1994).
[8] A. L. Dantas, A. S. Carriço, and R. L. Stamps, Phys. Rev. B **62**, 8650 (2000).
[9] S. Brown, J. W. Harrell, H. Fujiwara, and T. Takeuchi, J. Appl. Phys. **91**, 8243 (2002).
[10] L. Krusin-Elbaum, T. Shibauchi, B. Argyle, L. Gignac, and D. Weller, Nature **410**, 444 (2001).
[11] Y.-C. Cho, S.-B. Choe, and S.-C. Shin, Appl. Phys. Lett. **80**, 452 (2002).
[12] S.-B. Choe, D.-H. Kim, Y.-C. Cho, H.-J. Jang, K.-S. Ryu, H.-S. Lee, and S.-C. Shin, Rev. Sci. Instrum. **73**, 2910 (2002).
[13] J. Feder, Fractals (Plenum, New York, 1988).
[14] S.-B. Choe and S.-C. Shin, Appl. Phys. Lett. **70**, 3612 (1997).
[15] S.-B. Choe and S.-C. Shin, Phys. Rev. Lett. **86**, 532 (2001).