Switching field and thermal stability of CoPt/Ru dot arrays with various thicknesses

著者	北上　修
journal or publication title	IEEE Transactions on Magnetics
volume	43
number	6
page range	2160-2163
year	2007
URL	http://hdl.handle.net/10097/47580

doi: 10.1109/TMAG.2007.893129

Switching Field and Thermal Stability of CoPt/Ru Dot Arrays With Various Thicknesses

K. Mitsuzuka[1], N. Kikuchi[2], T. Shimatsu[1], O. Kitakami[2], H. Aoi[1], H. Muraoka[1], and J. C. Lodder[3]

[1]Research Institute of Electrical Communication, Tohoku University, Sendai 980-8577 Japan
[2]Institute of Multidisciplinary Research for Advanced Material, Tohoku University, Sendai 980-8577 Japan
[3]Information Storage Group, MESA+, University of Twente, Enschede 7500 AE, The Netherlands

The switching fields and thermal stability of CoPt/Ru dot arrays with various dot thickness δ (5–20 nm) were experimentally investigated as a function of the dot diameter, D, (130–300 nm). All dot arrays showed a single domain state, even after removal of an applied field equal to the remanence coercivity H_r. The angular dependence of H_r for the dot arrays indicated coherent rotation of the magnetization during nucleation. We estimated the values of the "intrinsic" remanence coercivity H_0 obtained by subtracting the effect of thermal agitation on the magnetization and the stabilizing energy barrier to nucleation $E_0/(k_B T)$. The variation in H_0 as a function of δ and D was qualitatively in good agreement with that of the effective anisotropy field at the dot center $H_k^{eff}(r = 0)$, calculated taking account of the demagnetizing field in the dots. The ratio of H_0 to $H_k^{eff}(r = 0)$ for the dot arrays with $\delta = 10$ nm increased from 0.53 to 0.70 as D decreased from 300 to 140 nm, and no significant difference in the $H_0/H_k^{eff}(r = 0)$ ratio due to the difference in δ was observed. On the other hand, $E_0/(k_B T)$ decreased as δ decreased. $E_0/(k_B T)$ increased slightly as D decreased, but, was not so sensitive to D over the present D range.

Index Terms—**CoPt perpendicular films, dot arrays, remanence coercivity, single domain, thermal stability, patterned media.**

I. Introduction

An introduction of a new recording system using patterned media is one possibility to overcome the tradeoff between thermal stability and recording writability. A large uniaxial magnetic anisotropy K_u of $1 \sim 2 \times 10^7$ erg/cm^3 was obtained in Co-20at%Pt perpendicular films deposited on Ru seed layers [1]. Our studies for patterned films of CoPt(20 nm)/Ru revealed [2], [3] that dot arrays with dot diameter $D = 80$–245 nm have a high thermal stability. Magnetic force microscopy (MFM) images revealed that all dot arrays showed a single domain state after removal of an applied field equal to the coercivity. It is generally assumed that the reversal of the single domain dot arrays begins with a nucleation, immediately followed by domain wall propagation [3]–[7]. The nucleation point is assumed to be located at the dot edges due to the damage during the dot fabrication [4], or some point within the dots due to structural inhomogeneities [5]–[7]. In this paper, the magnetic properties of CoPt/Ru dot arrays with various dot thicknesses δ were experimentally investigated as a function of D. We discuss the switching field and thermal stability of CoPt/Ru dot arrays in relation to the distribution of the effective anisotropy field in the dots due to the demagnetizing field.

II. Experimental Procedure

$Co_{80}Pt_{20}$ films with film thicknesses of 5, 10, and 20 nm were deposited with Ru seed layers on 4-in SiO_x/Si substrates using a dc-magnetron sputtering system (ANELVA, E8002) [1]. No substrate heating was carried out during the deposition process. Dot arrays having D of 130–300 nm were made using laser interference lithography (LIL), with a constant periodicity of 600 nm [2]. Inter-dot magnetostatic coupling was negligibly small in these dot arrays. The dot patterns were formed in the magnetic layers by means of ion beam etching (IBE) with Ar^+ ions. The magnetization curves of the dot arrays were examined by anomalous Hall effect (AHE) measurements [8]. The averaged AHE signals of about 3000 dots were detected. The remanence magnetization curves were measured at applied field sweep rates of $\sim$ 10 Oe/s (using an electromagnet) and $\sim 10^8$ Oe/s (using a pulse field). Remanence coercivities at $\sim$ 10 Oe/s and $\sim 10^8$ Oe/s were defined as H_r and H_r^p.

Digital Object Identifier 10.1109/TMAG.2007.893129

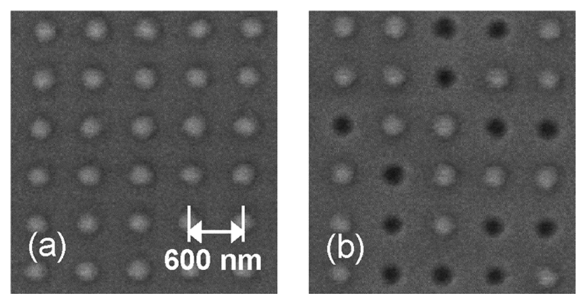

Fig. 1. MFM images of CoPt dot films with $D = 245$ nm. (a) Saturation remanent state. (b) After removal of an applied field equal to H_r.

III. Results and Discussions

A. Magnetic and Structural Properties of CoPt Dot Arrays

X-ray diffraction patterns indicated that CoPt films had a hcp structure with the c-axis perpendicular to the film plane and a c-axis distribution $\Delta\theta_{50}$ of about 2.8°, independent of film thickness [1]. Fig. 1 shows typical MFM images of dot arrays of $D = 245$ nm with $\delta = 20$ nm. The images were observed in (a) the saturation remanent and (b) after removal of a perpendicular applied field equal to H_r. MFM analysis revealed that all the dots showed a single domain state during the magnetization reversal in the present D (130–245 nm) and δ (5–20 nm) regions, although the exchange length of the magnetization of these films should be much smaller than D.

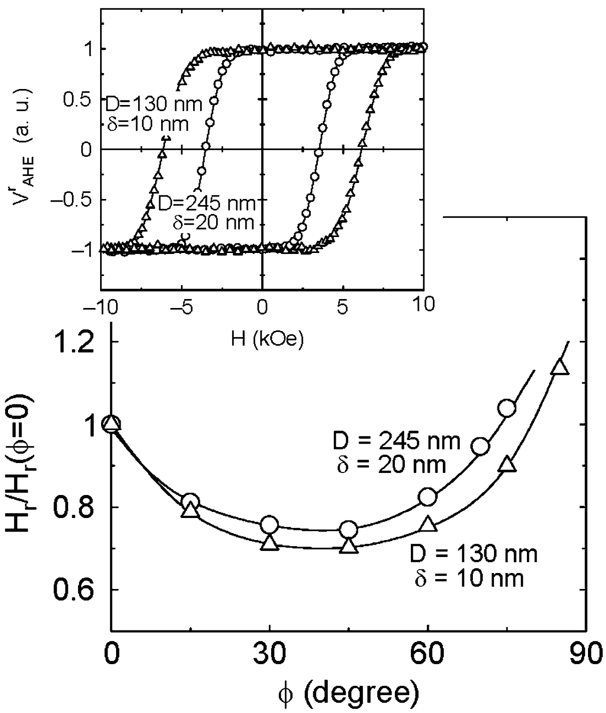

Fig. 2. Values of $H_{\rm r}/H_{\rm r}(\phi = 0)$ as a function of the angle ϕ between the applied field direction and the direction normal to the film plane. The inset shows magnetization curves and remanence magnetization curves along the perpendicular direction.

TABLE I
VALUES OF THE RATIO OF $H_{\rm k}^{\rm eff}(r = 0)$ TO $H_{\rm k}^{\rm eff}(r = 70)$ FOR DOT ARRAYS MADE OF VARIOUS MATERIALS (D = 140 NM AND δ = 20 NM)

	CoPt/Ru	Co/Pd superlattice	FePt
$M_{\rm s}$ (emu/cm^3)	1180	500	1100
$K_{\rm u}$ (x10^6 erg/cm^3)	12.4	5	50
$H_{\rm k}$ (kOe)	21	20	91
$H_{\rm k}^{\rm eff}(r=0)/H_{\rm k}^{\rm eff}(r=70)$	0.56	0.84	0.93

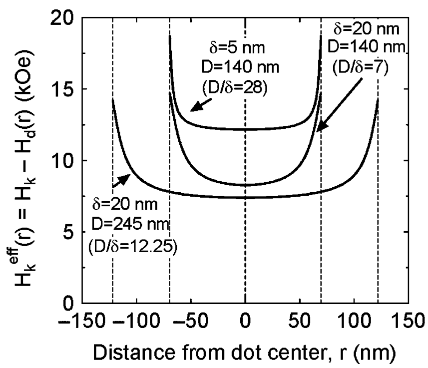

Fig. 3. Values of $H_{\rm k}^{\rm eff}$ in dots as a function of the distance from the dot center, r, for various CoPt dot having different D and δ. (M_s = 1180 emu/cm^3)

The inset to Fig. 2 shows magnetization curves (solid lines) and remanence magnetization curves (open symbols) measured along the perpendicular direction for dot arrays with different D and δ. The remanence magnetization curves were identical to the normal magnetization curves for all the dot arrays, indicating the magnetization reversal processes in the dots were irreversible. All the dot arrays showed similarly shaped magnetization curves, but the remanence coercivity $H_{\rm r}$ changed as a function of D and δ as we described later. It should be noted that the angular dependence of $H_{\rm r}$ for all dot arrays showed a minimum value at around $\phi = 45^\circ$ (ϕ is the angle between the applied field direction and the direction normal to the film plane) as shown in Fig. 2, indicating coherent rotation of the magnetization during nucleation in a small nucleation volume. No significant difference in the angular dependence of magnetization was observed due to the differences in D and δ.

B. Effective Anisotropy Field in Dots

We calculated the demagnetizing field in the dots along the perpendicular direction $H_{\rm d}$ as a function of the distance from the dot center r [3] and evaluated the distribution of the effective anisotropy field in the dots $H_{\rm k}^{\rm eff}$ using

$$H_{\rm k}^{\rm eff}(r) = H_{\rm k} - H_d(r) \qquad (1).$$

where $H_{\rm k}$ is the anisotropy field ($H_{\rm k} = 2K_{\rm u}/M_{\rm s}$, $M_{\rm s}$ is the saturation magnetization.) Fig. 3 shows the distribution of $H_{\rm k}^{\rm eff}$ in dots having various D and δ. $H_k^{\rm eff}$ shows a minimum at the dot center $r = 0$). Dots with a large D/δ ratio have a broad minimum of $H_{\rm k}^{\rm eff}$ but a decrease in the D/δ ratio results in a relatively pronounced minimum of $H_{\rm k}^{\rm eff}$ at the dot center. It should be noted that the value of $H_{\rm k}^{\rm eff}$ at the dot center $H_k^{\rm eff}(r = 0)$ for the dot arrays with $\delta = 5$ nm was larger than the others, in spite of having the largest D/δ ratio (the largest $H_{\rm d}$), because of a significant increase in $K_{\rm u}$ on reducing δ in CoPt/Ru films [1].

Table I shows the value of the ratio of $H_{\rm k}^{\rm eff}(r = 0)$ to $H_{\rm k}^{\rm eff}$ at the dot edges, $H_{\rm k}^{\rm eff}(r = 70)$, for CoPt/Ru dot arrays with $D = 140$ nm and $\delta = 20$nm $(D/\delta = 7)$. The values of $H_{\rm k}^{\rm eff}(r = 0)/H_{\rm k}^{\rm eff}(r = 70)$ calculated for dot arrays made of Co/Pd superlattice film and FePt ordered alloy film are also shown in the table, together with the $K_{\rm u}$ and $M_{\rm s}$ values used for the calculation. The value of $H_k^{\rm eff}(r = 0)/H_{\rm k}^{\rm eff}(r = 70)$ for CoPt dot arrays was remarkably smaller than the others, indicating a significant reduction in $H_{\rm k}^{\rm eff}$ at the dot center, due to a large $M_{\rm s}$ value (large $H_{\rm d}$) relative to $H_{\rm k}$.

C. H_r and Thermal Stability as Functions of D and δ

We assumed that the nucleation point for CoPt dot arrays was located around the center of the dot because of the significant reduction in $H_{\rm k}^{\rm eff}$ at the dot center. Assuming coherent rotation of the magnetization during nucleation, we estimated the values of H_0 and $E_0/k_{\rm B}T$ of all dot arrays by fitting the values of $H_{\rm r}$ and $H_{\rm r}^{\rm P}$ to the Sharrock equation [9]. H_0 corresponds to the "intrinsic" remanence coercivity obtained by subtracting the effect of thermal agitation on the magnetization, and E_0 is the stabilizing energy barrier to nucleation.

Fig. 4 shows the values of $H_{\rm r}$, H_0 and $H_{\rm k}^{\rm eff}(r = 0)$ as a function of D for dot arrays with various δ. $H_{\rm k}^{\rm eff}(r = 0)$ for thin dot arrays was larger than the others, in spite of having the largest D/δ ratio, as mentioned above. $H_{\rm k}^{\rm eff}(r = 0)$ increased slightly as D decreased in all series of dot arrays due to a decrease in $H_{\rm d}$. It should be noted that the variation in H_0 was qualitatively

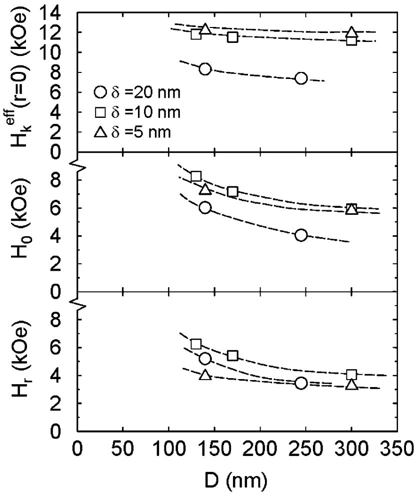

Fig. 4. Values of H_r, H_0, and $H_{\rm k}^{\rm eff}(r = 0)$ as a function of D for the dot arrays with various δ.

in good agreement with that in $H_k^{\rm eff}(r = 0)$; H_0 for the dot arrays with $\delta = 20$ nm was smaller than that for the thinner dot arrays; moreover, H_0 increased as D decreased in all series of dot arrays. The ratio of H_0 to $H_{\rm k}^{\rm eff}(r = 0)$ for the dot arrays with $\delta = 10$ nm increased from 0.53 to 0.70 as D decreased from 300 to 130 nm, and no significant difference in the $H_0/H_{\rm k}^{\rm eff}(r = 0)$ ratio due to the difference in δ was observed. A numerical calculation assuming Stoner–Wohlfarth type magnetization reversal [3] revealed that the c-axis distribution ($\Delta\theta_{50} = 2.8^\circ$) should reduce H_0 to be about 70%–78% of $H_{\rm k}^{\rm eff}(r = 0)$ in the present D/δ range. The calculated $H_0/H_{\rm k}^{\rm eff}(r = 0)$ values were in relatively good agreement with those obtained experimentally for dot arrays with a small D/δ ratio. On the other hand, $H_{\rm r}$ was slightly smaller than H_0 for the dot arrays with $\delta = 20$ nm, but $H_{\rm r}$ was reduced to nearly half of H_0 for the dot arrays with $\delta = 5$ nm due to the thermal agitation of magnetization.

Fig. 5 shows the values of $E_0/(k_{\rm B}T)$ of these dot arrays. ($k_{\rm B}$ is the Boltzmann constant and T is the absolute temperature.) The values of $E_0/(k_{\rm B}T)$ of the dot arrays with $\delta = 20$ nm were more than 600, indicating a high thermal stability, but $E_0/(k_{\rm B}T)$ decreased significantly as δ decreased, resulting in the reduction in the $H_{\rm r}/H_0$ ratio mentioned above. $E_0/(k_{\rm B}T)$ increased as D decreased in thick dot arrays, but $E_0/(k_{\rm B}T)$ of the dot array with $\delta = 5$ nm was not sensitive to the values of D over the present D range. The value of E_0 is described as the product of the effective anisotropy for nucleation $K_{\rm u}^{\rm eff}$ and the activated switching (nucleation) volume $V_{\rm act}$. $K_{\rm u}^{\rm eff}$ should increase as D decreases because of a reduction in $H_{\rm d}$. On the other hand, $V_{\rm act}$ should decrease as δ decreases, since the exchange length of magnetization, $L_{\rm ex} = 4(A/K_{\rm u}^{\rm eff})^{1/2}$, of the dot arrays (about 15 nm) is nearly the same as the δ value. It is likely

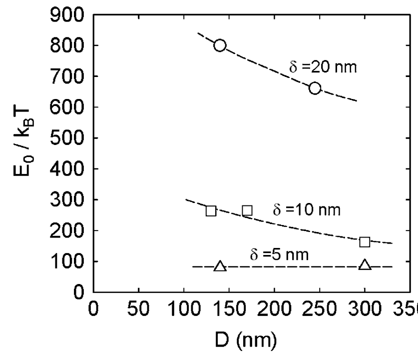

Fig. 5. Values of $E_0/k_{\rm B}T$ as a function of D for the dot arrays with various δ.

that the reduction in $V_{\rm act}$ on reducing δ is significant, compared to the increase in $K_{\rm u}^{\rm eff}$ on reducing D, and that $E_0/(k_{\rm B}T)$ was mainly determined by δ in the present D range.

ACKNOWLEDGMENT

This work was supported in part by the IT-program (RR2002) of MEXT and SRC.

REFERENCES

[1] T. Shimatsu, H. Sato, Y. Okazaki, H. Aoi, H. Muraoka, Y. Nakamura, S. Okamoto, and O. Kitakami, “Large uniaxial magnetic anisotropy by lattice deformation in CoPt/Ru perpendicular films,” *J. Appl. Phys*, vol. 99, pp. 08G908(1)–08G908(3), 2006.

[2] N. Kikuchi, R. Murillo, J. C. Lodder, K. Mitsuzuka, and T. Shimatsu, “Magnetization process of high anisotropy CoPt nanosized dots,” *IEEE Trans. Magn.*, vol. 41, no. 10, pp. 3613–3615, Oct. 2005.

[3] K. Mitsuzuka, T. Shimatsu, H. Muraoka, N. Kikuchi, and J. C. Lodder, “Magnetization reversal and switching field of CoPt/Ru patterned films,” *J. Magn. Soc. Jpn*, vol. 30, pp. 100–107, 2006.

[4] C. T. Rettner, S. Anders, T. Thomson, M. Albrecht, Y. Ikeda, E. Best, and B. D. Terris, “Magnetic characterization and recording properties of patterned $Co_{70}Cr_{18}Pt_{12}$ perpendicular media,” *IEEE Trans. Magn.*, vol. 38, no. 4, pt. 1, pp. 1725–1730, Jul. 2002.

[5] J.-P. Jamet, S. Lemerle, P. Meyer, J. Ferre, B. Bartenlian, N. Bardou, C. Chappert, P. Veillet, F. Rousseaux, D. Decanini, and H. Launois, “Dynamics of the magnetization reversal in Au/Co/Au micrometer-size dot arrays,” *Phys. Rev. B*, vol. 57, pp. 14320–14331, 1998.

[6] G. Hu, T. Thomson, C. T. Rettner, and B. D. Terris, “Rotation and wall propagation in multidomain Co/Pd islands,” *IEEE Trans. Magn.*, vol. 41, no. 10, pp. 3589–3591, Oct. 2005.

[7] T. Thomson, G. Hu, and B. D. Terris, “Intrinsic distribution of magnetic anisotropy in thin films probed by patterned nanostructure,” *Phys. Rev. Lett*, vol. 96, pp. 257204(1)–257204(2), 2006.

[8] N. Kikuchi, S. Okamoto, O. Kitakami, Y. Shimada, and K. Fukamichi, “Sensitive detection of irreversible switching in a single FePt nanosized dot,” *Appl. Phys. Lett.*, vol. 82, pp. 4313–4315, 2003.

[9] P. J. Flanders and M. P. Sharrock, “An analysis of time-dependent magnetization and coercivity and of their relationship to print-through in recording tapes,” *J. Appl. Phys*, vol. 62, pp. 2918–2928, 1987.

Manuscript received October 31, 2006 (e-mail: shimatsu@riec.tohoku.ac.jp).