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Pt Content Dependence of Magnetic Properties of CoPt/Ru Patterned Films

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The magnetic properties of dot arrays made of CoPt/Ru perpendicular films (20 nm thickness) were examined as a function of Pt content. The CoPt dot arrays with a dot size D of 140 nm showed a single domain state, after removal of the applied field equal to H_r. H_r decreased from 5.2 kOe to 3.0 kOe as the Pt content decreased from 20 at% to 14 at%. The angular dependence of H_r for these dot arrays indicated coherent rotation of the magnetization during nucleation. The effective magnetic anisotropy, including the demagnetizing energy due to the dot shape, K_u^{eff}, decreased as the Pt content decreased, resulting in the H_r reduction. The values of the switching volume for nucleation, V_{sw}, evaluated from the stabilizing energy barrier E_0, were a few percent of the dot volume. The switching diameter for nucleation, D_{sw}, increased slightly as the Pt content decreased, which was qualitatively in good agreement with the increase in the exchange length of magnetization. The value of E_0/k_BT (k_B is the Boltzmann constant and T is the absolute temperature) reduced as the Pt content decreased; however, E_0/k_BT still had a high of 440 even at 14 at% Pt content. We successfully demonstrated the reduction of H_r for CoPt/Ru patterned films on reducing the Pt content, while simultaneously maintaining a high thermal stability. A calculation based on the experimental results suggested the potential recording density of CoPt/Ru dot arrays used for patterned media to be over 1 Tb/in^2.

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

I. INTRODUCTION

ONE POSSIBILITY to overcome the tradeoff between thermal stability and overwrite performance is to introduce a new recording system using patterned media. We have been studying the magnetic properties of patterned films of $Co_{80}Pt_{20}$(20 nm)/Ru with a large perpendicular anisotropy, and our studies revealed [1], [2] that dot arrays with dot diameter $D = 80$–245 nm have a single domain state and a high thermal stability. However, the remanence coercivity H_r increased as D decreased, and reached 7.6 kOe at $D = 80$ nm. A further reduction in D below 80 nm is necessary for practical patterned media applications, which would result in a further increase in H_r; therefore, H_r has to be decreased from the viewpoint of writability. In this paper, the magnetic properties of patterned films of CoPt/Ru as a function of Pt content were examined. We discuss the reduction in H_r for CoPt/Ru patterned films, while simultaneously maintaining thermal stability.

II. EXPERIMENTAL PROCEDURE

CoPt films (20 nm thickness) with 14, 17, and 20 at%Pt content were deposited with Ru seed layers on 4-in SiO_x/Si substrates using a dc-magnetron sputtering system [1], [2]. No substrate heating was carried out during the deposition process. The uniaxial magnetic anisotropy K_u of the films was obtained by subtracting the shape anisotropy $2\pi M_s^2$ from the value measured by torque magnetometry. Dot arrays were made using laser interference lithography (LIL) [1]. The standard dot diameter was 140 nm, with a constant periodicity of 600 nm. Interdot magnetostatic coupling was negligibly small in these dot arrays. The magnetization curves of the dot arrays were examined by anomalous Hall effect (AHE) measurements [3]. We observed the averaged AHE signals of 3000 dots.

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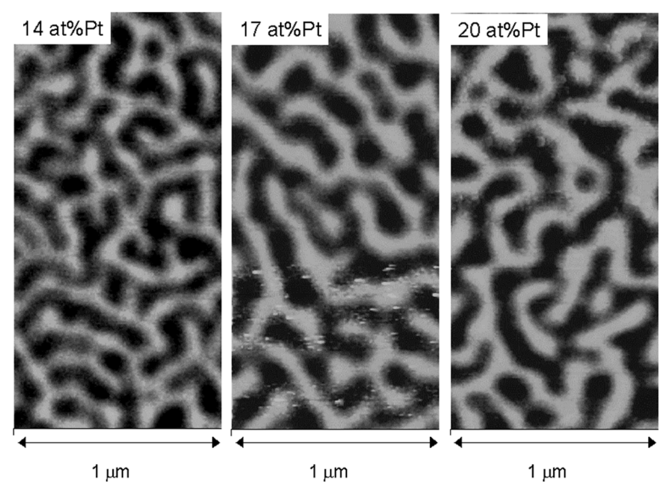

Fig. 1. MFM images of CoPt films with various Pt content (at dc-demagnetized state).

III. RESULTS AND DISCUSSIONS

A. Magnetic and Structural Properties of CoPt Films

X-ray diffraction patterns indicated that CoPt films had a hcp structure with the (002) plane parallel to the film plane, and a c-axis distribution of about 2.8 degrees, independent of Pt content [4]. Fig. 1 shows magnetic force microscopy (MFM) images of CoPt films with various Pt content. These were images observed after removal of an applied field equal to the remanence coercivity in the perpendicular direction. All the films exhibited a maze domain structure, and the domain width W_d decreased on reducing the Pt content. Table I shows the values of W_d, the saturation magnetization M_s, and K_u for these films.

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TABLE I
MAGNETIC PROPERTIES OF CoPt FILMS WITH VARIOUS Pt CONTENT

Pt content (at%)	14	17	20
W_d (nm)	144	172	181
M_s (emu/cm^3)	1233	1206	1180
K_u (x10^6 erg/cm^3)	10.2	11.9	12.4
A (x10^{-6} erg/cm)	1.21	1.05	0.95

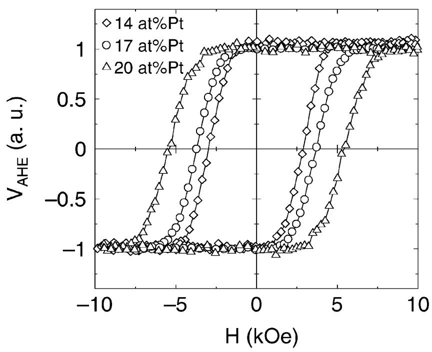

Fig. 2. Magnetization loops of dot arrays of 14, 17, and 20 at%Pt composition ($D = 140$ nm).

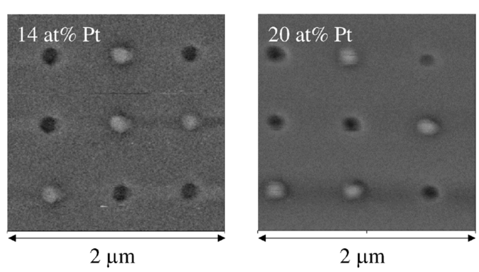

Fig. 3. MFM images of dot arrays of 14 and 20 at%Pt composition.

In the table, the values of the exchange stiffness constant A, calculated from the values of W_d, M_s, and K_u [5] are also shown. The value of W_d decreased from 181 to 144 nm as the Pt content decreased from 20 to 14 at%. It is likely that the W_d reduction on reducing Pt content was mainly caused by the increase in M_s (magnetostatic energy) and the reduction in K_u. The value of A calculated from these values increased as the Pt content decreased.

B. Magnetic Properties of CoPt Dot Arrays

Fig. 2 shows remanence magnetization curves for dot arrays with various Pt content ($D = 140$ nm). Fig. 3 shows MFM images observed after removal of applied field equal to H_r in the perpendicular direction. The dot arrays with 14 and 17 at%Pt content showed a single domain state, the same as the dot arrays with 20 at%Pt content [1], [2], although the exchange length of magnetization of these films should be much smaller than D. H_r decreased significantly from 5.2 to 3.0 kOe as the Pt content decreased from 20 to 14 at%. The angular dependence of H_r for the dot arrays of 14 and 17 at%Pt showed a minimum value at around $\phi = 45$ degrees (ϕ is the angle between the applied field direction and the direction normal to the film plane), similar to the dots with 20 at%Pt [1], [2], as seen in Fig. 4, indicating coherent rotation of the magnetization during nucleation.

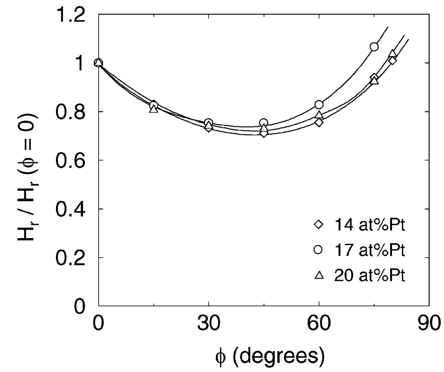

Fig. 4. Values of $H_r/H_r(\phi = 0)$ as a function of the angle ϕ between the applied field direction and the direction normal to the film plane.

TABLE II
MAGNETIC PROPERTIES OF DOT ARRAYS ($D = 140$ nm)

Pt content (at%)	14	17	20
K_u^{eff} (x10^6 erg/cm^3)	2.1	4.1	4.9
H_k^{eff} (kOe)	3.4	6.7	8.2
H_r (kOe)	3.0	3.9	5.2

No significant difference in the angular dependence of magnetization was observed, due to the difference in Pt content. We also observed magnetization curves and MFM images for dot arrays with $D = 180$ nm. It should be noted that the dot arrays with 14 at%Pt-Co films showed a multidomain structure after removal of an applied field equal to H_r, and the value of H_r reduced significantly to 1.4 kOe. However, the dot arrays with 17 and 20 at%Pt content maintained the single domain state. It is likely that the stability of the single domain state is related to the domain width shown in Fig. 1. The fact that W_d decreased as the Pt content decreased, as mentioned above, supports this consideration.

Table II shows the values of the effective anisotropy $K_u^{\rm eff}$ at the center of the dot calculated from K_u values, taking account of the demagnetizing energy due to the dot shape, the effective anisotropy field $H_k^{\rm eff}(= 2K_u^{\rm eff}/M_s)$, and H_r. $K_u^{\rm eff}$ decreased as the Pt content decreased, and this $K_u^{\rm eff}$ reduction resulted in a large reduction in $H_k^{\rm eff}$ from 8.2 to 3.4 kOe. Our previous studies suggested [2], [6] that the magnetization reversal of a $Co_{80}Pt_{20}$ dot occurs by two steps. The first step is a nucleation at the center of the dot, and this nucleation occurs by a rotational type of magnetization reversal. The second step is the propagation of the wall formed around the nucleation point, which occurs in the applied field immediately after the nucleation. Almost the same magnetization process is proposed for Co/Pd islands [7], although location of the nucleation site was not discussed. It is likely that the $H_k^{\rm eff}$ reduction on reducing the Pt content results in the H_r reduction. This result indicates that we can control the H_r value of CoPt dot arrays by controlling the Pt content.

The slope of magnetization curves in Fig. 2 indicates the dot-to-dot distribution of H_r, since each dot should have a rectangular shape of magnetization curve. No significant difference in the slope of curves was observed. Our studies suggested [2] that this distribution is mainly caused by distributions of dot shape (shape anisotropy) and c-axis of the hcp-lattice. No significant difference in the slope of curves is reasonable, because

TABLE III
THERMAL STABILITY OF DOT ARRAYS

Pt content (at%)	14	17	20
E_0 / ($k_B T$)	440	770	800
K_u^{eff} (x10^6 erg/cm^3)	2.1	4.1	4.9
V_{sw} (nm^3)	8780	7830	6820
D_{sw} (nm)	24	22	21
L_{ex}=4(A/K_u)$^{1/2}$ (nm)	13.8	11.9	11.1

the distributions of dot shape and c-axis should be nearly independent of Pt content.

We measured the remanence coercivity at a high applied field-sweep rate of $\sim 10^8$ Oe/s, H_r^P, using a pulse field magnetometer [6], and estimated the stabilizing energy barrier E_0 by fitting the values of H_r and H_r^P to the Sharrock equation [8]. Table III shows the values of $E_0/(k_B T)$ (k_B is the Boltzmann constant, and T is the absolute temperature), the switching volume for nucleation $V_{\rm sw}(= E_0/K_u^{\rm eff})$, the switching diameter for nucleation $D_{\rm sw}$, calculated from $V_{\rm sw}$ assuming a cylindrical nucleation volume, and the exchange length of magnetization $L_{\rm ex} = 4(A/K_u)^{1/2}$. $E_0/(k_B T)$ reduced from 800 to about 440 as the Pt content decreased; however, $E_0/(k_B T)$ was still several times larger than that of Co/Pt multilayer dots [9].

On the other hand, the values of $V_{\rm sw}$ were a few percent of the dot volume (about 3×10^5 nm^3) in all dot arrays, indicating that nucleation starts from a small region of the films [1], [2], [6]. The values of $V_{\rm sw}$ and $D_{\rm sw}$ increased slightly as the Pt content decreased. The increase in $D_{\rm sw}$ is in good agreement with the increase in $L_{\rm ex}$. However, these results suggest no significant change in the magnetization reversal process due to the reduction in Pt content.

C. Magnetic Properties of CoPt Dots for 1 Tb/in^2

We considered the requirements for CoPt dot arrays able to support 1 Tb/in^2, based on the magnetic properties mentioned above. The pitch of the dots at 1 Tb/in^2 corresponds to 25 nm, therefore, the dot diameter should be 15–20 nm. This dot size D is smaller than the $D_{\rm sw}$ of the CoPt dot arrays mentioned above, suggesting that the magnetization would reverse nearly coherently over the whole dot, and $D_{\rm sw}$ should be the same as that of the D used to calculate the thermal stability. Moreover, H_r should increase to nearly $H_k^{\rm eff}$, therefore, control of $H_k^{\rm eff}$ taking account of the dot-shape anisotropy is very important for realizing a sufficient writability.

On the other hand, the effect of interdot magnetostatic coupling on the magnetic properties should be taken into account, because of the high packing density of the dot arrays. Assuming that H_r should be equal to $H_k^{\rm eff}$, we calculated the values of H_r for dot arrays of $D = 15$ nm, with a dot pitch of 25 nm. Table IV shows the values of H_r for dot arrays with various Pt content and thickness. The H_r value depends on the magnetization of the surrounding dots. Therefore, the maximum $H_r, H_r^{\rm max}$, and the minimum $H_r, H_r^{\rm min}$, were also calculated and shown in the table. The reduction of Pt content from 20 to 14 at% reduces H_r from 23.2 to 18.8 kOe. However, the interdot magnetostatic coupling causes a significant distribution in H_r from $H_r^{\rm min}$ to $H_r^{\rm max}$. It should be noted that reduction in the dot thickness is very effective in reducing H_r and its distribution, as seen in Table IV, because of an increase in the demagnetizing field and a reduction in the interdot magnetostatic coupling. $E_0/(k_B T)$ at saturation remanence reduces on decreasing the Pt content and thickness. However, a high thermal stability of $E_0/(k_B T) = 110$ is still maintained, even for 5-nm-thick dot arrays of 14 at%Pt content.

TABLE IV
CALCULATED MAGNETIC PROPERTIES FOR DOT ARRAYS OF $D = 15$ nm, WITH A DOT PITCH OF 25 nm, CORRESPONDING TO 1 Tb/in ^{2}

Pt content (at%)	14	17	20	14
Dot thickness (nm)	20	20	20	5
H_r (kOe)	18.8	22.0	23.2	7.7
H_r^{max} (kOe)	23.2	26.2	27.4	9.0
H_r^{min} (kOe)	14.5	17.8	19.1	6.5
H_r^{max}-H_r^{min} (kOe)	8.7	8.4	8.3	2.5
E_0/($k_B T$) at remanence	970	1160	1220	110

IV. CONCLUSION

We successfully demonstrated the reduction of H_r for CoPt/Ru patterned films on reducing Pt content, while simultaneously maintaining a high thermal stability with a single domain state. It is likely that CoPt/Ru dot arrays have a high potential for use as patterned media at densities of over 1 Tb/in^2.

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