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Nucleation size of hcp-CoPt dot arrays characterized by time dependence of coercivity

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Abstract. The magnetization reversal process for dot arrays is likely to start from a nucleation followed by propagation process. In this study, we estimated the nucleation diameter \( D_n \) for dot arrays made from thin hcp-CoPt perpendicular films (thickness \( \delta = 3 \) nm) and Co/Pt multilayered films (\( \delta = 9 \) nm), respectively. The dot diameter, \( D \), was varied from 30 to 200 nm for CoPt dot arrays, and from 40 to 80 nm for Co/Pt dot arrays. The remanence coercivity was measured at measurement times \( t' = 10^{-3} \) s and \( 10^{-5} \) s (pulse field), and defined as \( H_r \) and \( H_r^P \). The energy barrier \( \Delta E \) was evaluated by fitting \( H_r \) and \( H_r^P \) to Sharrock’s equation. The value of \( D_n \) was estimated from \( \Delta E \), \( \delta \) and the effective magnetic anisotropy of dot arrays including the demagnetizing energy due to the dot shape \( K_u^{eff} \). \( D_n \) was independent of \( D \) in both series of dot arrays, and about 17 nm for CoPt dot arrays and about 11 nm for Co/Pt dot arrays. These values were close to both the grain size and the exchange length of these films.

1. Introduction

Dot arrays with perpendicular magnetization are technically attractive for applications to bit patterned media and magnetic random access memories. It is generally assumed that the reversal of single domain dot arrays begins with a nucleation, immediately followed by domain wall propagation [1-9]. The nucleation point is assumed to be located at the dot edges due to damage during dot fabrication [2], or at some points within the dots due to structural inhomogeneities such as grains with a low magnetic anisotropy [1,3-5,8]. We have been studying the magnetic properties of dot arrays of hcp-Co-Pt, and our experimental results suggest that the nucleation point is located around the dot centre due to the large demagnetizing field in the dot centre [6,7]. The nucleation size has been previously reported as a few tens of nm [5,9,10], however, the relation between the nucleation size and the dot diameter and/or magnetic/structural properties remains unclear.

In this study, magnetization curves of dot arrays made from thin hcp-CoPt perpendicular films, with various dot diameters \( D \) from 30 nm to 200 nm, were examined by Anomalous Hall effect (AHE) measurements [11] using a pulse field. The nucleation diameters \( D_n \) of these dot arrays were estimated and discussed as a function of \( D \), and compared with \( D_n \) values for dot arrays made from Co/Pt multilayered (Co/Pt ML) films.
2. Experimental procedure

Hcp-Co-25at%Pt films with film thicknesses, $\delta$, of 3 nm were deposited on 4 inch SiO$_x$/Si substrates covered with Ru underlayers using a dc-magnetron sputtering system (ANELVA, E8002) [12]. [Co(0.4 nm)/Pt (0.6 nm)]$_9$ multilayered films ($\delta=9$ nm) were deposited on Pt underlayers in the same sputtering system. Dot arrays were formed using high resolution e-beam lithography and reactive ion etching. The dot diameter $D$ was varied from 30 to 200 nm for hcp-CoPt dot arrays, and from 40 to 80 nm for Co/Pt ML dot arrays. We used partially etched Ru or Pt underlayers, 12 $\mu$m wide crosses having four contacts pads, as electrodes for the AHE measurement as shown in Fig.1, and observed the averaged AHE signals of about 900-20000 dots on the cross. Remanence AHE curves were measured at applied field sweep rates of $\sim$10 Oe/s (using a superconductive magnet) and $\sim$10$^8$ Oe/s (a pulse field). The effective magnetic anisotropy of the dot arrays, $K_u^\text{eff}$, including the shape anisotropy of the dots was measured by the GST method [13] using the Anomalous Hall Effect.

3. Results and discussion

X-ray diffraction patterns indicated that Co-Pt films had a hcp structure with the c-axis perpendicular to the film plane and a c-axis dispersion, $\Delta\theta_{50}$, of about 2.8 degrees [12]. The values of the saturation magnetization, $M_s$, were 1183 emu/cm$^3$ for Co-Pt films and 774 emu/cm$^3$ for Co/Pt ML films. Fig.2 shows a magnetic force microscopy (MFM) image of Co-Pt dot arrays with $D=30$ nm. The image was observed 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 $D$ range for dot arrays of both Co-Pt and Co/Pt ML.

Fig.3 shows remanence AHE curves (open symbols) measured at applied field sweep rates of $\sim$10 Oe/s and $\sim$10$^8$ Oe/s, respectively, for Co-Pt dot arrays of $D=30$ nm. Remanence coercivities were obtained from these curves, and defined as $H_c$ and $H_c^\beta$, respectively. In the figure the AHE hysteresis loop measured at $\sim$10 Oe/s (dotted line) is also shown for comparison. The remanence AHE curve at $\sim$10 Oe/s was identical to the AHE hysteresis loop, indicating that all the magnetization reversal processes in the dots were irreversible. It is likely that reversal of the single domain dot arrays begins with a nucleation, immediately followed by domain wall propagation. The AHE curves were not rectangular, because the AHE signal was averaged over 900-20000 dots as mentioned above. $H_c$ (7.2 kOe) was smaller than $H_c^\beta$ (10.1 kOe) due to thermal agitation of magnetization.

Fig.4 shows the angular dependence of $H_c$ for the Co-Pt dot arrays ($D=30$ nm) and Co/Pt ML dot arrays ($D=40$ nm, $\delta=9$ nm). It should be noted that the angular dependence of $H_c$ for all dot arrays showed a minimum value at around $\phi=45$ degrees ($\phi$ is the angle of the applied field from the film normal), indicating coherent rotation of the magnetization during nucleation. No significant difference in the angular dependence of magnetization was observed due to the differences in $D$, although the angular variation for the Co/Pt ML dot arrays was smaller than that of the Co-Pt dot arrays.
We obtained the values of $H_0$ and $\Delta E/k_BT$ of these dot arrays by fitting the values of $H_t$ and $H_t^p$ to the following equation [14], as illustrated in Fig.5.

$$H_t(t') = H_0 \left[ 1 - \left( k_B T / \Delta E \right) \ln(f_0 t'/0.693) \right]^n ,$$  

where, $f_0$ is the frequency factor (assumed to be $5 \times 10^9$ Hz), $k_B$ is the Boltzmann constant, $T$ is the absolute temperature (300 K) and $\Delta E$ is the energy barrier for nucleation. The variable $n$ was assumed to be 1/2 because of coherent rotation of magnetization during nucleation. $H_0$ corresponds to the “intrinsic” remanence coercivity obtained by subtracting the effect of thermal agitation on the magnetization. $t'$ is the time needed for a constant field equal to $H_t$ to reduce the magnetization from remanent saturation to zero.

The value of $\Delta E$ for dot arrays of Co-Pt with $D=30$ nm was $112 k_BT$. $\Delta E$ should be the product of the nucleation volume, $V_n$, and $K_u^{eff}$. $V_n$ for the dot arrays was 638 nm$^3$, about 30% of the dot volume. The value of $D_n$ calculated assuming a cylindrical shape for the nucleation volume ($D_n=2(V_n/(\delta \pi))^{1/2}=2(\Delta E/K_u^{eff}/(\delta \pi))^{1/2}$) was 16.5 nm, which was nearly half of $D$.

Table 1 shows $\Delta E/k_BT$, $V_n$ and $D_n$ for dot arrays of Co-Pt ($D=30$ and 200 nm) and Co/Pt ML ($D=40$ and 80 nm). $D_n$ for dot arrays of Co-Pt with $D=200$ nm was 16.9 nm, which was nearly the same as the dot arrays with $D=30$ nm. $D_n$ for dot arrays of Co/Pt ML was about 11 nm, and was almost independent of $D$, similar the results for Co-Pt, however $D_n$ was smaller than for Co-Pt. These results suggest that $D_n$ is almost independent of the dot size, and probably depends on material and dot thickness. TEM (Transmission Electron Microscopy) images revealed that the mean grain size was about 16 nm for Co-Pt films and about 18 nm for Co/Pt ML films, implying that the values of $D_n$ for these dot arrays were nearly the same as, or smaller than, the grain size. Assuming an exchange length of $\pi(A/K_u^{eff})^{1/2}$ and exchange stiffness $A$ of $1 \times 10^{-6}$ erg/cm, the calculated values of $L_{ex}$ were about 10-12 nm for both kinds of dot arrays. The values of $D_n$ were very close not only to the grain size, but also to the exchange length, and the main factor determining $D_n$ could not be concluded in the present study.

4. Conclusion
Our results indicated that $D_n$ was almost independent of the dot size, and was about 17 nm for dot arrays of hcp-CoPt ($\delta=3$ nm) and about 11 nm for dot arrays of Co/Pt ML ($\delta=9$ nm). More intensive efforts are required to clarify the origin of the nucleation diameter.
Table 1. $\Delta E$, $V_n$ and $D_n$ for dot arrays of hcp-CoPt and Co/Pt ML with various $D$.

| Material (thickness) | $D$ (nm) | $\Delta E/k_BT$ ($T=300K$) | $V_n$ (nm$^3$) | $D_n$ (nm) |
|---------------------|----------|---------------------------|--------------|----------|
| hcp-Co-Pt (3 nm)    | 30       | 112                       | 638          | 16.5     |
| Co/Pt ML (9 nm)     | 40       | 169                       | 836          | 10.9     |
|                     | 80       | 191                       | 775          | 10.5     |

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