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Magnetic properties of Co–Pt/Co hard/soft stacked dot arrays

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The magnetic properties of $Co_{80}Pt_{20}$(10 nm)/Co(0,3,5 nm) hard/soft stacked dot arrays with dot diameters D of about 50 nm were studied. Co–Pt films were deposited on Ru (001) seed layers, resulting in a large uniaxial magnetic anisotropy K_u with the c axis perpendicular to the film plane. Dot patterns were formed using high resolution e-beam lithography and reactive ion etching. Magnetic force microscopy images revealed that all dot arrays showed a single domain state, even after removal of an applied field equal to the coercivity. The remanence coercivity H_r decreased from 9.1 to 6.9 kOe as the Co layer thickness increased from 0 to 5 nm, indicating that the hard/soft stacked structure was effective at reducing the switching field, as theoretically predicted. The applied field angular dependence of H_r for 10-nm-thick Co–Pt dot arrays was in good agreement with calculations based on the Stoner–Wohlfarth model, $H_{\text{S-W}}$ indicating coherent rotation of the magnetization during nucleation. Moreover, it was confirmed that the hard/soft stacked structure reduced the angular variation of H_r. *© 2008 American Institute of Physics.*
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I. INTRODUCTION

A new recording system using patterned media is one possibility to overcome the trade-off between thermal stability and recording writability. We have been studying the magnetic properties of dot arrays of Co–Pt perpendicular films with a large uniaxial magnetic anisotropy K_u deposited on Ru seed layers.[1–3] Our studies revealed that the Co–Pt/Ru dot arrays possessed the high stability of a single domain state over a wide range of dot diameters D from 80 to 300 nm and high thermal stability. The remanence coercivity H_r increased as D decreased, and reached 7.6 kOe at D=80 nm for a 20-nm-thick dot with $Co_{80}Pt_{20}$ composition. The switching field of Co-Pt/Ru dot arrays is nearly proportional to the effective anisotropy field in the dots, H_k^{eff},[2] taking account of the demagnetizing field. Therefore, a reduction in D below 80 nm, which is necessary for practical patterned media applications, would result in a further increase in H_r. The value of H_r has to be decreased, while maintaining thermal stability, from the viewpoint of writability.

A composite dot structure consisting of magnetically hard and soft layers[4–8] is one possibility to reduce the switching field, while maintaining thermal stability. In this study, magnetic properties of Co–Pt/Co hard/soft stacked dot arrays with D of about 50 nm were studied.

II. EXPERIMENTAL PROCEDURE

$Co_{80}Pt_{20}$ films were deposited with Ru (001) seed layers on 4 in. SiO_x/Si substrates using a dc-magnetron sputtering system, resulting in films with a large K_u with the c axis perpendicular to the film plane.[9] The thickness of Co–Pt layer was fixed at 10 nm. Co films with thicknesses of 0, 3, and 5 nm were then deposited directly onto the Co–Pt films. No substrate heating was carried out during the deposition process. Dot patterns were formed using high resolution e-beam lithography and reactive ion etching. The value of D in the present study was about 50 nm, with a periodicity of 160 nm. The magnetization curves of the dot arrays were examined by Anomalous Hall effect (AHE) measurements.[10] We observed the averaged AHE signals of 6000 dots.

III. RESULTS AND DISCUSSION

X-ray diffraction patterns indicated that the Co–Pt 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°.[9] Magnetic force microscopy (MFM) images of Co–Pt (10 nm) dot arrays are shown in Figs. 1(a) and 1(b). The images were observed in (a) the saturation remanent state, and (b) after demagnetization along the film normal direction. The demagnetizing process was carried out by applying alternating dc magnetic fields with decreasing amplitude. All dots showed a single domain state even after demagnetization along the film normal direction, although the exchange length of the magnetization of these films should be much smaller than D. MFM images of Co–Pt(10 nm)/Co stacked dot arrays with Co layer thicknesses of 3 and 5 nm are shown in Figs. 1(c) and 1(d), respectively. These images were observed after demagnetization along the film normal direction. All dot arrays showed a single domain state, similar to the Co–Pt single layer dot arrays, indicating that the single domain state is stable even for the stacked dot arrays with Co layers up to 5 nm thick.

Figure 2 shows AHE loops (solid lines) for the dot arrays of (a) Co–Pt(10 nm), (b) Co–Pt(10 nm)/Co(3 nm), and (c) Co–Pt(10 nm)/Co(5 nm) shown in Fig. 1. These loops were

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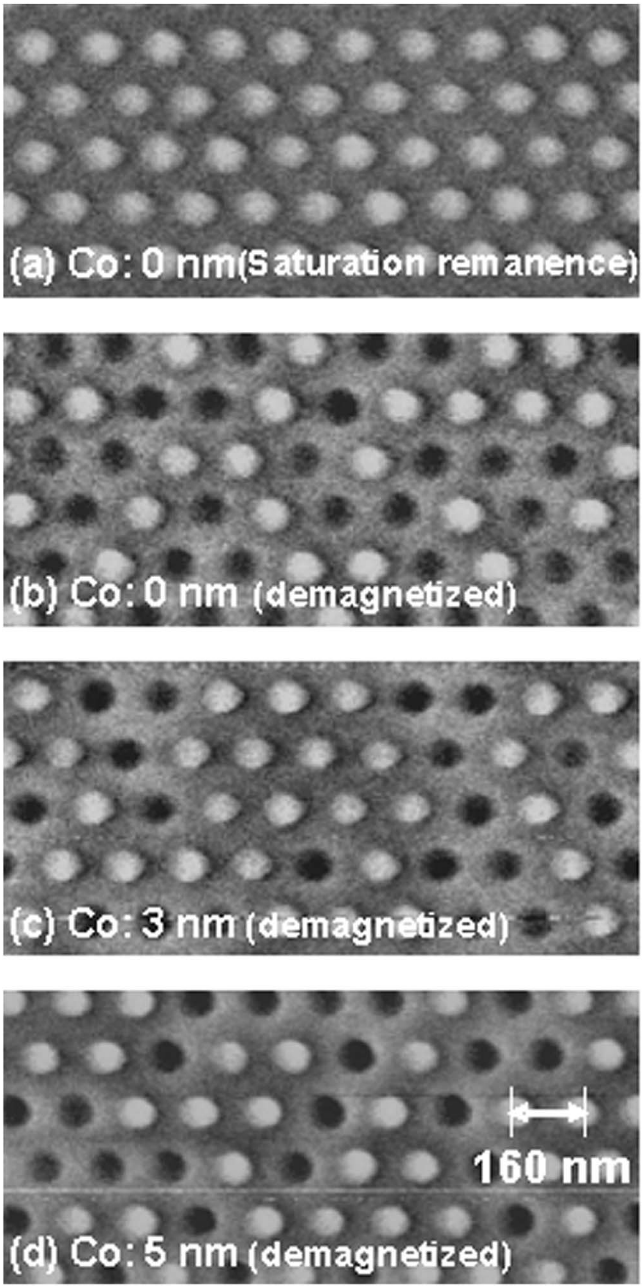

FIG. 1. MFM images of Co–Pt(10 nm) dot arrays for (a) the saturation remanent state and (b) after demagnetization along the film normal direction. (c) and (d) are images of Co–Pt(10 nm)/Co stacked dot arrays with Co layer thicknesses of 3 and 5 nm, respectively, after demagnetization along the film normal direction.

measured along the film normal direction. Remanence AHE loops (open symbols) are also shown for comparison.

The remanence AHE curves were identical to the normal AHE curves for all dot arrays, indicating that the magnetization reversal processes in these dots were irreversible. It is likely that reversal of the dots started with a nucleation immediately followed by domain wall propagation.[2,3,11–14] However, the AHE curves were not rectangular, because the AHE signal was averaged over 6000 dots. The slope of the AHE curves from the negative saturation to the positive saturation was caused by dot-to-dot variations in the switching field. We calculated numerically the interdot magnetostatic

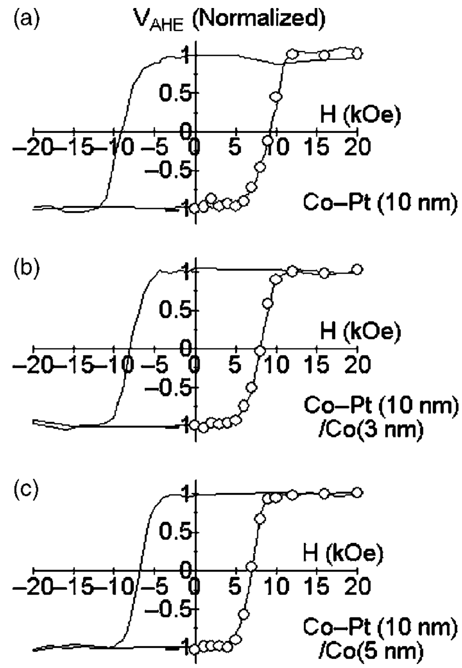

FIG. 2. AHE loops of Co–Pt(10 nm)/Co stacked dot arrays with Co layer thicknesses of (a) 0 nm, (b) 3 nm, and (c) 5 nm. In the figure, remanence AHE curves (open symbols) are also shown for comparison.

field at the dot center, H_{static}, for dot arrays in the saturation remanence state. H_{static} increased from about 80 Oe to about 120 Oe with increasing Co layer thickness from 0 to 5 nm. H_{static} is small compared to the variation in the switching field, therefore, it is likely that the slope of the loop slope is mainly caused by the switching field distribution (SFD) of the dots.

The value of H_r decreased from about 9.1 kOe to about 6.9 kOe as the Co layer thickness increased from 0 to 5 nm, indicating that the hard/soft stacked structure was effective at reducing the switching field. This significant reduction in H_r was probably caused by an enhancement of magnetization reversal due to an enhancement of the Zeeman energy on stacking the Co layer. However, decrease of H_r on increasing the Co layer thickness was around half of the decrease in the effective anisotropy field H_k^{eff}, calculated from the mean values of K_u and the saturation magnetization M_s of the stacked dots, taking into account the demagnetizing field of the dots.[2,3] This is probably due to the trapezoidal dot shape (in the cross section) formed by overetching; the effective volume ratio of Co to Co–Pt is smaller than the thickness ratio.

Figure 3 shows the value of H_r for Co–Pt(10 nm)/Co(5 nm) and Co–Pt(10 nm) dot arrays as a function of applied field angle from the film normal, ϕ. In the figure, the angular dependence of remanence coercivity $H_{\text{S-W}}$ for the Co–Pt(10 nm) single dot arrays calculated from the value of H_k^{eff} assuming a coherent magnetization switching model (Stoner-Wohlfarth model), and a c-axis distribution equal to that of the Co–Pt films ($\Delta\theta_{50}=2.8°$) is shown for comparison. The value of H_k^{eff} was calculated from the K_u and M_s values of the Co–Pt films ($K_u=1.32\times10^7$ erg/cm^3, $M_s=1140$ emu/cm^3).

The angular dependence of H_r for Co–Pt dot arrays was in good agreement with that of $H_{\text{S-W}}$, indicating coherent

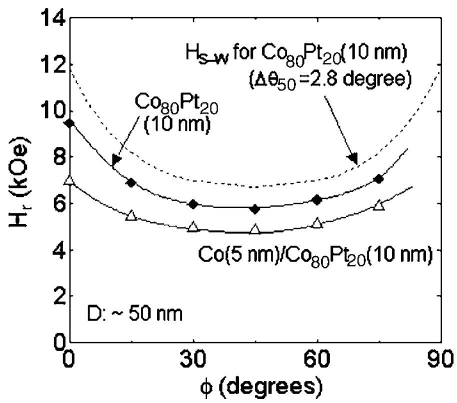

FIG. 3. The value of H_r for CoPt(10 nm)/Co(5 nm) and CoPt(10 nm) dot arrays as a function of applied field angle from the film normal, ϕ.

rotation of the magnetization during nucleation. The values of H_r for Co–Pt/Co stacked dot arrays were smaller than those for Co–Pt dot arrays for all values of ϕ, and it should be noted that the hard/soft stacked structure also reduced the angular variation of H_r. This result is qualitatively in good agreement with experimental results for FePt hard/soft stacked nanocomposite particle assemblies[8] and with theoretical predictions.[4,6] This result suggests that application of the applied field initially caused the magnetization of the soft region to rotate and the exchange field at the interface enhanced the rotation of the magnetization of the hard layer.[6,7] For practical patterned media applications, a small angular variation of H_r is a desirable property for reducing adjacent track erasure, which is a serious problem in high-density recording.[15]

Figure 4 shows the AHE loops with the horizontal axis normalized to the values of coercivity H_c $(=\sim H_r)$ for the dot arrays shown in Fig. 2. The normalized AHE loops almost overlapped one other. We estimated the applied fields where the magnetization reached $-M_s/2$ and $M_s/2$, respectively, and defined the difference between the two fields as ΔH_c. The value of SFD, defined as $\Delta H_c/H_c$, was about 0.25, and

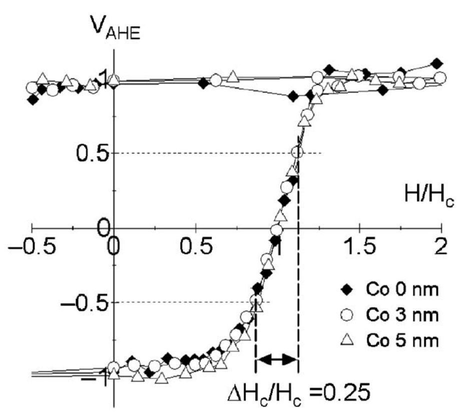

FIG. 4. AHE loops with the horizontal axis normalized to the values of coercivity H_c $(=\sim H_r)$ for CoPt(10 nm)/Co dot arrays with the Co layer thicknesses of 0, 3, and 5 nm.

was nearly independent of the Co layer thickness. No clear effect on the SFD was observed from the reduction of the angular variation of H_r. A simple calculation revealed that $\Delta H_c/H_c$ was 1.35 times larger than σ_c/H_c, where σ_c is the standard deviation of the SFD, assuming a Gaussian distribution function (i.e., σ_c/H_c=0.185).

It is likely that a reduction of the distributions of dot size, dot shape, and magnetic anisotropy,[14] besides a further reduction in the angular variation of H_r, is vital to reduce the SFD of the dot arrays.

IV. CONCLUSION

It was successfully demonstrated that hard/soft stacked structure is effective at reducing the switching field of Co–Pt dot arrays, moreover, the stacked structure reduced the angular variation of H_r, although the thermal stability of the dot arrays on stacking Co layers has not been clarified yet. More intensive efforts are required to clarify the switching mechanism of the hard/soft stacked dot arrays.

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