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Magnetic intergranular interaction in nanocomposite Co_xPt_{100-x}:C thin films

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Magnetization reversal and intergranular interactions have been studied in composite Co_xPt_{100-x}:C thin films using several magnetic characterization techniques. The intergranular interactions, as determined by ΔM curves, were strongly dependent on the ratio of Co and Pt concentration. For films with high Co content, the intergranular exchange coupling was predominant, while dipolar interactions were exhibited in the film with the equiatomic concentration of Co and Pt. Magnetic intergranular interaction was directly observed using magnetic force microscopy. There is a strong correlation between the value of the ΔM and magnetic correlation length obtained from the magnetic domain images. [DOI: 10.1063/1.1453353]

The areal density in magnetic recording has been increasing from 40% to 60% per year due to the introduction of the magnetoresistive head, and recently, has been increasingly driven to 100% per year by introduction of giant mangetoresistive head.[1] The increase of recording densities at this rate has meant a dramatic reduction in the size of an actual bit. Nanocomposite CoPt:C thin films that consist of nonmagnetic C matrix and high anisotropy fct CoPt nanocrystallites with small grain sizes have been proposed to be a potential candidate for the extremely high density recording media (100 Gbit/in.^{2}). The film fabrication method, coercivity, grain size, saturation magnetization, and average activation volumes with the C concentration and annealing process have been investigated systematically.[2,3] The requirement for extremely high recording media includes many issues such as low media noise. Many studies have shown that intergranular exchange coupling in the thin film media is a key parameter in limiting media noise that ultimately controls areal density. It is very important to have a better control of intergranular exchange interactions in thin-film media because it can reduce the media noise. In order to better understand intergranular exchange interactions and magnetization reversal properties, the remanence curve, hysteresis loops, and the magnetic domain images of two CoPt:C composite films with different Co content were studied.

The Co_xPt_{100-x}:C composite films were prepared from a multilayered structure of Co/Pt/Co/C. Using this multilayered structure, the film composition was controlled by adjusting the thickness ratio of the Co, Pt, and C layer. Two samples with different Co concentrations ($x=57$ and $x=50$) and C concentration of 35 vol. % were prepared in this study. The total thickness of the films is 11 nm. All as-deposited films were annealed in vacuum (10^{-7} Torr) for 30 min at 600 °C to obtain the fct phase. The magnetic measurements were made on an alternating gradient force magnetometer. Magnetic domain images were observed on a commercial magnetic force microscope (MFM).

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The magnetic properties of two samples are shown in Table I. Sample 1 is equiatomic concentration of Co and Pt and sample 2 has a higher Co concentration. H_{cr} and $H_{cr'}$ are the remanence coercivity obtained from the dc demagnetization (DCD) curve and isothermal remanent magnetization (IRM), respectively. IFF is the interaction field factor. Hysteresis loops for those two samples are shown in Fig. 1. The different shape of the hysteresis suggests that the two samples have different magnetization reversal mechanisms. For sample 2, a squarer loop with a higher saturation squareness S, and coercive squareness S^* suggests that grains are exchange coupled and magnetization reversal is realized through reversed domains.[4] For sample 1, the round hysteresis loop indicates less intergranular exchange coupling for this sample. Reduced exchange coupling could be expected to result in the formation of smaller domains. In this case the magnetic grains may be reversed individually and a more rounded hysteresis loop is exhibited.

Two types of remanence curves, the IRM and the DCD, provide information about the irreversible magnetization changes which have taken place. Figure 2 shows the IRM and DCD curves for those two samples. From those DCD and IRM curves, two remanence coercivities H_{cr} and $H_{cr'}$ can be determined. For sample 1, the value of H_{cr} is smaller than that of $H_{cr'}$ while for sample 2 the value of H_{cr} is larger than that of $H_{cr'}$. Corradi and Wohlfarth[5] described the interaction field factor defined by $\mathrm{IFF}=(H_{cr}-H_{cr'})/H_c$, where H_c is coercive field obtained from the M vs H hysteresis loop. As shown in Table I, the value of IFF is negative 0.017 for $Co_{50}Pt_{50}$:C films and the value of IFF is positive 0.031 for $Co_{57}Pt_{43}$:C films. Although it is not clear how the magnitude of IFF is related to the intergranular coupling strength, the difference of sign indicates that the nature of the coupling is changed. According to O'Grady *et al.*,[6] the granular interactions could be described by the differential of the IRM and DCD curves. The IRM differential, $\chi_{irr}{}^d(H)$, is related to the energy barrier distribution of the pinning sites. Because the IRM curve measures from a demagnetization state, existing domains are increased in size by the usual domain-wall movement process. The DCD differential susceptibility,

TABLE I. The magnetic parameters of the composite CoPt:C thin films.[a]

Sample	Composition	M_s (emu/cc)	S	S^*	H_c (Oe)	H_{cr} (Oe)	$H_{cr'}$ (Oe)	IFF
1	$Co_{50}Pt_{50}$	310	0.83	0.57	5180	5940	6010	−0.014
2	$Co_{57}Pt_{43}$	420	0.89	0.71	5280	5610	5450	+0.030

[a]C concentration 35 vol. %, film thickness 11 nm, IFF$=(H_{cr}-H_{cr'})/H_c$.

$\chi_{irr}{}^d(H)$, where the process starts with the material already saturated, measures the energy barrier to domain nucleation in the first instance, and then examines the mechanism by which reversal proceeds. For a system without interaction, the relation of $\chi_{irr}{}^i(H)$ and $\chi_{irr}{}^d(H)$ should be $2\chi_{irr}{}^i(H) = \chi_{irr}{}^d(H)$. The $\chi_{irr}{}^d(H)$ and $\chi_{irr}{}^i(H)$ curves for $Co_{50}Pt_{50}$:C and $Co_{57}Pt_{43}$:C films are shown in Fig. 3. The dotted lines in Fig. 3 show the $2\chi_{irr}{}^i(H)$. Our data show that the energy barrier distribution (SFD) narrows and is shifted to a lower field for the $Co_{57}Pt_{43}$:C film. Because the shape of the SFD is governed by intergranular exchange or dipolar coupling, these results suggest that the grains in the $Co_{57}Pt_{43}$:C film are more exchange coupled, while grains in the $Co_{50}Pt_{50}$:C film have weak interactions.

ΔM curve measurement is a common method to directly obtain the information about magnetic intergranular interactions in recording media. Large-scale numerical micromagnetic models[7] have confirmed the interpretation of the ΔM plot, where a positive value of the curve indicates intergranular exchange coupling and a negative ΔM profile indicates dipolar interaction. Figure 4 shows ΔM curves for those two samples. It is seen that the ΔM plot shows both the positive and the negative peaks for the $Co_{57}Pt_{43}$:C film. This suggests that interactions are complex due to the presence of intergranular exchange coupling. However, the higher positive peak implies that intergranular exchange coupling is predominant for this sample. For $Co_{50}Pt_{50}$:C film, the negative peak indicates that only a small amount of dipolar interactions are present, which is a characteristic of isolated single-domain particles.

MFM images have been used to analyze the magnetization reversal[8] and recording bit patterns.[9] Here, we use MFM images to observe the exchange coupling strength directly.

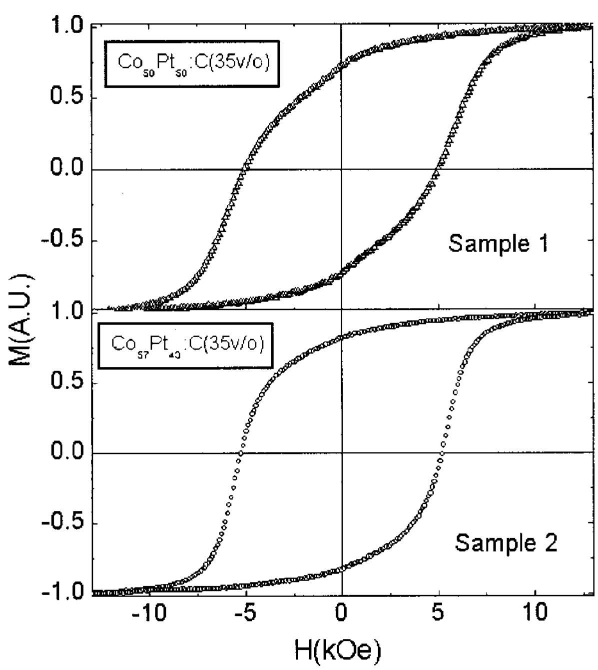

FIG. 1. Hysteresis loops for $Co_{50}Pt_{50}$:C (35 v/o) and $Co_{57}Pt_{43}$:C (35 v/o) composite films.

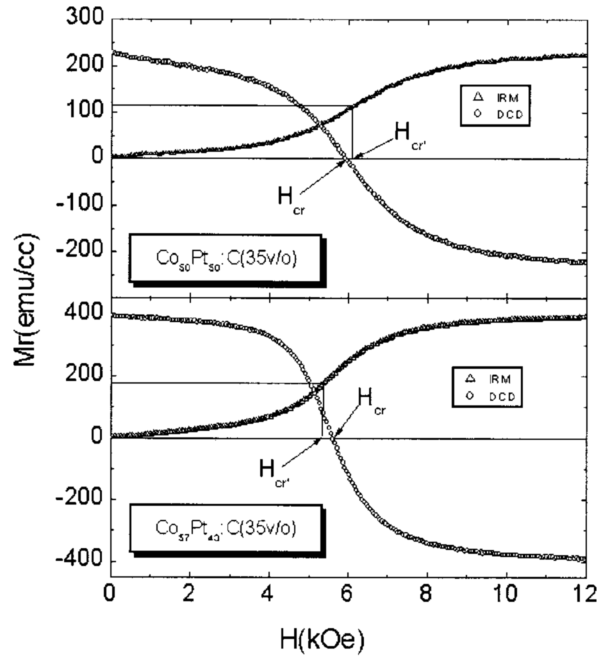

FIG. 2. IRM and DCD curves for $Co_{50}Pt_{50}$:C (35 v/o) and $Co_{57}Pt_{43}$:C (35 v/o) composite films. H_{cr} is the remanent coercivity and $H_{cr'}$ is the half-saturation point on the IRM curve.

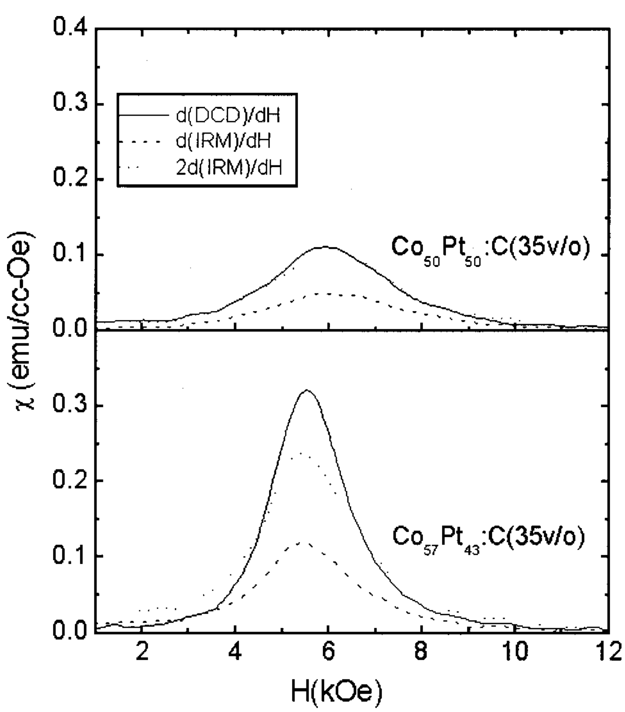

FIG. 3. Differentials of remanence curves for $Co_{50}Pt_{50}$:C and $Co_{57}Pt_{43}$:C films. Dash-dotted line is the curve $2\chi_{irr}{}^i(H)=\chi_{irr}{}^d(H)$.

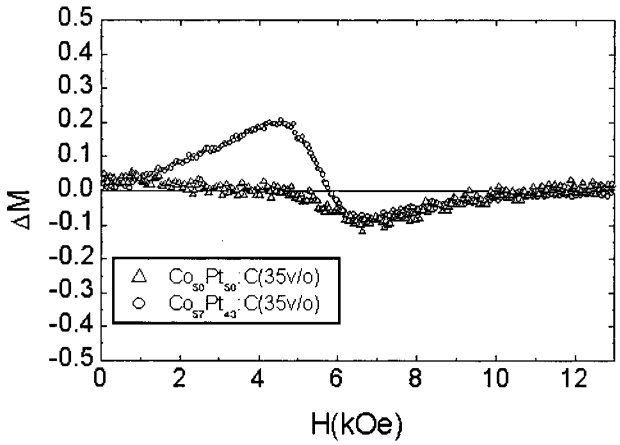

FIG. 4. ΔM curves for $Co_{50}Pt_{50}$:C and $Co_{57}Pt_{43}$:C composite films.

Figures 5(a) and 5(b) show the MFM images of 2 μm $\times$2 μm scan for $Co_{50}Pt_{50}$:C and $Co_{57}Pt_{43}$:C films. The samples were in the thermally demagnetized states. The images were obtained using a high coercivity CoPt MFM tip which was magnetized along the *z* direction (perpendicular to the sample surface). The MFM tip we used has a CoPt particle of around 50 nm at the end of tip. The MFM images were measured using a 10 nm lift height. The magnetic features as small as 30 nm can be distinguished. The light and dark contrast in Figs. 5(a) and 5(b) corresponds to the strength of the stray-field gradient on the sample surface. The lighter color represents a larger frequency shift of the MFM tip in which the magnetization of the sample and MFM tip is in the same direction. From Figs. 5(a) and 5(b) we observed that the coupling of magnetic grains in the $Co_{57}Pt_{43}$:C film is larger than that in the $Co_{50}Pt_{50}$:C. Grain-size-analysis software was used to determine the transition width of the magnetization, which is related to the coupling strength between the magnetic grains. Since both samples have the same frequency shift, about 8 Hz, we use a threshold at 50% of the highest peak (the largest frequency shift) in the images for analysis. The images above the threshold are shown in Figs. 5(c) and 5(d). We chose the ten largest sizes of coupled magnetic grains to calculate the mean value. The mean value for the area is $27\,299\pm17\,478$ nm^2 for $Co_{57}Pt_{43}$:C, and $15\,991 \pm 5476$ nm^2 for $Co_{50}Pt_{50}$:C, respectively. Correlation lengths were estimated by taking the square root of the mean area: 165 ± 132 nm for $Co_{57}Pt_{43}$:C, and 126 ± 74 nm for $Co_{50}Pt_{50}$:C. Not only are the magnetic correlation lengths of $Co_{57}Pt_{43}$:C film larger than the $Co_{50}Pt_{50}$:C film, but also, the distribution of correlation lengths for $Co_{57}Pt_{43}$:C has a wider range than that of $Co_{50}Pt_{50}$:C. This result is consistent with the ΔM measurement that the exchange coupling of the $Co_{57}Pt_{43}$:C film is stronger than that in the $Co_{50}Pt_{50}$:C film. It can be seen that there is a clear correlation between intergranular coupling (ΔM) and coupling length measured from MFM.

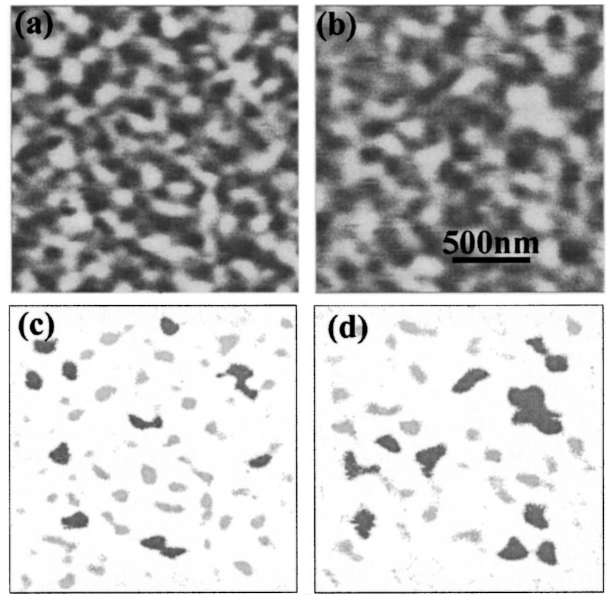

FIG. 5. MFM domain images. (a) and (b) Images of 2 μm$\times$2 μm scan for $Co_{50}Pt_{50}$:C and $Co_{57}Pt_{43}$:C films. (c) and (d) The images above the threshold [at 50% of the highest peak in the images (a) and (b)].

In summary, we have shown that the intergranular interactions in nanocomposite CoPt:C films are strongly dependent on the film composition. The nature of granular interactions can be controlled by adjusting the Co concentration. MFM images have been shown to clearly correlate with intergranular interactions, which demonstrates a new way to directly observe exchange coupling.

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