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Enhanced temperature effect on magnetoresistance in Fe/Mo multilayers

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High coercivity rare earth–cobalt films

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Rare earth–cobalt (RCO, R=Sm, Pr) films with thicknesses from 30 to 700 nm have been prepared with and without a Cr underlayer by dc magnetron sputtering from a R2Co7 composite target. The as-deposited SmCo films with a Cr underlayer have magnetic coercivities of about 500–2800 Oe and the PrCo/Cr films have coercivities of about 100–300 Oe, but after annealing at 500 °C coercivities as high as 31 kOe for SmCo/Cr films and 10 kOe for PrCo/Cr films were observed. The as-deposited PrCo films are composed mostly of an amorphous phase with about 30 vol % of crystallites but after annealing at 500 °C the film is transformed completely to crystallites of about 10 nm diameter as revealed by high-resolution transmission electron microscopy (HRTEM). Nanodiffraction and HRTEM studies show that the crystallites have a closed-packed hexagonal structure. HRTEM study also shows that the annealed SmCo films with a Cr underlayer have grain sizes of about 20 nm and the SmCo films without the Cr underlayer have grain sizes of about 10 nm. The large increase in coercivity for the annealed films is due to the growth of the crystallites. © 1996 American Institute of Physics. [S0021-8979(96)33808-1]

INTRODUCTION

Thin films of hard magnetic materials such as rare earth–transition metal alloys are of interest for device applications and magnetic recording media. Among rare earth semi-hard magnetic films, SmCo films with a Cr underlayer prepared at room temperature with high magnetic coercivity (Hc) of 3–4 kOe, small grain size and high uniaxial anisotropy have shown good potential for high density recording media.1–3 Velu et al.4 have shown that SmCo4 films on a Cr underlayer have a coercivity value of 3 kOe at room temperature. Recently, Okumura et al.5 reported Hc of about 3.5 kOe for Sm135Co65/Cr films. Liu et al.6–8 reported systematic studies of the microstructure of SmCo/Cr films including the Cr underlayer, SmCo layer, and the nanocrystallites in the SmCo layer. The dependence of Hc on the SmCo composition1–3 is unclear but it has been shown that the Hc strongly depends on the sputtering condition such as substrate temperature and Ar pressure during deposition of Cr and SmCo. This dependence may be related to the microstructure of the films. The Cr underlayer helps to increase the coercivity by controlling the grain size and morphology of the SmCo layer and also improves the in-plane magnetization. Hence if crystallinity and grain growth is promoted in the SmCo layer a much higher value of coercivity can be obtained. This can be achieved by either depositing the film at high substrate temperature or by post-annealing the as-deposited films. A coercivity of 30 kOe was obtained for 4000-Å-thick Co366Cu135Sm films prepared at substrate temperature of 600 °C by Theurer et al.9 Cadieu et al.10 have shown that SmCo3 films directly crystallized on to a heated substrate have Hc of about 23 kOe. The reason for this high coercivity was associated with the high magnetic anisotropy and the fine grain structure.

In the rare earth–cobalt system the low Co phase adjacent to SmCo2 is in general of the Sm2Co7 type which has reasonably high anisotropy field $H_A > 200$ kOe.11 The PrCo compounds also feature excellent intrinsic magnetic properties comparable to the SmCo compounds. The Pr2Co7 phase has $H_A > 100$ kOe11 and the Pr5Co19 phase has $H_A > 38$ kOe.12 In this work we report the effect of post-annealing for Pr2Co7 and Sm2Co7 films with and without the Cr underlayer.

EXPERIMENTAL PROCEDURE

R2Co7 (R=Sm, Pr) films with thickness from 30 to 700 nm were prepared with and without a Cr underlayer by dc magnetron sputtering from a composite target. All the films have a Cr overlayer of 10 nm to protect the RCo layer. The Sm2Co7 target was made by pressing the Sm2Co7 powder and then sintering in vacuum at 1100 °C for 30 min and the Pr2Co7 target was made by pressing the Pr2Co7 powder and then sintering in vacuum at 30 min at 1050 °C. The Cr target was obtained commercially and had a 99.9% purity. The base pressure of the sputtering system was $5 \times 10^{-8}$ Torr and the Ar pressure during sputtering was 20 mTorr. The sputtering rate for Pr2Co7 and Sm2Co7 was 1.1 Å/s and for Cr was 5 Å/s.

The magnetic properties of the films were measured with an alternating gradient force magnetometer (AGFM) and SQUID magnetometer. The composition of the films was analyzed by energy dispersive x-ray analysis (EDAX) and was found to be close to the target composition. The structure was studied by x-ray diffraction and high resolution electron microscopy (HRTEM).
RESULTS AND DISCUSSION

We first discuss the magnetic and structural properties for the as-deposited and annealed PrCo films. Figure 1 shows the dependence of the coercivity on the PrCo layer thickness for the PrCo/Cr films with a Cr underlayer of 80 nm. The as-deposited films show a coercivity of only about 100–300 Oe but after annealing at 500 °C in vacuum for 20 min there is a large enhancement of coercivity. The $H_c$ of the films annealed at 500 °C decreases from about 10 to 5.9 kOe as the film thickness increases from 28 to 640 nm. It was also observed for the 28-nm-thick PrCo/Cr film that upon annealing up to 350 °C, $H_c$ was nearly unchanged but at 400 °C $H_c$ increased drastically to about 7.7 kOe and at 500 °C the $H_c$ reached about 10 kOe. A bright-field TEM micrograph of the 28-nm-thick PrCo/Cr film annealed at 500 °C is shown in Fig. 2. The as-deposited films are composed of a mostly amorphous PrCo layer with about 30% volume fraction of crystallites and have small coercivity values because of the mostly amorphous PrCo layer. The film annealed at 500 °C shown in Fig. 2(a) contains nearly 100% crystallites with a grain size of 10 nm resulting in the large increase in the coercivity. The x-ray diffraction pattern of the as-deposited 420-nm-thick PrCo film only shows the (110) diffraction peak of bcc Cr and no PrCo peaks are observed for the films with and without the Cr underlayer. This is due to the large amount of amorphous phase and small crystallites in the PrCo films. After annealing at 500 °C the PrCo layer is crystalized and we observe a few sets of peaks from the x-ray diffraction pattern. The two most intense reflections are observed for 2$\theta$=35.5° and 2$\theta$=42°. It is difficult to identify the crystal structure unambiguously from the x-ray diffraction pattern because of the limited number of peaks and the several possible phases around the Pr/Co atomic ratio of 3.5, these include the PrCo$_3$, Pr$_2$Co$_3$, and Pr$_2$Co$_{19}$ phases. The detailed crystal structure of the annealed 28-nm-thick PrCo/Cr film was then investigated by nanodiffraction and HRTEM. It was found that the crystallites as shown in Fig. 2(b) have a hexagonal closed packed structure with frequent stacking faults. The nanodiffraction pattern can be well matched to the hexagonal closed packed structure.

In order to investigate whether the Cr underlayer was crucial for the enhancement of coercivity after annealing we compared the magnetic properties of a 420-nm-thick PrCo film with and without a Cr underlayer. It was observed that for the 420-nm-thick PrCo film with no Cr underlayer but with a Cr overlayer of 10 nm the $H_c$ was about 9 kOe and $M_s$=400 emu/cc after annealing at 500 °C whereas for the 420-nm-thick PrCo film with a Cr underlayer of 80 nm and a Cr overlayer of 10 nm the $H_c$ was about 7.5 kOe and $M_s$=300 emu/cc after annealing at 500 °C. Both the samples have squareness $S(M_s/M_r)$=0.8, but the coercivity squareness $S^*$ for the film with the Cr underlayer was 0.7 and for the film without the Cr underlayer the $S^*$ was about 0.35. Hence we show that if crystallinity and grain growth are promoted a large increase in coercivity can be obtained for the PrCo films with and without the Cr underlayer, except that the films with a Cr underlayer have a better hysteresis loop squareness.

Next we report the magnetic properties of the as-deposited and annealed SmCo films with and without the Cr underlayer. Figure 3 shows the dependence of the coercivity on the SmCo layer thickness for the SmCo/Cr films with and without the Cr underlayer. The as-deposited films show $H_c$ of about 500–2800 Oe but after annealing at 500 °C for 20 min in vacuum there is a large increase in coercivity. The coercivity of the films with the Cr underlayer of 80 nm and a Cr overlayer of 10 nm annealed at 500 °C varies from 21 to 29 kOe with the maximum coercivity value obtained for 100-nm-thick SmCo film. The $H_c$ of the SmCo film without the

FIG. 1. Coercivity vs PrCo layer thickness for the as-deposited and annealed at 500 °C PrCo/Cr films with a Cr underlayer of 80 nm.

FIG. 2. (a) HRTEM image of Cr(80 nm)/PrCo(28 nm)/Cr(10 nm) film annealed at 500 °C. (b) HRTEM image of a crystallite in (a).

FIG. 3. Coercivity vs SmCo layer thickness for the as-deposited and annealed at 500 °C SmCo films with and without a Cr underlayer.
Cr underlayer but with a Cr overlayer of 10 nm after annealing at 500 °C shows a large increase in coercivity only for SmCo films with thicknesses of at least 100 nm and above. A maximum $H_c$ value of 29 kOe is obtained for 300-nm-thick SmCo film. For films without the Cr underlayer and SmCo layer thickness less than 100 nm the reason for no remarkable increase in coercivity after annealing is not clear at this point. This behavior is also observed for the PrCo film with thicknesses less than 100 nm and no Cr underlayer. The point. This behavior is also observed for the PrCo film with thicknesses less than 100 nm and no Cr underlayer. The film with the Cr underlayer of only 20 nm the enhancement in coercivity after annealing is very likely due to crystallization of the SmCo grains.

M. S. Malhotra, Y. Liu, Z. S. Shan, S. H. Liou, D. C. Stafford, and D. J. Sellmyer

CONCLUSION

In this work we have shown that 28-nm-thick PrCo films with a Cr underlayer of 80 nm after annealing at 500 °C have in-plane coercivity as high as 10 kOe, $S=0.9$ and $S^*=0.75$. The PrCo|Cr films have magnetic properties and microstructure which show potential as high density recording media. Nanodiffraction and HRTEM studies show that the crystallites in the annealed film have a hexagonal closed packed structure with frequent stacking faults. The enhancement of $H_c$ after annealing is likely due to the crystallization of the PrCo grain.

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