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Effect of microstructure on coercivity of c-axis in-plane-oriented Co/Cr multilayered films

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The effect of the insertion of nonmagnetic Cr planes on coercivities of thin Co films has been studied in Co/Cr multilayered films. The in-plane coercivity $H_{\|}$ can be as high as 1800 Oe and can be adjusted easily, ranging from 650 to 1800 Oe. The large $H_{\|}$ is related to the Co (110) in-plane orientation which is induced by a Cr (100) in-plane-oriented underlayer. In addition, it appears that a decreasing saturation magnetization $M_s$, a decreasing average structural coherence length $D$ in the direction perpendicular to the film, and a narrowing distribution of $D$ are correlated to the increasing in $H_{\|}$. The effects of texture, Cr interlayers, $D$ and its distribution, and the Cr underlayer on the magnetic properties are discussed.

I. INTRODUCTION

Co/Cr multilayered films have been studied for reasons of both basic physics and possible applications. Most work has been done on films grown on room-temperature substrates. It was reported that the saturation magnetization is considerably less than the bulk value even when the Co layer thickness is as large as 70 Å, indicating an essential interface effect. There is a long distance interfacial Cr atomic diffusion especially under high-temperature annealing. Usually the coercivity $H_{\|}$ was below 1200 Oe. We report here a much higher $H_{\|}$ which might lead to certain applications, and some results of the effects of crystal orientation, coherence length, Cr layer thickness, and Cr underlayer on the magnetic properties. Because of the space limitations here, other aspects of this work will be published elsewhere.

II. EXPERIMENT

Co/Cr multilayered films were prepared in a multiple-gun dc sputtering system. Detailed experimental procedure is similar to that described in Ref. 5. Substrate temperature $T_s$ values between 20 and 450 °C were investigated. The crystal orientation and the $H_{\|}$ were maximized for $T_s = 400$ °C. This temperature is about the value predicted by the “golden rule” (the ratio of 0.618), noting the melting point for Co is 1495 °C. The base pressure was below 5 x 10$^{-7}$ Torr and the argon pressure during sputtering was 10 mTorr. The thickness of the Cr underlayer was kept at 4000 Å and the total Co thickness was kept at 600 Å. The crystal structure, texture, and coherence length were studied by x-ray diffractometry on a Rigaku DMAXB system. The layer structure was checked by small-angle x-ray diffraction on the same system. Vibrating sample magnetometry was used to measure the magnetic properties at room temperature, with a maximum field of 16 kOe.

III. RESULTS AND DISCUSSION

A. Crystal structure

Small-angle x-ray-diffraction (XRD) data show only one peak for the films with bilayer thickness less than 100 Å. This indicates that the Co/Cr interface is very diffuse and the composition profile is close to a sinusoidal distribution. The films with larger bilayer thicknesses are likely to have layered structure though we failed to observe the small-angle XRD peak, because of the large background possibly caused by the total internal reflection from the film surface. Large-angle XRD data are shown in Fig. 1(a) for a typical film. The film has 200 Å Co, 50 Å Cr, 3 bilayers total, and was deposited at $T_s = 400$ °C on a 4000-Å Cr underlayer. The crystal structure is hcp for Co and bcc for the Cr underlayer. Three Co peaks are present besides the Cr(110) and Cr(200) peaks which are mainly (if not totally) from the underlayer. The basal plane Co(002) peak is very close to the Cr(110) peak. Even when the Co(002) peak is discernible it is smaller than the Co(110) peak. Comparing with the standard Co powder XRD pattern we know that the film is oriented with the c axis basically parallel to the film plane but tipped out a little. 4000-Å Cr underlayer is oriented with (100) planes in the film plane and this produces the Co layer oriented with the c axis in the film plane by epitaxial growth. Without the Cr underlayer the films show an orientation with the c axis perpendicular to the film plane [Figs. 1(b) and 1(d)]. With a Cr underlayer and a room-temperature substrate the Cr underlayer is (110) oriented and the Co layer is less oriented [Fig. 1(c)]. For the group of films with different Cr layer thicknesses, the XRD patterns are all similar to that shown in Fig. 1(a). This means that the different Cr thickness does not significantly affect the crystal structure and microstructure of the Co layer, which has a constant thickness of 200 Å.
B. Microstructure

Figure 2(a) gives the relationship of the Co(110) axis dispersion $\Delta \theta_{90}$ and Fig. 2(b) the remanence orientation ratio $(\sigma_{f}/\sigma_{a})$ as functions of Cr layer thickness for a group of films with 200 Å Co, 3 bilayers total, $T_s = 400^\circ$C, and a 4000-Å Cr substrate. $\Delta \theta_{90}$ is defined as the full width at half intensity of the rocking curve for the Co(110) peak. $\Delta \theta_{90}$ increases sharply up to 10 Å Cr and then stays close to 5.7°. This means that all the films in this group are highly textured, and even more so for those with thinner Cr. The remanence orientation ratio drops abruptly at 5 Å Cr and then takes a value around 3.0. The nonferromagnetic Cr interlayers, which interrupt the Co layer, act as "planar defects" on microstructure and micromagnetic structure for the whole film. These planar defects further affect the separated Co layers by diffusion. To evaluate this effect, a parameter $D$, called the structural coherent length, was obtained from the shape of the Co(110) peak in the XRD data. $D$ is a length scale of the periodicity of the crystal lattice within each Co layer in the film-normal direction. Figure 3 gives the $D$ distribution for the group of films with different Cr thicknesses. Because the programmed Co layer thicknesses are the same for all the films in this case, the decrement in $D$ with increasing Cr thickness is mainly caused by the additional Co-Cr interdiffusion and weaker epitaxial growth. It will be seen that a narrower $D$ distribution as well as a smaller average $D$ value favors a larger $H_{cyl}$.

C. Magnetic properties

Figure 4(a) gives the hysteresis loops for a typical film. $H_{cyl}$ is about 1700 Oe. This is much higher than the value obtained for homogenous CoCr alloy films in any composition at any deposition and annealing conditions. This means that the planar defects, i.e., the nonmagnetic Cr layers, play an important role in the magnetization reversal process. It is noticed that the saturation magnetization, $\sigma_s$ of 80 emu/g of Co here is much less than the bulk value of 161 emu/g at room temperature. This is likely to result from the alloying effect at the interfaces, and much could be at the interface with the thick Cr underlayer.
FIG. 5. Cr layer thickness dependences of $H_{\|}$ and $H_{\perp}$ and their ratio for the films as shown in Fig. 2.

4(b) shows the loops of the film deposited at $T_r = 400^\circ$C but without the Cr underlayer. $H_{\|}$ is about one-third of the value of the film with the Cr underlayer, and apparently two magnetic phases are present. The reason for this two-phase phenomenon is not clear. For the film with $T_r = 20^\circ$C and without the Cr underlayer the loops are shown in Fig. 4(c). Here no evidence of two phases was observed. The facts that $H_{\|}$ is smaller and $\sigma_r$ is higher indicate two alloying effect at low $T_r$. Figure 4(d) shows the loops for the film deposited at $T_r = 20^\circ$C and with the Cr underlayer. $H_{\|}$ is a little larger than that of the film without a Cr underlayer but much less than that of the film with $T_r = 400^\circ$C.

Figure 5 gives the Cr layer thickness dependence of $H_r$ for the films as shown in Fig. 2. $H_r$ increases as the Cr becomes thicker and almost saturates when the Cr is 50 Å thick. The saturation value is about 1800 Oe when the Cr thickness is about 200 Å. $H_{\perp}$ increases rapidly as Cr becomes thicker at first and reaches a maximum of about 2 kOe at a Cr thickness of 20 Å. After this Cr thickness $H_{\perp}$ decreases slowly. Figure 6 shows the Cr layer thickness dependence of $\sigma_r$ and the in-plane squareness, $\sigma_{\|}/\sigma_r = S$, for the same group of films as in Fig. 5. $\sigma_r$ decreases rapidly as the Cr becomes thicker up to 20 Å and then decreases slowly up to the film with the thickest Cr layer (200 Å). The fact that the magnetic moment for Cu is only affected by the nearest neighbors suggests there is considerable atomic diffusion. $S$ is always around 0.75. As seen in Figs. 5 and 6, there is a clear correlation between the decrease in $\sigma_r$ and the increase in $H_{\perp}$, as a function of Cr layer thickness. This trend might be explained by the relation

$$H_{\perp} = C(2K/M_s) - N_{\text{eff}}M_s$$

where $C$ is a constant, $K$ is the uniaxial crystalline anisotropy constant, and $N_{\text{eff}}$ is the effective demagnetizing factor. $N_{\text{eff}}$ has a complex relation with the composition distribution, the planar defects, the grain size and shape, and the coupling strength among them. The interface anisotropy which is not included here could be small because the interfaces are diffuse, and the layer thicknesses are relatively large.

IV. SUMMARY

High $H_{\|}$ can be obtained on Co/Cr multilayered films in a wide range of Cr thicknesses, with a 4000-Å Cr underlayer and a $T_r$ of 400°C. These conditions lead to the Cr(100) and Co(110) crystal planes being mainly aligned in the film plane. The interruption of the magnetic layer by the Cr layer and the narrow coherence length distribution, as well as the Cr underlayer, proper crystal orientation, and the large extent and amount of atomic diffusion, are responsible for the increase of the $H_{\perp}$. A fuller understanding of the change in $H_{\perp}$ with thickness will require detailed information on the microstructure of this system.

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