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Abstract--Studies of the effects of substrate temperature T_S on the evolution of Co(110)/Cr(002) texture, magnetic and physical grain size, intergrain-interaction, anisotropy, orientation ratio of remanence and coercivity were investigated experimentally. It is found that the hcp-Co(110)/bcc-Cr(002) texture is improved with increasing T_S from 27°C to 265°C. The intergrain-interaction, magnetic and physical grain size decrease with increasing T_S and reach their minima at $T_S \approx 265$°C where the magnetic grain size is close to the physical grain size. The correlation between the film microstructure and magnetic properties is studied systematically.

Index terms—Co(110)/Cr(002) texture, magnetic grain, intergrain-interaction, x-ray rocking curve.

I. Introduction

In recent decades the areal density of longitudinal magnetic recording has been increasing at the rate of about a factor of 10 every 10 years and recently the rate has been increased to a compound annual growth rate of about 60%. One of the main reasons for such rapid advance is the significant achievements in understanding the correlation among the film structure, magnetic properties and recording performance. There is an increasing effort to survey the correlation between structure and magnetic properties of thin films[1,2,3]. In this paper we report our systematic studies of the effects of substrate temperature T_S on the evolution of Co(110)/Cr(002) texture and its correlation with magnetic properties.

II. Experiment

CoCrTaPt films with CrRu underlayer were sputtered onto NiP-plated Al-substrates, which had been mechanically textured circumferentially with average surface roughness of 6 Å, by DC magnetron sputtering. Substrate temperature T_S varied from room temperature to 317°C and all other sputtering conditions were fixed for all films. Structural properties were investigated by x-ray diffraction with CuK_α radiation and TEM. Both x-ray rocking curves and $\theta \sim 2\theta$ scans were used to investigate the Co(110)/Cr(002) texture. Magnetic properties were measured with a VSM and an alternating gradient field magnetometer (AGFM).

III. Results and Discussion
Evolution of Co(110)/Cr(002) texture and grains

Film structure, which is controlled largely by the processing conditions, significantly affects magnetic and recording properties of media, such as coercivity H_C, noise and thermal stability. The $\theta \sim 2\theta$ scan offers the information of Co(110) and Cr(002) crystal planes parallel to the film surface and the rocking curve offers additional information on the orientation distribution of Co(110) and Cr(002) crystal planes. The magnetic and physical grain sizes were measured to investigate the grain configuration, and the correlation between film structure and magnetic properties.[4]

The evolution of the hcp-Co(110)/bcc-Cr(002) texture as a function of T_S is depicted in Figs. 1 and 2. As shown in Fig.1, the Co(110) and Cr(002) peaks cannot be seen at T_S=27°C and their peak-height increases rapidly with increasing T_S from 27 to 287°C. As T_S increases further, the Co(110) peak-height decreases and the so-called "Ni conversion" occurs at T_S=317 °C, i.e. the NiP-plated layer starts to be partially ordered magnetically at such higher T_S. The x-ray rocking curves in Fig. 2 indicate that the width W is decreasing first rather rapidly, then slowly as T_S increases. Therefore combining the information from $\theta \sim 2\theta$ and rocking scans, it is concluded: (i) The onset of Co(110)/Cr(002) texture is around T_S=150°C, this texture reaches its optimum around T_S=243~287°C, and then degrades as T_S increases further.[5] (ii) As T_S increases from 27 to 287°C, not only the peak-height of Co(110) planes increases, but also its orientation distribution is improved. These features will be seen below when discussing film magnetic properties which are sensitive to the film microstructure. (iii) As T_S increases further from 287 to 317°C, the Cr(002)-peak continues to increase, but the Co(110)-peak decreases. As shown in Fig. 1b, the Co(110) peak is shifted towards lower 2θ values as T_S increases. This shift and the degraded Co(110) texture at T_S=317°C may be due to the diffusion of Cr into the Co alloy.

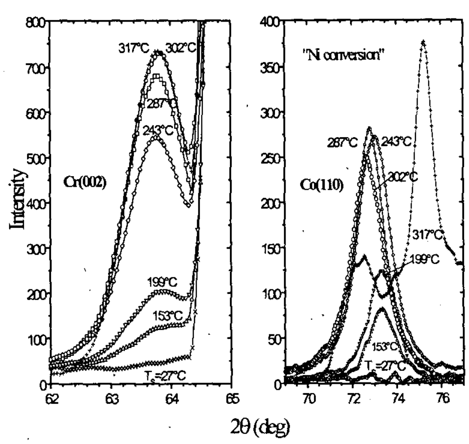

Fig. 1. Evolution of Co(110) and Cr(002) peaks in $\theta \sim 2\theta$ scan as a function of substrate temperature.

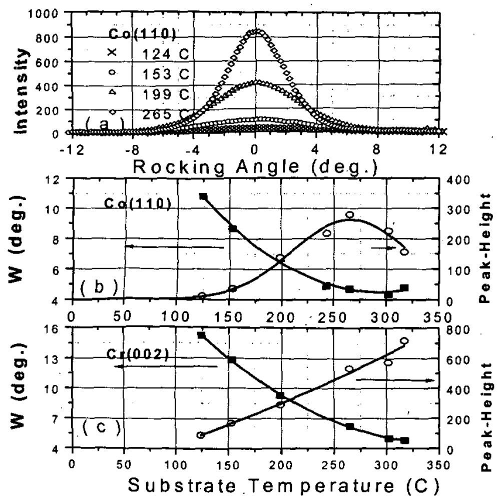

Fig. 2. Evolution of Co(110) rocking curves as a function of substrate temperature (a). Evolution of W (the full width at 50% of amplitude) and peak-height of rocking curves for Co(110) planes (b) and for Cr(002) planes.

It is well known that the grain configuration has strong influence on the coercivity H_C, medium noise and thermal stability. Also it has been noticed that the magnetic grain or activation volume **V*** is closely related to thermal stability and medium noise. **V*** values of films studied in this work were determined with both approaches of " field-sweep-rate effect on H_C" and "time decay of magnetization and irreversible susceptibility"[6], and are listed in Table I. Assuming a cylindrical shape of magnetic grain, the dimension **d*** of magnetic grain **V*** can be estimated as $\mathbf{d^*} = (4\mathbf{V^*}/\pi t)^{1/2}$ (where t is the magnetic layer-thickness) and the **d*** values are also listed in Table I. The physical grain dimension **d** estimated from the TEM picture for selected samples is given in Table I as well. It is found: (i) Magnetic grain **V*** and **d*** decrease rapidly as T_S changes from 27 to 199°C, and retains this low value as T_S varies from 199~265°C. **V*** and **d*** increase for increasing T_S further where the so-called "Ni conversion" occurs. (ii) The physical grain dimension **d** shows smaller value at $T_S \cong 265$°C and larger at lower T_S. (iii) The magnetic grain dimension **d*** is close to the physical grain size d as T_S approaches 265°C. Therefore the interaction between magnetic grains may be reduced at $T_S \approx 265$°C. More detailed discussion about this property will be presented when analyzing the intergrain interaction and H_C properties.

Table I. Magnetic and physical grain size

T_S (°C)	27	153	199	221	265	302
V* (10^{-18}cm^3)	18.7	10.2	4.33	4.27	4.21	5.80
d* (nm)	26	23	15	15	15	17
d (nm)	~100				~20	~30

The evolution of lattice-constants, lattice-matching, and coherence-length of CrRu and CoCrTaPt alloys has been measured as well. Because of the space limits, we only point out that the lattice-matching between Co(110) and Cr(002) becomes worse with increasing T_S and this result will be used in the discussion of coercivity behavior below.

Correlation between structure and magnetic properties

Low intergrain interaction and high anisotropy are critical for ultra-high-density medium to achieve the necessary properties of high coercivity, thermal stability and low noise. Besides alloy composition, these properties are sensitive to the film microstructure. For example, the formation of a columnar structure will tend to decouple the grains and the Co(110)/ Cr(002) texture will increase the anisotropy essentially.

Intergrain interaction can be estimated with the so-called ΔM method and the measurement results are demonstrated in Fig. 3. It is found: (i) the large and positive peaks with steep slope for T_S=27°C and 153°C films indicate the strong exchange interaction since the isolated-columnar structure is not well formed at such low T_S. (ii) The decreasing of ΔM-peak and its slope with increasing T_S from 153°C to 243°C indicates that the formation of the isolated-columnar structure in CrRu and CoCrTaPt layers is able to reduce greatly the grain interaction. (iii) ΔM-peak increases gradually as T_S increases further. This may be associated with the compositional segregation and worsen film structural at such high T_S of 302°C, and further investigation is needed. (iv) From this ΔM behavior, the evolution of magnetic grain V* as shown in Table I can be understood reasonably: the larger value of V* at lower T_S (27°C< T_S <153°C) is correlated with the strong exchange-interaction and the lower value of V* in the region (199°C< T_S <265°C) is due to the reduced exchange-interaction; as T_S increases from 265°C, ΔM-peak value increase gradually, as does **V***.

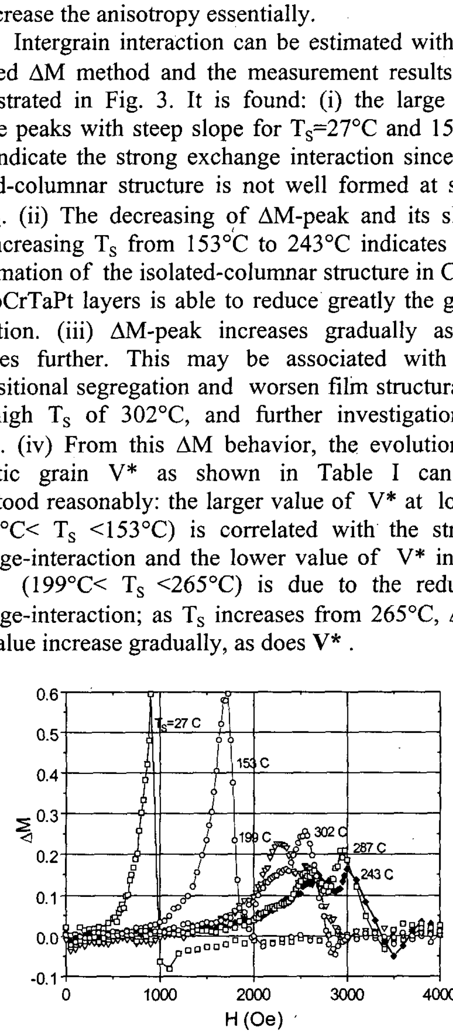

Fig. 3. Evolution of ΔM curves as a function of substrate temperature.

Evolution of hysteresis loops as a function of T_S has been measured with the H field in the following three directions: along the circumferential, along the radial, and film normal directions. The measured anisotropy K'_u ($K'_u = K_{int} + K_{shape}$, where K_{int} and K_{shape} are the intrinsic and shape anisotropy, respectively) can be estimated from the area between the "circumferential and film normal hysteresis loops", and the orientation ratio of remanence (OR) can be determined from the "circumferential and radial hysteresis loops".[7] Figure 4a and 4b display the evolution of K'_u and OR as a function of substrate temperature T_S. It is seen: (i) OR $\approx$ 1 at low T_S implies that the c-axis of Co-alloy is distributed nearly isotropicly in the film plane. (ii) Due to the development of the Co(110)/Cr(002) texture, both K'_u and OR increase as T_s increases from room temperature to 265°C. Further increasing T_S results in the decreasing of K'_u and OR values because of the degraded Co(110)/Cr(002) texture.

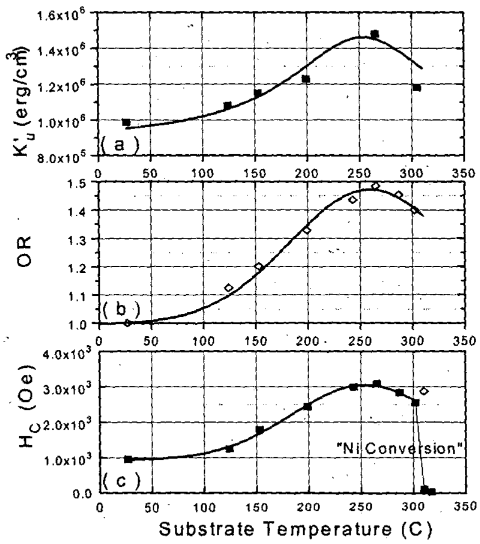

Fig. 4. Substrate temperature effects on measured anisotropy K'_u (a), orientation ratio of remanence OR (b), and coercivity H_C (c).

Evolution of coercivity H_C as a function of T_S is shown in Fig. 4c. It is seen that H_C is only ~1000 Oe for 27°C < T_S < 125°C; H_C increases remarkably and reaches its maximum as T_S varies from 153°C to 265°C. As T_S increases further H_C first decreases gradually (265°C ~302°C) and then dramatically (302°C ~ 317°C) which is associated with the occurrence of so-called "Ni conversion". The relationships among coercivity, anisotropy , and intergrain interaction have been analyzed with the micromagnetics in many papers[1,8] and it was concluded that coercivity increases with increasing anisotropy and decreases with increasing intergrain interaction. The evolution behavior of H_C as shown in Fig. 4c can be understood reasonably with the micromagnetic results: as T_S increases from 27°C to 265°C, the increasing anisotropy (Fig. 4a) and decreasing intergrain-interaction (Fig. 3) enhance H_C which reaches its maximum at T_S≈265°C; as T_S increases from 265°C to 302°C, H_C decreases because of the decreasing anisotropy and increasing intergrain-interaction. Also the decrease of H_C in higher $T_S \approx$ 302°C may be correlated with the larger lattice-mismatching between Co(110) and Cr(002) planes as has been pointed out before, however this effect may have been included already in the degradation of the anisotropy values in this T_S region.

In summary, there is a close correlation between the structure and magnetic properties of films. It is noticed that not only the intensity of Co(110) and Cr(002) planes, but also their angular orientation distributions are improved as T_S varies from room-temperature to 265°C. The rapid decrease in intergrain interaction, magnetic grain **V*** and increase in coercivity H_C occur around $T_S \approx$ 153°C which is the onset of Co(110)/Cr(002) texture; the intergrain interaction and **V*** reach their minima (K'_u and H_C their maximum) at $T_S \approx$ 265°C where the film has the best Co(110)/Cr(002) texture. The information on grain configuration is valuable for investigating the interaction properties between grains: the magnetic grain dimension **d*** approaches the physical grain dimension **d** around $T_S \approx$ 265°C, which may be the important reason that the intergrain interaction becomes weaker: the physical grains are isolated from each other fairly well in this T_S region. The significant effects of substrate temperature on film microstructure and consequently magnetic behavior offers an approach to tailoring the film properties.

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