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Quantitative evaluation of magnetocrystalline anisotropy of columnar grains and thickness of initial layer in CoCr-based perpendicular media

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We propose a quantitative analysis using perpendicular torquemetry to evaluate the thickness of the initial layer which consists of nanocrystalline grains, whose *c* axes are three-dimensionally randomly oriented, and the intrinsic magnetocrystalline anisotropy of the columnar grains with its *c* plane parallel to the film plane for CoCr-based perpendicular thin-film media. By applying this analysis to CoNiCrTa, CoCrPtTa, and CoCrPtB media, we found that the initial layer can be completely removed in the CoCrPtB medium epitaxially grown on an hcp-structured $Co_{60}Cr_{40}$ intermediate layer. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1445467]

For perpendicular recording media, it has been pointed out that the initial growth region in the recording layer formed on top of the underlayer should be removed, since it behaves like a soft magnetic layer, resulting in the decreases of perpendicular coercive force and squareness of the film.[1,2] However, in most reports on perpendicular media, only the macroscopic magnetic properties of the whole film were discussed, although the film structure is inhomogeneous due to the existence of the initial layer. In this study, we propose an analysis to evaluate the intrinsic magnetocrystalline anisotropy of the columnar structure, and the thickness of the initial layer using perpendicular torquemetry.

The thin-film media were fabricated by the dc magnetron sputtering method on 65-mm-diam glass substrates using the so-called ultraclean sputtering system.[3] The substrate was heated by a quartz lamp and the temperature was kept in the range from 200 to 250 °C. The sputtering was made under Ar pressure of 2–4 mTorr. $Co_{67}Ni_{13}Cr_{16}Ta_4$, $Co_{68}Cr_{20}Pt_8Ta_4$, $Co_{72}Cr_{16}Pt_8B_4$, $Co_{60}Cr_{24}Pt_{12}B_4$, and $Co_{69}Cr_{19}Pt_8B_4$ thin-film media were deposited onto the substrate without and with a Ti or Ta underlayer. Detail of layer structures for the media is described in Table I. The x-ray diffraction (XRD) profiles were examined by the grazing-incident angle XRD (in-plane XRD; $2\theta_\chi$ scan) method, using Cu $K\alpha$ radiation. The incident angles were 0.4°, which meant about 20-nm-thick penetration of x rays from the incident surface. The microstructure was examined by the cross-sectional transmission electron microscope (TEM) method. The saturation magnetization and perpendicular magnetic anisotropy were evaluated by a vibrating sample magnetometer (VSM) and a high-sensitive torque magnetometer, respectively. The torque curves measured in various fields up to 18 kOe were Fourier analyzed. The saturated torque coefficients of twofold and fourfold components, $L_{2\theta}^{sat}$ and $L_{4\theta}^{sat}$, were obtained by extrapolating the coefficients versus $1/H$ curves to $H \to \infty$. It is found that the value of $L_{4\theta}^{sat}$ is one order smaller than that of $L_{2\theta}^{sat}$. By taking into account the self-energy caused by the demagnetizing field, the experimentally obtained total perpendicular magnetic anisotropy of the whole film, $K_{u\perp}^{exp}$, can be expressed as

$$K_{u\perp}^{exp} = L_{2\theta}^{sat} + 2\pi M_s^2. \quad (1)$$

Figure 1 shows changes in the perpendicular magnetic anisotropy of the whole film, $K_{u\perp}^{exp}$, as a function of magnetic film thickness, d_{mag} for the CoNiCrTa media with and without a Ti underlayer. In both media, for d_{mag} less than 35 nm, the $K_{u\perp}^{exp}$ rapidly decreases with decreasing d_{mag}. This fact suggests the existence of structural heterogeneity along the film depth.

Figure 2 shows the in-plane XRD profiles for CoNiCrTa films on (a) a glass substrate and (b) a Ti underlayer, respectively, as a function of d_{mag}. For media (a), with $d_{mag} = 10$ nm, no diffracted line was observed. With increasing d_{mag} more than 17 nm, a diffracted line from the (100) plane of the hcp structure gradually appears and the intensity becomes larger. On the other hand, for media (b), the diffracted line from the (100) plane was clearly detected even for the film of $d_{mag} = 10$ nm. The fact that the diffracted line from the (100) plane of the hcp structure was observed in the in-plane XRD profile suggests that there exist the hcp grains with their *c*-plane parallel to the film plane. This suggestion is consistent with the experimental results of the conven-

TABLE I. K_u^{grain} and d_{ini} determined from the $K_{u\perp}^{exp} \times d_{mag}$ vs d_{mag} plot for CoNiCrTa, CoCrPtTa, and CoCrPtB media.

Media	d_{ini} (nm)	K_u^{grain} (erg/cm^3)	M_s (emu/cm^3)
$Co_{67}Ni_{13}Cr_{16}Ta_4$	14.0	1.29×10^6	420
$Co_{67}Ni_{13}Cr_{16}Ta_4$/Ti (7.5 nm)	8.8	1.91×10^6	440
$Co_{68}Cr_{20}Pt_8Ta_4$	16.3	1.37×10^6	260
$Co_{68}Cr_{20}Pt_8Ta_4$/Ti (7.5 nm)	7.4	1.13×10^6	250
$Co_{69}Cr_{19}Pt_8B_4$/Ti (25 nm)	2.0	2.04×10^6	433
$Co_{69}Cr_{19}Pt_8B_4$/$Co_{60}Cr_{40}$ (20 nm) /C (1 nm)/Ti (25 nm)	0	2.64×10^6	477

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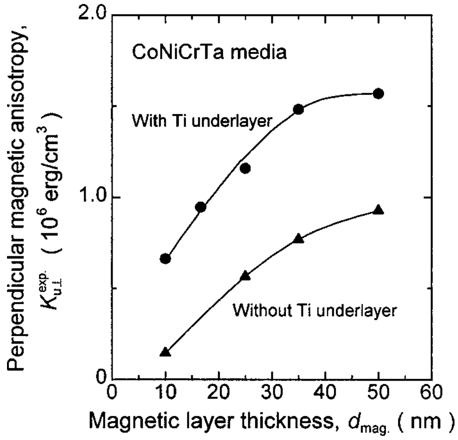

FIG. 1. Perpendicular magnetic anisotropy $K_{u\perp}^{\mathrm{exp}}$ as a function of magnetic film thickness d_{mag} for CoNiCrTa media with and without the Ti underlayer.

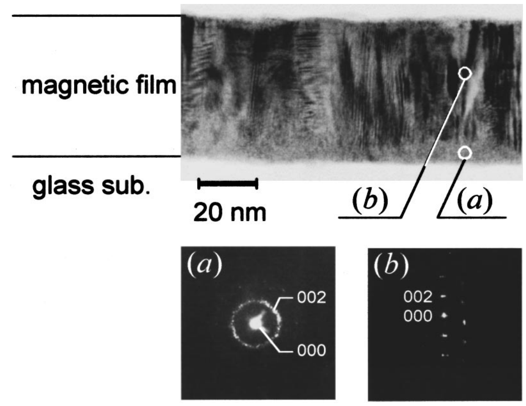

FIG. 3. Bright-field image and electron diffraction patterns obtained by cross-sectional TEM analysis for the CoNiCrTa film with a thickness of 50 nm deposited directly on the glass substrate.

tional 2θ–θ XRD evaluation.[4] The rocking curve measurement reveals that *c*-axis dispersion to the film normal direction is less than 8.0° for the film of $d_{\mathrm{mag}} \geqslant 17$ nm.

Figure 3 shows a bright-field image and electron diffraction patterns obtained by cross-sectional TEM for a CoNiCrTa film with the thickness of 50 nm deposited on a glass substrate. In the bright-field image, a layer structure with gray contrast can be clearly seen on the surface of the glass substrate and a columnar structure can be observed on top of the gray layer. According to the electron diffraction images, a ring pattern from the gray zone and a spot pattern from the columnar structure were observed, respectively. These patterns are assigned to the diffraction from the *c* plane of the hcp structure. These facts indicate that the layer structure with the gray contrast consists of many nanocrystalline grains whose *c* axes are three-dimensionally (3D) randomly oriented, and that the columnar structure consisted of a hcp single grain with its *c* plane parallel to the film plane. The same results were obtained for the medium with a Ti underlayer. The gray zone is usually called the initial layer, and its nanocrystalline structure is very well known in perpendicular media study.[5]

Concerning the structural heterogeneity mentioned in Fig. 3, $K_{u\perp}^{\mathrm{exp}}$ can be considered as the summation of the perpendicular magnetic anisotropy of both the columnar structure and the initial layer. In this case, the experimentally determined $K_{u\perp}^{\mathrm{exp}}$ can be expressed by the following equation:

$$K_{u\perp}^{\mathrm{exp}} = K_{u\perp}^{\mathrm{column}} \times (V_{\mathrm{mag}} - V_{\mathrm{ini}})/V_{\mathrm{mag}} + K_{u\perp}^{\mathrm{ini}} \times V_{\mathrm{ini}}/V_{\mathrm{mag}}, \tag{2}$$

where $K_{u\perp}^{\mathrm{column}}$ and $K_{u\perp}^{\mathrm{ini}}$ are the average perpendicular magnetic anisotropy of the columnar structure and the initial layer, respectively, and V_{mag} and V_{ini} are the volume of the whole magnetic film and the initial layer, respectively. By assuming that the interface between the initial layer and the columnar structure is flat, Eq. (2) can be expressed as follows:

$$K_{u\perp}^{\mathrm{exp}} = K_{u\perp}^{\mathrm{column}} \times (d_{\mathrm{mag}} - d_{\mathrm{ini}})/d_{\mathrm{mag}} + K_{u\perp}^{\mathrm{ini}} \times d_{\mathrm{ini}}/d_{\mathrm{mag}}. \tag{3}$$

As described in Fig. 3, since the initial layer consists of nanocrystalline grains whose *c* axes are 3D randomly distributed, the whole ensemble of magnetocrystalline anisotropy of nanocrystalline grains, $K_{u\perp}^{\mathrm{ini}}$, is considered to be nearly zero:

$$K_{u\perp}^{\mathrm{ini}} = 0. \tag{4}$$

Furthermore, since the columnar structure consists of single-crystal grains whose *c* plane is parallel to the film plane, the average perpendicular magnetic anisotropy of the whole columnar structures, $K_{u\perp}^{\mathrm{column}}$, can be easily expected to be equal to the average magnetocrystalline anisotropy of each grain with uniaxial symmetry in the hexagonal structure, K_u^{grain}:

$$K_{u\perp}^{\mathrm{column}} = K_u^{\mathrm{grain}}. \tag{5}$$

Therefore, Eq. (3) can be rewritten in the following form:

$$K_{u\perp}^{\mathrm{exp}} \times d_{\mathrm{mag}} = K_u^{\mathrm{grain}} \times (d_{\mathrm{mag}} - d_{\mathrm{ini}}). \tag{6}$$

Based on Eq. (6), for perpendicular media composed of the initial layer and columnar structure, we can simply derive K_u^{grain} and d_{ini} from the $K_{u\perp}^{\mathrm{exp}} \times d_{\mathrm{mag}}$ vs d_{mag} plot. Using a linear portion of the $K_{u\perp}^{\mathrm{exp}} \times d_{\mathrm{mag}}$ vs d_{mag} plot, K_u^{grain} can be uniquely determined from the gradient, and d_{ini} also can be determined from the intersection of the extended line with the d_{mag} axis.

In Fig. 4, $K_{u\perp}^{\mathrm{exp}} \times d_{\mathrm{mag}}$ is plotted as a function of d_{mag} for CoNiCrTa media on a glass substrate with and without the Ti underlayer. $K_{u\perp}^{\mathrm{exp}} \times d_{\mathrm{mag}}$ shows a linear correlation with d_{mag} in the range of $d_{\mathrm{mag}} > 25$ nm for the media without the Ti underlayer and in the range of $d_{\mathrm{mag}} > 10$ nm for the media with the Ti underlayer, respectively. Note that these experi-

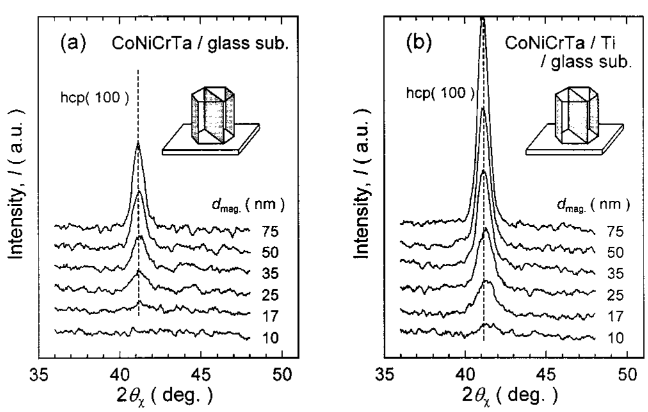

FIG. 2. In-plane XRD profiles for CoNiCrTa films deposited on (a) a glass substrate and (b) a Ti underlayer with various magnetic-layer thicknesses.

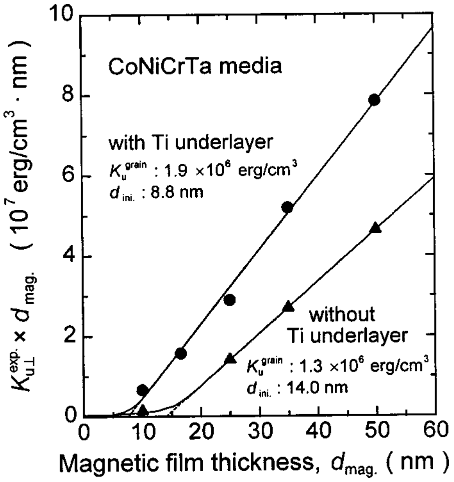

FIG. 4. $K_{u\perp}^{exp} \times d_{mag}$ vs d_{mag} plot for CoNiCrTa media deposited on the glass substrate and Ti underlayer.

mental results correspond very well to the model assumption expressed in Eq. (6). It is found that the initial layer is formed for both media, and that the intrinsic magnetocrystalline anisotropy of the columnar grains is constant, independent of d_{mag}. K_u^{grain} and d_{ini} determined from this method are 1.3×10^6 erg/cm^3 and 14.0 nm for the media without the underlayer, and 1.9×10^6 erg/cm^3 and 8.8 nm for the media with the Ti underlayer, respectively.

We have further applied this method to evaluate K_u^{grain} and d_{ini} for other films, and have summarized the results in Table I. In these films, it was confirmed by the in-plane XRD analysis that the magnetic film consisted of the initial growth layer with nanocrystalline grains and the columnar structure with *c*-plane oriented grains. It is found that K_u^{grain} and d_{ini} of the films with the same magnetic layer vary with the underlayer material. This means that the initial growth mechanism of the magnetic layer depends on the underlayer material, and the Cr-segregation microstructure of the columnar structure is affected by the initial growth layer. Finally, we found that d_{ini} is nearly equal to zero in CoCrPtB/CoCr/C/Ti media, in which the columnar grain of magnetic layer grows epitaxially on the hcp-structured $Co_{60}Cr_{40}$ intermediate layer.

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