

R.F.-SPUTTERED Co-Cr LAYERS FOR PERPENDICULAR MAGNETIC RECORDING

II: MAGNETIC ANISOTROPY

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The magnetic anisotropy of Co-Cr layers was investigated with a torque magnetometer, using Fourier analysis. The results could be fitted to the hexagonal anisotropy, described by a first-order and a second-order uniaxial anisotropy constant. The second-order uniaxial anisotropy constant K_2 was 2%-4% of the first-order anisotropy constant K_1 . Higher order anisotropy constants were not significant.

The magnetic anisotropy and the saturation magnetization appeared to be almost independent of the layer thickness. Magnetostriction was found to give a negative contribution to the first-order anisotropy constant.

1. INTRODUCTION

R.f.-sputtered Co-Cr layers possess a uniaxial perpendicular magnetic anisotropy which makes them suitable as a magnetic medium for perpendicular recording^{1,2}.

It was shown in Part I³, by means of electron microscopy and X-ray analyses, that the layers have an h.c.p. crystalline structure with the c axis perpendicular to the film plane. Our films are highly oriented with a few degrees deviation of the c axis from the normal of the film plane.

The crystallographic structure is similar to the crystal structure of pure h.c.p. cobalt bulk (see Part I) and layers⁴. Since the h.c.p. structure is related to the uniaxial anisotropy model⁵ and because the Co-Cr layers which are suitable for perpendicular recording are strongly cobalt dominated (about 80-85 at.% Co), we can expect agreement between the magnetic anisotropy of Co-Cr and that of pure cobalt layers. Pure h.c.p. cobalt layers have a second-order uniaxial magnetic anisotropy with a relatively large second-order anisotropy constant K_2 ($K_1 \approx 50 \times 10^5$ erg cm⁻³, $K_2 \approx 10 \times 10^5$ erg cm⁻³) at room temperature⁴. In order to analyse the anisotropy of Co-Cr layers, measurements were carried out with a torque magnetometer and a vibrating sample magnetometer (VSM).

The VSM is primarily used to measure the saturation magnetization M_s . However, the in-plane hysteresis loop also provides information about the intrinsic anisotropy of the layer⁵. From the in-plane hysteresis loop we can determine the

anisotropy field H_k (Fig. 1) and therefore also the first-order anisotropy constant K_1 ($K_1 = M_s H_k/2$), if the demagnetizing field can be neglected because of the demagnetized state of the layer.

More reliable information about the anisotropy is obtained from torque measurements. The applied magnetic field H was chosen to be greater than the anisotropy field H_k in order to avoid hysteresis effects. The torque curves were analysed by Fourier expansion in order to see whether the curves could be fitted to the second-order uniaxial anisotropy.

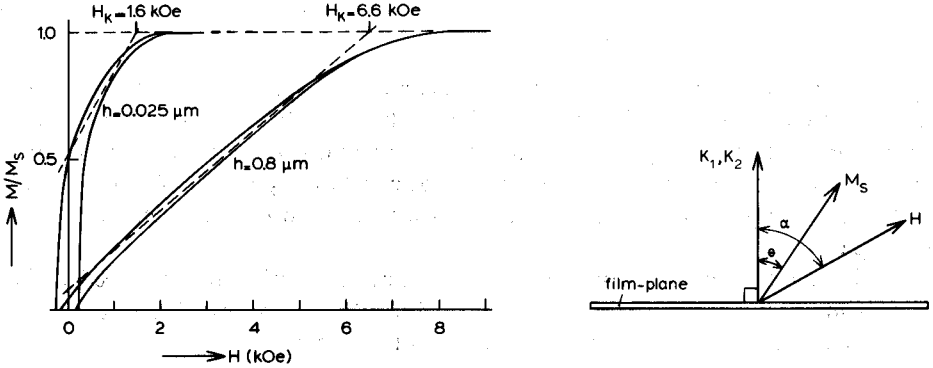


Fig. 1. In-plane hysteresis loops and determination of the anisotropy field H_k (multitarget layers).

Fig. 2. Second-order uniaxial anisotropy model of a uniform magnetized layer.

Measurements were performed with layers, sputtered from a multitarget as well as an alloyed target, yielding layer compositions of about 85at.%Co–15at.%Cr and about 81at.%Co–19at.%Cr respectively. The chemical composition and the thickness of the layer were measured by X-ray fluorescence. The layers were sputtered in the thickness range from 0.025 to 1 μm on silicon substrates of 10 mm \times 10 mm. The sputter conditions are described in Part I. The contribution of magnetostriction to the anisotropy was investigated by separating the layer from the substrate and measuring the anisotropy both before and after the separation.

2. FOURIER EXPANSION OF TORQUE CURVES

Because of the h.c.p. structure of Co–Cr layers it should be possible to describe the magnetic anisotropy of the Co–Cr layers by the uniaxial anisotropy. The single-domain uniaxial anisotropy model of an h.c.p. layer is shown in Fig. 2. The applied field H must be high enough to direct the magnetization to a one-domain film.

The intrinsic magnetic anisotropy energy is expressed by the first two coefficients of a power series in $\sin^2 \theta$ (odd coefficients can be seen to be zero because of symmetry considerations):

$$\frac{E_k}{V} = K_1 \sin^2 \theta + K_2 \sin^4 \theta \quad (1)$$

E_k is the intrinsic anisotropy and V is the volume of the layer. K_1 and K_2 are the first- and second-order anisotropy constants; θ is the angle between the saturated

magnetization and the uniaxial direction. Higher order coefficients of the power series are assumed to be negligible because of experimental results for cobalt⁴ and Co-Cr layers, as will be shown later.

To obtain an expression for the total energy of the layer we extend eqn. (1) by adding a shape anisotropy energy E_s , which has the opposite sign to the uniaxial anisotropy energy and is given by

$$\frac{E_s}{V} = -2\pi M_s^2 \sin^2\theta \quad (2)$$

and the magnetostatic energy E_{MH} due to the angle between the field and magnetization direction, given by

$$\frac{E_{MH}}{V} = M_s H \cos(\alpha - \theta) \quad (3)$$

where α is the angle between the perpendicular direction and the applied field.

The total energy is then given by the sum of eqns. (1)–(3):

$$\frac{E_t}{V} = M_s H \cos(\alpha - \theta) + (K_1 - 2\pi M_s^2) \sin^2\theta + K_2 \sin^4\theta \quad (4)$$

The torque L is expressed by

$$\frac{L}{V} = -M_s H \sin(\alpha - \theta) \quad (5)$$

Differentiating eqn. (4) with respect to θ in order to find the M_s direction for minimum energy and using eqn. (5), we obtain an expression for L as a function of the angle θ :

$$\frac{L}{V} = A \sin(2\theta) + B \sin(4\theta) \quad (6a)$$

$$A = K_1 + K_2 - 2\pi M_s^2 \quad (6b)$$

$$B = -\frac{1}{2}K_2 \quad (6c)$$

If M_s is known (by VSM measurement), the anisotropy constants K_1 and K_2 are given by the expressions (5) and (6) and an L versus α curve. If the applied field H is high enough ($H \gg H_k$) to ensure that the angles α and θ are almost equal (Fig. 2), K_1 and K_2 can easily be found by Fourier expansion of the torque curve. (A and B are respectively the first- and second-order Fourier coefficients of the sine-like torque curve $L = f(2\theta)$.)

In the case of the pure cobalt and Co-Cr layers, however, the magnetic anisotropy is too high to force the magnetization in the field direction. Correction of the torque curve is now necessary^{6,7}. Before expanding the torque curve by Fourier analysis, we eliminate the unknown angle θ in eqn. (6a) using eqn. (5).

Problems may arise if the film is not homogeneous in its magnetic properties (*i.e.* due to the relatively large contribution to the anisotropy of initial layers in very thin films). In this case we prefer to extrapolate the Fourier coefficients of the uncorrected torque curves to infinite field in order to analyse the anisotropy.

All torque curves were analysed using both torque correction and extrapolation of the Fourier coefficients. The discrepancies will be discussed.

3. MEASUREMENTS

The torque curves were automatically measured and Fourier analysed with a torque magnetometer connected to an on-line microcomputer. The Fourier coefficients of both the corrected and uncorrected curves were computed up to the fifth order, taking the magnitude of the torque at 180 equidistant points each related to its neighbours by 1° rotations. We measured the torque curves at various intensities of the magnetic field H in steps of 2 kOe, starting at a field slightly higher than H_k .

Figure 3 shows the corrected and uncorrected Fourier coefficients R_n of an alloyed target layer ($h = 0.6 \mu\text{m}$; $H_k \approx 4 \text{ kOe}$) as functions of the inverse of the applied field. This figure is typical for an alloyed target layer thicker than $0.2 \mu\text{m}$. The linear dependence of R_2 on $1/H$ has been pointed out by Dali *et al.*⁸ In this case, correction of the torque curve gives the same results as extrapolation of the first- and second-order Fourier coefficients R_1 and R_2 to infinite field. Linear extrapolation of the third- and higher order coefficients of the uncorrected curves, however, does not give the same results as when the curve is corrected before Fourier analysis.

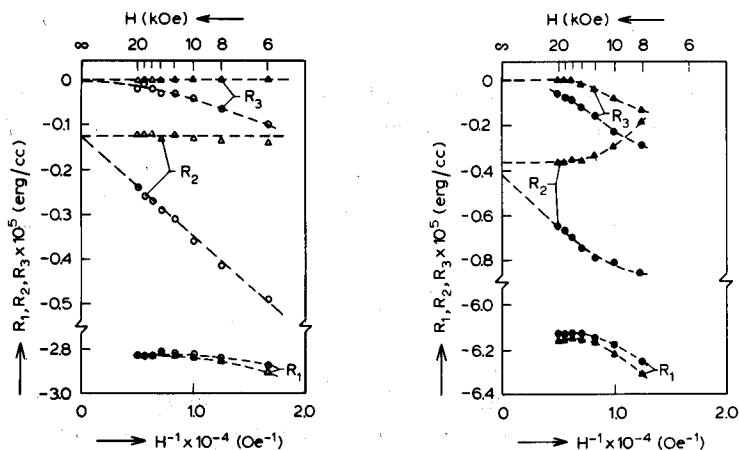


Fig. 3. Fourier coefficients R_1 , R_2 and R_3 for an alloyed target layer vs. the inverse magnetic field $1/H$: \circ , uncorrected; \triangle , corrected.

Fig. 4. Fourier coefficients R_1 , R_2 and R_3 for a multitarget layer vs. the inverse magnetic field $1/H$: \bullet , uncorrected; \blacktriangle , corrected.

Figure 4 shows the Fourier coefficients *versus* $1/H$ for a multitarget layer ($h = 0.4 \mu\text{m}$; $H_k \approx 7 \text{ kOe}$). It can be seen that the correction of the torque curve yields good results when H is larger than 14 kOe (the corrected R_3 becomes zero; R_1 and R_2 become field independent). It was found that layers thicker than $0.1 \mu\text{m}$ always show field-independent corrected Fourier coefficients if the applied field H has an intensity greater than about twice the anisotropy field H_k .

Figure 5 and Fig. 6 respectively show the first- and second-order anisotropy

constants K_1 and K_2 as functions of the layer thickness h . K_1 and K_2 are determined by means of torque curve correction for layers thicker than $0.1 \mu\text{m}$. K_1 and K_2 for very thin layers are determined by extrapolation of the uncorrected Fourier coefficients, which leads to some uncertainty about the correctness of K_2 . (Correction of the torque curves in this case did not result in negligible third- and higher order Fourier coefficients.) Furthermore, K_1 was also determined from the in-plane hysteresis loops (Fig. 1). For the layers which were thicker than $0.1 \mu\text{m}$ there was good agreement between the "torque" K_1 and the "hysteresis" K_1 (Fig. 5).

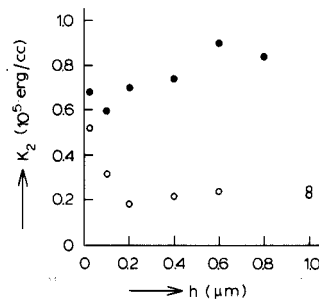
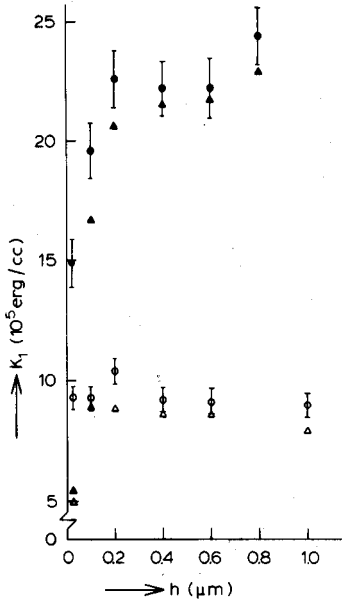


Fig. 5. First-order anisotropy constants K_1 as a function of the thickness h : ●, ▲, multitarget; ○, △, alloyed target; ●, ○, torque meter; ▲, △, VSM.

Fig. 6. Second-order anisotropy constant K_2 as a function of the thickness h : ●, multitarget; ○, alloyed target.

The error in the first-order anisotropy constant K_1 (torque) as shown in Fig. 5 is mainly caused by the inaccuracy in the magnetization M_s (measured with the VSM). Figures 7 and 8 show that M_s is a function of the layer composition rather than of the thickness h . On account of the reproducibility of the VSM measurement (2%) and the results in Fig. 8 we can assume a relative accuracy of 2% in M_s which results in an accuracy of 4% in the demagnetizing energy $2\pi M_s^2$. Because the effective anisotropy A and the second-order anisotropy constant K_2 are small compared with $2\pi M_s^2$ (eqn. (6b)), the error in the calculated K_1 depends almost entirely on the accuracy of the magnetization measurement.

4. MAGNETOSTRICTION

In order to determine the contribution of the magnetostriction anisotropy to the total anisotropy, a Co-Cr layer was measured both before and after separation

of the layer from a carbon-covered mica substrate. The Co-Cr layer was separated from the mica substrate by removing the Co-Cr and carbon layer in water.

Torque measurements showed an increment in K_1 after the layer had been separated from the substrate. This negative magnetostriction contribution ($\Delta K_1 \approx 2.2 \times 10^5 \text{ erg cm}^{-3}$) is of the same order of magnitude as that found by Aboaf and Kloholm⁹ for approximately the same layer composition. They found a film stress $\tau \approx -1.5 \times 10^{10} \text{ dyn cm}^{-2}$ and a saturation magnetostriction $\lambda_s \approx -12 \times 10^{-6}$, yielding a magnetostriction anisotropy $\Delta K_1 = -(3/2)\tau\lambda_s = -2.7 \times 10^5 \text{ erg cm}^{-3}$.

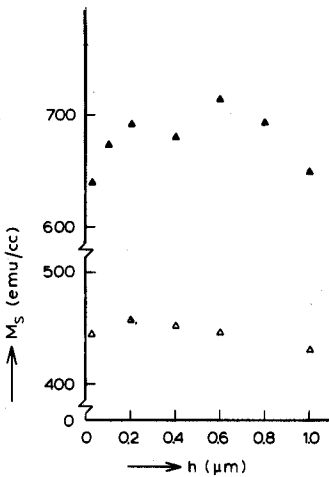
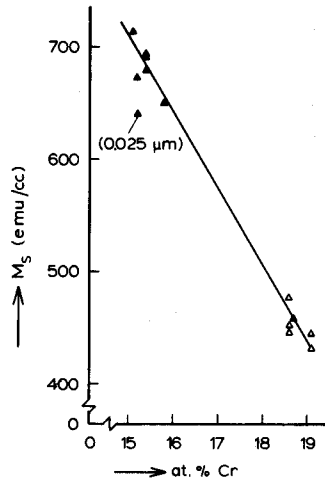


Fig. 7. Saturation magnetization M_s as a function of the thickness h : ▲, multitarget; △, alloyed target.

Fig. 8. Saturation magnetization M_s as a function of the layer composition (atomic per cent chromium) (symbols as in Fig. 7).



5. DISCUSSION AND CONCLUSIONS

Fourier analysis of torque curves showed that the magnetic anisotropy of Co-Cr layers can be described by the second-order uniaxial anisotropy model, as could be expected because of the h.c.p. crystal structure. Although hysteresis effects disappear when the applied field exceeds the anisotropy field, correction of the torque curves only yields proper results in all cases if the applied field exceeds twice the anisotropy field.

The second-order anisotropy constant K_2 only amounts to approximately 2%–4% of the first-order anisotropy constant K_1 , which is much less than the second-order contribution to the anisotropy of pure cobalt ($K_2 \approx 0.2K_1$ ⁴). The first-order anisotropy constant of the multitarget layers ($K_1 \approx 22 \times 10^5 \text{ erg cm}^{-3}$ and $M_s \approx 680 \text{ e.m.u. cm}^{-3}$, yielding an anisotropy field $H_k \approx 6.5 \text{ kOe}$) confirms the results of Iwasaki *et al.*¹⁰ However, the anisotropy of the alloyed target layers ($K_1 \approx 9 \times 10^5 \text{ erg cm}^{-3}$; $M_s \approx 425 \text{ e.m.u. cm}^{-3}$; $H_k \approx 4 \text{ kOe}$) showed a discrepancy with the results of Iwasaki *et al.* ($H_k \approx 6 \text{ kOe}$ for $M_s = 300\text{--}1000 \text{ e.m.u. cm}^{-3}$).

Magnetostriction was found to give a negative contribution to the first-order anisotropy constant K_1 .

Torque and VSM measurements showed that the magnetic properties (anisotropy and magnetization) are almost independent of the thickness of the layer. This is in agreement with the results in Part I, where it was shown that all layers possess an h.c.p. crystal structure with only a few per cent dispersion of the easy axis, which is almost independent of the layer thickness.

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