Asymmetric co-evaporated Co–Cr films: magnetic parameters and reversal mechanism

Herma van Kranenburg, Cock Lodder and Theo J.A. Popma

Mesa Research Institute, University of Twente, P.O. Box 217, 7500 AE Enschede, The Netherlands

The magnetic parameters of co-evaporated Co–Cr films, where Cr was deposited obliquely, are investigated. Process-induced compositional separation enhanced the energy product. When the substrate was rotated during evaporation, the perpendicular characteristics were lost.

1. Introduction

Co-evaporated Co–Cr films were deposited with two e-beam sources. The Co vapour reached the substrate under normal incidence, and the Cr vapour at an incidence angle of 45–48°. The substrate was Si and the deposition was carried out at room temperature (T_R). The average Cr content was varied from 14 to 36 at%; film thicknesses were 200–290 nm. One series was made with non-rotating substrates (referred to as L + number); a second series was made with rotating substrates (referred to as LR + number), with rotation speeds of either 30 or 82 rpm. The total deposition rate was approximately 13 Å/s (L24 and L25) or 9 Å/s (rest). Typical background pressures were $2\text{--}4 \times 10^{-7}$ mbar.

The magnetic properties were characterized by VSM (hysteresis behaviour) and torque measurements (anisotropy constants). Average compositions were measured by XRF. The microstructure was investigated with SEM (columnar size) and XRD (texture and phase configuration). The growth of the (L-) films was simulated using a 2D Monte Carlo simulation program.

2. Results

With the two separate vapour flux directions of Co and Cr, the resulting morphology was determined by the two angles of incidence and partial vapour rates. A weighted average of these yielded an effective incoming vapor direction. In the case of the L-samples the effective incoming direction was tilted slightly towards the Cr source. This effective incidence angle results in a tilted columnar structure; e.g., for sample L25F (see

table 1) we measured a columnar tilt angle of around 10–11° with respect to the film normal. In the case of the LR samples the tilt angle of the Cr vapour averaged to zero, and a perpendicular microstructure was observed. The structure of both L and LR samples was hcp with (0002) lattice spacing 2.027 Å (≤ 24 at%Cr) or 2.030 Å (≥ 26 at%Cr). In all cases the *c*-axis was perpendicular to the substrate.

The effect of the oblique deposition of Cr is that shadowing plays a role in film formation. For the L samples Cr is most likely to impinge on one side of the columns at every stage of film growth. The low substrate temperature prohibits large adatom mobility and thus the Cr atoms will stick to a place near the impingement spot, resulting in local variations in Co and Cr, where Cr is enriched at one side of the columns: the process-induced compositional separation. This process-geometry induced effect has been found to exist in symmetrical co-evaporated Co–Cr films [1], where it enhanced the energy product ($M_s \times H_{c\perp}$). The shadowing concept is applied in a 2D Monte Carlo simulation of film growth. The programme includes surface relaxation by thermally induced surface diffusion and atomic attraction for a two-component system. For model interaction energies, a link to the real bonding energies of Co and Cr was made [2]. Figure 1 shows a simulation result for low diffusion, which can be compared with the L samples (in a one-component system the degree of diffusion was comparable with a quotient of the substrate and melting temperature of 0.285). Clearly observable is a small tilt of the columnar-alikes towards the Cr source and the enhanced Cr distribution at one side. As in symmetrical co-evaporated Co–Cr films, this results in an enhanced energy product. Saturation magnetizations are much higher than those for homogeneous bulk Co–Cr layers and coercivity values are moderate, decreasing with increasing M_s . Figure 2 shows a typical saturation magnetization curve measured with VSM. Table 1 gives

Correspondence to: Dr. J.C. Lodder, Mesa Research Institute, University of Twente, P.O. Box 217, 7500 AE Enschede, the Netherlands. Tel.: +31-53-892750; telefax: +3153-309547; telex 44200; E-mail: LODDER@UTWENTE.NL.

Table 1

Magnetic properties; samples LR19 and LR30 were rotated at 82 rpm, and LR31 and LR03 at 30 rpm

Film	h [nm]	Cr [at%]	M_s [kA/m]	$H_{c\perp}$ [kA/m]	$H_{c\parallel}$ [kA/m]	K_1 [kJ m ⁻³]	K_t [kJ m ⁻³]	γ [deg]
L24F	284	13.8	772	31	21	–	–	–
L24E	288	15.2	727	33	23	153	15	8
L24D	289	16.3	681	38	24	187	22	6
L25F	207	21.7	477	55	27	120	20	9
L25E	211	23.0	427	60	29	110	21	8
L25D	214	24.5	380	62	32	104	21	7
L05F	198	28.6	285	50	28	50	15	9
L05E	205	30.2	232	55	25	74	14	5
L05D	213	32.7	198	61	24	68	14	5
LR19F	196	26.8	361	13	10	124	0.7	0
LR19E	204	26.0	342	12	10	112	0.3	0
LR30	207	20.8	503	18	20	138	–	0
LR31F	205	17.6	612	23	22	–	–	–
LR31E	207	18.4	613	22	22	146	0.6	0
LR03	199	35.6	63	5	8	14	–	0

Fig. 1. Simulated microstructure with 22 at%Cr and 78 at%Co. The arrows above the figure indicate the vapour flux directions.

Fig. 2. Typical $M-H$ curves for the L samples (LM plane).

values of M_s , H_c and the anisotropy constants for L films with various average compositions. $H_{c\parallel}$ values are measured in the evaporation plane (the so-called LM plane). In the transversal in-plane direction (TM) $H_{c\parallel}$ is slightly smaller. In the transversal direction there is a homogeneous supply of vapour material and no shadowing (no oblique incidence) occurs. This should result in a higher packing density, whereas the shadowing in the evaporation plane causes open regions. The discontinuities caused by the open regions hinder domain wall movement by acting as pinning centres. This raises the coercivity, so that a higher $H_{c\parallel}$ in the evaporation plane with respect to the transversal direction is possible. From the hcp crystalline anisotropy the second-order constant is smaller than 10% of the first-order constant. In table 1 we listed K_1 : a combination of hcp crystalline (oriented $\parallel c$ -axis, which is $\perp$ substrate) and columnar shape anisotropy. K_1 is slightly tilted towards the Cr direction. Both the magnitude and tilt angle (γ : measured with respect to the film normal) of K_1 decrease with increasing Cr content. The L films also have an in-plane anisotropy constant in the transversal direction K_t which is some 20% of K_1 . Since the 'projection' of the oblique anisotropy constants in-plane is smaller than K_t the transversal direction is the effective in-plane easy axis direction. An effective quality factor would therefore be slightly smaller in the transversal than in the longitudinal direction. K_t may be caused by the shape anisotropy of aggregates of columns in the transversal direction. In high-resolution SEM observations we could not distinguish any (clear) aggregation due to the small columnar size (< 10 nm).

The rotated samples (LR films) have totally different saturation magnetization curves from those of L films; large shoulders are present in the $M-H$ loops (see fig. 3). The shoulders are more pronounced in the faster rotated films, which is accompanied by a trend of decreasing $H_{c\perp}$. All LR films have low coercivities: $H_{c\perp} = 10-20$ kA/m. There are no longer differences

Fig. 3. Typical $M-H$ curves for the LR samples (LM = TM plane).

between $H_{c\parallel}$ in the LM and TM directions. The anisotropy constant K_1 is around 130 kJ/m^{-3} and is perpendicular (see table 1). In-plane no preferred anisotropy axis is present (in-plane isotropic). The latter two facts are understandable: rotation during evaporation averages out all induced effects from the oblique Cr direction. During low rotation in every rotation cycle, an average of 4.9 atoms arrive at the film surface (and 7.2 in the high rotation). The problem for not obtaining a high $H_{c\perp}$ probably has its origin in the smaller discontinuities (less broad open regions and Cr-rich regions). At every stage of film growth the Cr and Co arrive at the same height of film development. Preferably, the Co should be deposited before the Cr, such that the Co columns form first, and the Cr then impinges on the boundaries rather than on the tops of the columns. The curvature of the columnar top is certainly important in this matter. In LR films the effective incoming vapour direction is perpendicular to the substrate so that the columnar tops are unlikely to be slanted in one direction, which will not encourage (process-induced) separation of Cr and Co. The average columnar size (< 10 nm) in LR films is smaller than that of L films.

Fig. 4. Angle dependence of H_c and W_h for L25E.

Fig. 5. Angle dependence of H_c and W_h for LR19E.

The angle-dependent coercivity and hysteresis loss W_h are given in figs. 4 and 5 for a L and LR films, respectively. A proper interpretation of our-of-plane coercivity measurements requires demagnetization corrections using a biaxial VSM [3]. We were unable to perform such measurements, so we give only a very qualitative interpretation of the (uncorrected) curves of figs. 4 and 5. The strong decrease in both H_c and W_h towards the in-plane direction (angle 90° in fig. 4) for the L film indicates that considerable domain wall pinning occurs. Reversal of the magnetization is most likely to proceed through either rotation or domain wall movement where the displacement of domain walls

is largely hindered by the open regions in between the columns and by chemical inhomogeneities, i.e. the Cr-rich regions formed by the process-induced compositional separation. The LR films show different behaviour. The coercivity is not a straightforward decreasing function of the angle, but has a local maximum around $20\text{--}40^\circ$ from the film normal. The hysteresis loss also does not decrease as steeply, indicating that in LR films domain wall displacement is likely to dominate.

3. Conclusions

Co-evaporated Co-Cr films, where Cr was deposited obliquely and the substrate was not rotated, show enhanced perpendicular characteristics due to process-induced compositional separation. When the substrate was rotated during evaporation the distribution of Cr and Co was more homogeneous and the perpendicular characteristics were lost.

References

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