STRIPE AND BUBBLE DOMAINS IN CoCr FILMS

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Abstract - Using the colloid-SEM method we investigated the domain structure of CoCr films (400-1740 nm thick) at different points of the hysteresis loop. In some cases an ac field exceeding the value of the coercive force was applied in addition to the dc field. For low coercivity samples ($H_c/H_k \sim 0.02$) a bubble structure, which is energetically more favourable above a certain critical field, was observed. From the dependence of the bubble density on the dc field the value of the anhysteretic collapse field was estimated and compared with the theory.

First attempts were also made to observe the field dependence of the domain structure of high coercivity samples ($H_c/H_k \sim 0.08$) having different thickness. For one sample our results were compared with those determined using the Kerr effect. For thicker films the colloid-SEM method permits the simultaneous observation of the magnetic domains and the columnar structure at the surface of the sample.

Introduction

CoCr films are excellent candidates for perpendicular magnetic recording with linear densities nearly 700 kFRPI. A great amount of work was carried out to find out whether the mechanism of magnetization reversal in these films is based on wall displacements - continuous model [1], [2] or caused by incoherent rotation - particulate model [3]: buckling mechanism [4] or curling mechanism [5], [6], [7] or if a continuous transition between these modes exists [4], [8], [9].

CoCr films exhibit a columnar grain structure with a segregated microstructure with the microvoids running parallel to the columnar boundaries (see e.g. [10], [11]). Up to now there are very few papers connecting the film structure with the magnetization reversal mechanism (see e.g. [12]). The magnetization reversal processes are greatly dependent on whether the film is made up of isolated magnetic particles embedded in a non-magnetic matrix or of a system of particles connected by exchange or dipole-dipole forces [3], [13], [14]. The value of the coercive force H_c , one of the most relevant parameters in recording, is mainly affected by the conditions of film preparation (temperature of substrate, pressure etc.).

For low coercivity films the continuous model (wall displacements) is likely. The sample is assumed to be a continuous medium (the diameter of the columns $D \leq 40$ nm). Using the colloid-SEM method we measured the field dependence of the anhysteretic values of the stripe period of four samples ($H_c/H_k \sim 0.02$, where H_k is the uniaxial anisotropy field) [15] and we found agreement with the theory of Kooy and Enz [16]. In the present paper we studied these samples with the emphasis on their bubble structure.

For high coercivity films ($H_c/H_k \sim 0.08$) we present our preliminary results i.e. the investigation of the domain structure on the descending branch of the hysteresis loop carried out on three samples with differing columnar structure at the surface.

Experimental

The CoCr films were deposited on Si substrates by r.f. magnetron sputtering [17]. The samples CoCr 78/22 at % are characterized by their thickness h [nm] determined by X-ray fluorescence, their saturation magnetization M_s and coercive force H_c in kA/m measured by a vibrating sample magnetometer and the column diameter D [nm] at the surface determined by SEM. For more details see Table 1 and 2. The observation of the dried colloid pattern was carried out using a JEOL JSX 733 SEM operated at 15 kV.

Different colloids were tried for our observations i.e. with respect to appropriate density and wetting capability. The particle size distribution of the colloidal solution was checked using a high voltage TEM [18] and its value was 15 ± 4 nm.

Low coercivity samples

The basic domain structure of low coercivity samples is a stripe structure in agreement with the theory of thin films having an easy axis normal to the surface and high anisotropy [16]. The stripe period changes with the value of the external field applied normal to the film plane. With this type of material we find a considerable hysteresis of the period on the ascending and descending branches of the magnetizing curve. This hysteresis makes the comparison of experiment and the theory more difficult. In [15] we therefore measured the anhysteretic period. This was determined in such a way that for each given dc field an additionally applied ac field was slowly reduced to zero. The initial value of this ac field had to be chosen sufficiently high with regard to H_c so as to obtain more or less the same anhysteretic period both on the ascending and the descending branches of hysteresis loop.

On low coercivity samples (see Table 1) we observed in the anhysteretic regime in higher fields ($H/M_s > 0.4-0.5$) the existence of bubble domains either in the form of coherent lattices or as a mixture of bubbles and short stripes (Fig.1). Without an additional ac field the stripe structure predominates.

According to the theory [19] a critical field exists, above which the bubble structure is energetically more favourable than the stripe structure. The value of the critical field depends on the parameter $\lambda = \sigma_w / (\mu_0 M_s^2 h)$ (where σ_w is domain wall energy).

In highly perfect single crystal films of magnetic materials having a uniaxial anisotropy with an easy axis perpendicular to the film plane (e.g. epitaxial garnets, which were thoroughly investigated for bubble memories application) no formation of bubble lattices in fields normal to the film plane was observed (not even with the additional ac field applied). In contrast to this such a structure is realized in CoCr films. This is obviously connected with the fact that garnet films are very perfect crystals having very few nucleation centers for the formation of bubble lattices in decreasing fields while in increasing fields the disintegration of stripes into bubbles is not realized due to the high energy barrier present. The existence of the inhomogeneous columnar structure, statistical distribution of the orientation of the easy axes of the crystal anisotropy in the individual columns in CoCr films obviously enhances the formation of bubble domains.

Fig.1 VSM hysteresis loop (including the initial curve) of film No. 2 (Table 1) with the corresponding domain structures. Ascending field: a; descending field: b; ascending anhysteretic: c,d; descending anhysteretic: e-g.

We measured the bubble lattice density as a function of the applied field. The results of these measurements are presented in Fig. 2. Extrapolating this dependence to vanishing densities we obtain the value of the anhysteretic bubble collapse field H_{cb} which for most samples is in very good agreement with the theoretical collapse field for bubbles H'_{cb} according to [20] (see also Table 1). The theoretical collapse field for stripe structure is lower.

Fig.2 The bubble density as a function of the reduced dc magnetic field for samples No.1-4 (Table 1):

sample No.	ascend.	descend.	H'_{cb}/M_s	H'_{cs}/M_s
1	△	●	①	①
2	○	●	②	②
3	□	■	③	③
4	▽	▼	④	④

The straight lines were obtained using linear regression. H'_{cb} and H'_{cs} are the theoretical collapse fields for bubbles and stripes respectively [20].

Table 1

Sample No.	h [nm]	M_s [kA/m]	H_c [kA/m]	H_{cb} [kA/m]	H'_{cb} [kA/m]
1	493	360	8	301	281
2	520	402	8	320	317
3	770	420	12	331	349
4	1230	404	8	374	350

Parameters of four low coercivity CoCr films: thickness h , saturation magnetization M_s , coercive force H_c , anhysteretic bubble collapse field H_{cb} , theoretical bubble collapse field H'_{cb} (according to [20]).

High coercivity samples

Due to a more irregular domain structure (short stripes and "dots"), larger inhomogeneities at the surface and some other factors the observation of the domain structure of high coercivity samples is more difficult. We observed the field dependence of the domain period on the descending branch of the hysteresis loop on three high coercivity ($H_c/H_k \sim 0.08$) films with differing columnar structure (Table 2). The observed structure is illustrated for sample No. 6 in Fig. 3. Our results i.e. measurements of the reduced domain period versus the normalized magnetic field on the descending branch of the hysteresis loop are in good agreement with the Kerr technique measurements carried out on the same sample [17] (see Fig. 4).

Fig.3 VSM hysteresis loop of film No. 6 (Table 2) with the corresponding domain structures. Descending fields: a-d.

Fig.4 The field dependence of the reduced period p/p_r of sample No. 6 ($p_r = 850$ nm measured by Kerr method [17]) for the descending branch of the hysteresis loop: Kerr method - ●, our results: p/p_r - ○ (the bars on the experimental points are the errors mostly caused by the irregularity of the structure), p_f/p_r - △.

To exclude subjective errors in the determination of the period p we carried out two-dimensional Fourier analysis of the digitalized photographs. From these spectra we picked out the smallest characteristic period p_f ; this value is nevertheless usually somewhat larger (see Fig.4) than the value p obtained from that visually measured on about 10 different places of the photograph (see also our paper [21]).

Fig. 5 demonstrates the advantages of the colloid-SEM method permitting the simultaneous observation of the Bitter patterns and the underlying columnar structure at the surface of one sample. With regard to the roughness of the surface, however, it will be desirable to carry out a check on a CoCr film planarized by applying a thin polyimide film.

Fig.5 Domain structure of the sample No.7 - descending branch 160kA/m. The figure shows simultaneous observation of the dried Bitter patterns and the column size at the surface. The inset was obtained on colloid free surface.

Table 2 contains values of the domain period for 3 samples (in the nearly remanent state - 32kA/m) and the number of columns per domain - $p_r/2D$.

Table 2

Sample No.	h [nm]	M_s [kA/m]	H_c [kA/m]	p_r [nm]	D [nm]	$\frac{p_r}{2D}$
5	420	400	68	680 ± 100	80	4.2
6	1220	413	46	760 ± 80	130	2.9
7	1740	460	58	1170 ± 100	300	2.0

Parameters of three high coercivity CoCr films. The nearly remanent domain period p_r [nm], the diameter of the column at the surface D [nm].

Discussion and Conclusions

Low coercivity samples

Some previous papers [1],[22] already mentioned the existence of bubbles in CoCr films and foils. In this paper we present detailed investigations (for low coercivity samples and additional ac field) showing that above a certain value of the applied field bubbles are energetically more favourable which is in agreement with the theory [19]. From the dependence of the anhysteretic bubble lattice density versus the static magnetic field we were able to determine the value of the anhysteretic collapse field and to compare this value for 4 samples with the theoretical one for the collapse of stripes and bubbles [20]. The anomalous behaviour of sample No. 1 is probably caused by its low magnetization and small thickness indicated by the worse agreement [21] with the theory of Kooy and Enz.

We would like to point out that the observed structure of bubbles with densities greater than $10^8/\text{cm}^2$ might be interesting for perpendicular recording. However, the existence of bubbles is dependent on the relatively high value of the applied dc field.

High coercivity samples

The applicability of the colloid-SEM method was demonstrated for this type of material (agreement with the measurements using the Kerr technique [17]). These

high coercivity materials are characterized by the formation of a great number of oppositely magnetized domains when lowering the static magnetic field from saturation. The pinning centers at the grain boundaries, or at possible non-magnetic cores inside the columns [10] hinder the displacements of the walls. The observed dependence of $p(H)$ (Fig. 4) is in disagreement with existing theories for stripe and bubble domains.

The observed structure of short stripes and "dots" exhibited in these materials a certain increase of the remanent domain period p with increasing thickness (see Table 2), however, the determination of the period (as follows from the photographs) is burdened by a large error. The two-dimensional Fourier analysis does not improve the precision in the determination of the domain period.

The dependence of the diameter of the columns at the surface on the film thickness h was already observed earlier [23]. From the measured value of p we can approximately assess the number of columns per domains width. This value is from two to four columns per domain; in rough agreement with the estimates published in the papers [9],[24] (5-6 columns per domain).

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