Domain Structures in Co/Pd Multilayers

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Abstract- Domain observations and measurements of mean domain sizes in Co/Pd multilayers with high perpendicular anisotropy are reported and compared with the predictions of the stacked-stripe model of domain structure. The estimated high wall energies are consistent with measured anisotropy. Properties of the model in the thin-layer limit are discussed.

I. INTRODUCTION

Potential application of Co/Pd and Co/Pt multilayers in magneto-optical recording draws attention to films with large perpendicular anisotropy, coercivity and remanence. Inferences about the domain structure of "hard" films are mostly based on comparison [1-5] of measured hysteresis loops with predictions of the stripe-domain model extended to multilayers [1,2], although direct domain observations [4,6] and measurements [7] have recently been reported.

We report direct measurements of domain sizes in "hard" Co/Pd multilayers prepared by rf sputtering [8] and compare them with the model predictions. A comment is added on the similarity of these predictions to those based on averaged uniform material parameters, noticed in the behaviour of theoretical hysteresis loops [4].

II. MODEL CALCULATION

In the periodic-stripe model extended to multilayers [1,2] (Fig. 1) the magnetostatic energy E_d is computed as a function of the domain width, D . The formulation [2] allows to evaluate the left-hand side of the force-balance equation

$$F_m \equiv D \partial e_m / \partial D = \sigma / D \quad (1)$$

where $e_m = E_d / V_m$ is scaled to the magnetic (Co) volume, V_m , σ is the wall energy density and F_m has the meaning of magnetostatic pressure (force per unit wall area).

Fig. 2 is a scaled plot of this quantity in the (presently) relevant range of model parameters: D is the domain width, T is the total film thickness, $f = V_m / V_f$ is the filling factor (V_f is the total film volume), and N is the number of bilayers.

Selecting scales for this plot, we find that

$$F_{f0} = f^{-1} F_m / (0.5 \mu_0 M_s^2) \quad (2)$$

(where M_s pertains to magnetic layers), vs. T/D gives curves which only little depend on the stacking parameter N and f . This feature is discussed in sect.IV.

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Figure 1 The periodic stack-stripe domain model

Fig. 2 Normalized wall-pressure F_{f0} (2) vs. film thickness-to-domain width ratio.

From (1) and Fig. 2 the wall energy may be determined if the equilibrium D is estimated experimentally.

III. EXPERIMENT

Magnetic properties of a series of Co/Pd multilayers prepared by rf sputtering in Ar have been reported previously [8]. The following table summarizes parameters of the samples used in the present domain study.

TABLE I
THICKNESS AND MAGNETIC PROPERTIES OF SAMPLES a AND b (N=25)

	t_m	T	f	M_s	H_c	K_u
	nm	nm		MAm ⁻¹	kAm ⁻¹	MJm ⁻³
a	0.85	57.4	0.37	1.85	36	2.5
b	0.43	83.9	0.13	1.6	111	3.2

Fig. 3 Colloid-SEM images of domain structure of samples *a* and *b*.

We used the CSEM method (dried colloid Bitter patterns observed by scanning electron microscopy [9]) to obtain images of the domain structure in various states of film magnetization. Figs. 3a, b show the domain structures on the two samples, decorated after saturation followed by several cycles on minor loops in the field range ± 160 kA/m. In accordance with our previous experience on medium-coercivity CoCr films [10], the domain widths in such states are close to those obtained by ac demagnetization. This was also verified on our sample *a*. The average transverse domain dimensions (D) obtained statistically on samples *a* and *b* are 90 nm and 145 nm, respectively.

IV. DISCUSSION

A. Scaling of magnetostatic forces.

The normalized pressure F_0 (2) plotted in Fig. 2 is a film-averaged quantity: it may be written as

$$F_0 = (D \partial e_f / \partial D) / (0.5 \mu_0 M_f^2) \quad (3)$$

with $e_f = E_d / V_f$ and $M_f = f M_s$ scaled to the total film volume. This pressure is formally balanced by the average surface energy $\sigma_f = f \sigma$ in the geometrical stack-domain boundary. The balance (1) may be written in two "normalized" forms, $F_{m0} = L_m / D$ or $F_{f0} = L_f / D$, where $L_m = \sigma / (0.5 \mu_0 M_s^2)$ and $L_f = \sigma_f / (0.5 \mu_0 M_f^2)$, resp., denote the "material lengths" of the magnetic layers and of the multilayer as a whole. The second viewpoint is assumed by Hashimoto *et al.* [11] in crude estimates of the expected domain dimensions.

Figs. 2 and 4a indicate that, indeed, in the "thin-flat" limit ($t_m \ll D$), F_{f0} and hence also L_f are appropriate characteristics: the equilibrium domain sizes can be approximately obtained in terms of these average parameters (ignoring the actual geometrical alignment of individual layers) from single-layer theory [12]. This is confirmed by the common scaling at the "thin" end of Fig. 4b which shows the equilibrium domain size vs. total film thickness, both normalized to L_f .

Fig. 4a Normalized wall pressure F_0 vs. film thickness-to-domain width ratio.

Fig. 4b Reduced domain width vs. reduced film thickness ($f=0.25$).

Fig. 5 Reduced domain width vs. magnetic layer thickness ($f=0.25$)

The sharp departure from the "average" scaling in these plots is connected with keeping constant f and N on individual curves, which corresponds to T increased by proportional "inflation" of the magnetic (t_m) and spacer (t_s) layers. The D vs. T plots have only one minimum if T increases by "stacking" [2,4,7] (T proportional to N at constant t_m and f : read D values on verticals of given t_m/L_m or of $T/L_f = N t_m/L_m$ in Figs. 5 and 4b, resp.).

Appropriate scaling of these "inflation" plots at high T/D is in terms of magnetic-layer parameters, t_m and F_m (M_s and L_m), as shown in Fig. 5. The high- t_m/D end is the Kittel limit

Fig.6 Norm.pressure components and derivative S_0 (see text; $f=0.25, N=50$)

[13,12] where dipolar fields between laterally neighbouring domains are confined to individual layers.

On the other hand, the intuitively obvious reason for the "alloy-analogy" in domain behaviour on the "thin" end is the penetration of stray-fields of flat domains across the whole film thickness (so that all dipoles effectively interact with each other). This is illustrated in Fig.6 where the part of F_0 arising from interaction between different layers, $F(int)$, is separated from the derivatives of the self-energy of individual layers, $F(self)$. If $t_m \ll D$, the inter-layer force accounts for practically all the magneto-static pressure which generates the domains; and the observed narrow domains can only be sustained magnetostatically if they penetrate the whole film.

The transition between relatively strong and weak inter-layer force occurs in a narrow range of magnetic and spacer thickness; plots analogous to Figs.4, 5 and 6 show a critical range at $\sqrt{(t_m t_s)} \approx 3 L_m$, and a relation between the bilayer thickness and the domain size in this range,

$$t_m + t_s \approx 0.6 D. \quad (4)$$

The weak line in Fig.6 is a plot of $S_0 = [F_0 + D \partial F_0 / \partial D] / 2$ which is proportional to $D^2 \partial^2 (E_d + E_{wall}) / \partial D^2$ and thus measures stability of the model structure; its deep minima in the range (4) are close to the (negative) minima of $F(int)$.

The relation (4) and the "resonant" feature in the inter-layer pressure (Fig.6) allow an intuitive interpretation based on local estimates of the stray field of a single thin flat domain (Fig.1): the field at a distance z below its centre is positive (parallel to M) and equal to $2\mu_0 M_s \vartheta / \pi$, where (for $t_m \ll z, D$) $\vartheta \approx (2t/D) / (1 + 4z^2/D^2)$ indicates effective penetration to $z_0 \approx D/2$. At such (fixed) distance, the angle ϑ and hence the positive field decreases with either increasing or diminishing D , which explains the changing sign of the energy derivative (negative inter-layer pressure) in Fig.6.

B. Estimated domain wall energy.

Comparing the observed domain sizes with the predictions of the stripe model, we estimate the "material length" L_m

(denoted τ in recent model studies [1,2,5,7]), $L_m = D F_{m0} = f D F_0$ and the wall energy density: $L_m = 9.2$ and 5.5 nm, $\sigma = 20$ and 9 mJ/m², for samples *a* and *b*, respectively. The higher value corresponds well to the expected wall energy, $\sigma = 4\sqrt{(AK_u)}$ with the measured anisotropy constant K_u and the value of exchange constant A for bulk Co (≈ 10 pJ/m). The lower values obtained for sample *b* with lower Co thickness are closer to those reported by Zeper *et al.* [5] and Donnet *et al.* [7], corresponding to "effective" exchange stiffness of only 20% of the bulk value. This may be easily ascribed to deteriorating lateral coherence of very thin Co films in sputtered multilayers, with columnar structure. Preliminary measurement on other "hard" samples with small t_m ($H_c = 96$ and 152 kA/m) leads, however, to $L_m \approx 6$ to 8 nm, and detailed investigation of the differences in domain structure and morphology is desirable.

V. CONCLUSIONS

Observation of the domain structure and measurement of domain sizes on minor hysteresis loops of magnetically "hard" Co/Pd multilayers (combined with previously measured magnetic parameters) shows good and moderate agreement with predictions of the stripe-domain model [2] in the case of medium and high coercivity films, respectively; possible correlation with structural properties deserves further investigation.

Formal results of model calculations are discussed: the analogy between domain patterns expected in thin multilayers and in films of corresponding alloys follows from prevalence of inter-layer magnetostatic forces; rather sharp transitions to significantly denser domain patterns can be expected with increasing bilayer thickness.

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