Domain Structures in Co/Pd Multilayers

V. Kamberský, P. de Haan, J.C. Lodder, J. Šimšová1, R. Gemperle1
MESA, University of Twente, P.O. Box 217, 7500 AE Enschede
1Institute of Physics, Czech Acad.Sci.,Cukrovarnicka 10,16200 Prague

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 investigation of films with large perpendicular anisotropy, coercivity and remanence. Inferences about the domain structure of such "hard" films are mostly based on comparison [1-5] of measured hysteresis loops with predictions of the stripe-domain model extended to multilayers ("stacked stripes") [1,2], although direct domain observations [4,6] and measurements [7] have recently also 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 $E_m$ 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

$$ F_m = -D \partial e_m / \partial D = \sigma / D $$

where $e_m = E_m / V_m$ is scaled to the magnetic (Co) volume, $V_m$, $\sigma$ 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

$$ F_0 = 2f^{-1} F_m / \mu_0 M_s^2 $$

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

Fig. 2 Normalized wall-pressure $F_0$ (eq. (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>
<thead>
<tr>
<th>TABLE I</th>
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<tr>
<td>THICKNESS AND MAGNETIC PROPERTIES OF SAMPLES a AND b (N=25)</td>
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<tr>
<td>$t_{Co}$</td>
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<tr>
<td>nm</td>
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<td>a</td>
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We used the CSEM method (dried colloid Bitter patterns subsequently 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 representative samples, decorated after saturation followed by several cycles on minor loops in the field range ±160 kA/m, in negative field. In accordance with our previous experience on medium- and high-coercivity CoCr films [10], the domain widths in such states are quite 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 may also be written as

$$F_0 = 2H_m^2 / \mu_0 (\mu M_s)^2$$

where $\mu M_s$ is the average film magnetization and $H_m$ is the average pressure in the geometrical stack-domain boundary extending through the multilayer. According to Fig. 2, $F_0$ and thus also the "bulk" pressure $H_m$ only weakly depends on the stacking parameters (multilayer geometry). This means that also the force balance (1) (multiplied by $f$) and hence the equilibrium domain size in the multilayer is similar to that in an alloy with corresponding averaged material parameters, $f\mu M_s$ and also $f\mu$. Fig. 4a shows that this

![Diagram](image1.png)

Fig. 4a Normalized wall pressure $F_0$ (eq. 2) vs. film thickness-to-domain width ratio.

![Diagram](image2.png)

Fig. 5 Part of the normalized wall pressure $F_0$ derived from inter-layer interaction alone, vs. film thickness-to-domain width ratio.

![Diagram](image3.png)

Fig. 4b Normalized wall pressure $F_{m0}$ (eq. 3) vs. magnetic layer thickness-to-domain width ratio.

![Diagram](image4.png)

Fig. 6 Equilibrium domain width $D_e$ vs. magnetic layer thickness $t$, normalized to $L=2\mu /\mu_0 M_s^2$, at constant filling factor $f$ and number of layers $N$. 
"average" scaling fails at higher $t/D$. For $D << t$ the single-layer parameters $t$, $M_s$, and $F_{mo} = 2F_m/\mu_0M_s^2$ give proper scaling in accordance with single-layer theory (Fig. 4b).

The different behavior of magnetostatic forces at low and high $t/D$ ratios is intuitively understandable as a consequence of different geometry of prevailing dipolar interactions: at high $t/D$ the stray field lines close between laterally neighboring domains while at low $t/D$, interaction between different layers becomes the only important factor (depending significantly on $D$). To illustrate the last point, Fig. 5 shows separately the part of $F_o$ deriving only from magnetic forces between different layers.

The schematic Fig. 1 helps to assess the magnitude of the inter-layer fields in the thin limit and also to understand the kind of shape resonance in the last plot. The field of a single flat stripe domain at distance $z$ below its centre is positive (parallel to $M$) and equal to $\mu_0M_s \theta/\pi$, where (for $t << z, D$) the angle $\theta = (2t/D)/(1+4z^2/D^2)$ indicates effective penetration to $z_o = D/2$. At such (fixed) distance, the angle $\theta$ and hence the positive field decreases with both diminishing and increasing $D$, which qualitatively corresponds to the changing sign of the inter-layer pressure in Fig. 5.

Fig. 6 shows the consequences of the changing field geometry for the equilibrium domain width plotted as a function of layer thickness (both divided by a material length $L = \sigma/\mu_0M_s^2$). In a wide range, at constant parameters $f$ and $N$.

B. Estimated domain wall energy.

Comparing the observed domain sizes with the predictions of the stripe model, we obtain estimates of the wall energy density, $\sigma$ = 20 mJ/m$^2$ and 9 mJ/m$^2$ for samples $a$ and $b$, respectively. The higher value corresponds well to the formula for wall energy $\sigma = 4\sqrt{AK_d}$ with the measured anisotropy constant $K_u$ and the value of exchange constant $A$ for bulk Co ($=10^{-11}$ J/m). The lower value of $\sigma$ obtained for sample $b$ with lower Co thickness is not surprising with regard to larger influence of the columnar structure of the sputtered films [8] and to larger actual wall length in the observed irregular structure, in comparison with the model.

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 in the case of medium and high coercivity, resp. Formal results of model [2] calculations are intuitively illustrated.

References