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EXPERIMENTAL AND THEORETICAL DOMAIN PERIODS IN $BaCo_xTi_yFe_{12-x-y}O_{19}$

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Abstract - Domain sizes in demagnetized samples are reported for polycrystalline films of thickness down to 30 nm and for thin single crystal weges of pure and Co/Ti doped BaM hexaferrites. The results compare well with domain theory which is amended by taking into account results of micromagnetic computations. KEYWORDS: HEXAGONAL FERRITES, DOMAINS, MICROMAGNETICS

INTRODUCTION

Pure and, particularly, Co/Ti doped BaM hexaferrite films are promising materials for perpendicular and MO recording. Magnetic domain characteristics affect potential recording performance and usefully supplement structural and magnetic diagnostics combined with technological efforts. In a previous work [1,2] we have compared domain sizes in demagnetized hexaferrite samples with simple theoretical models [3-5] and estimated the 'critical' thickness below which the demagnetized domain period should sharply increase [4,5]. In this paper we report on domain sizes in a series of thin polycrystalline films, from 30 to 500 nm, and in three wedge form single crystals. We also improve comparison with domain theory including new results of micromagnetic calculations.

EXPERIMENTAL RESULTS

Polycrystalline $BaCo_xTi_yFe_{12-x-y}O_{19}$ films have been prepared by pulsed laser ablation deposition in oxygen atmosphere of 0.1 mbar on heated sapphire (00.1) substrate [6]. Bulk single crystals were grown by slow cooling of flux melts [1], platelets cut perpendicular to the hexagonal (00.1) axis were mechanically polished to thin low-angle wedges. X-ray powder diffractometer analysis of the films indicates the magnetoplumbite phase (BaM) with c-axis preferentially oriented perpendicular to the film surface [7]. The composition of the samples and also their thickness were measured by electron microprobe analysis using a numerical procedure regarding the small film thickness. The thickness was checked by α-step. Magnetic characteristics (M_s, H_K and $H_c^{\perp}$) were measured by VSM.

The colloid-SEM method (i.e. observations of dried Bitter patterns in a scanning electron microscope) was used to measure the equilibrium domain period (required for comparison with theory as well as for application considerations), i.e., after careful demagnetization.

In Figs.1a,b and 2a,b are examples of colloid-SEM photographs from which the average domain periods were statistically determined.

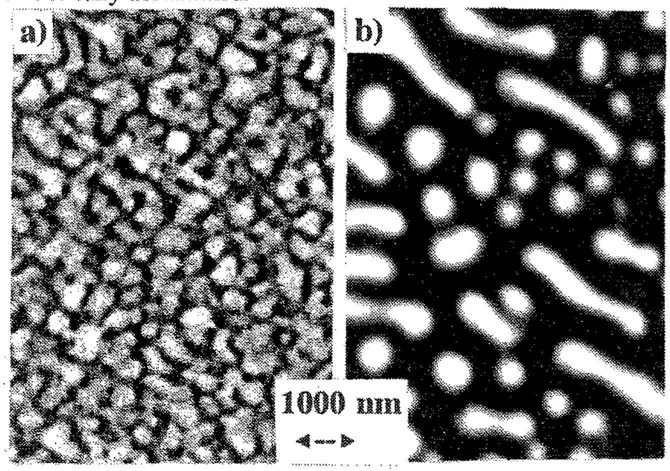

Fig. 1 Domain structure in $BaFe_{12}O_{19}$ polycrystalline films:
a) h=280 nm (above 'critical')
b) h= 30 nm (below 'critical').

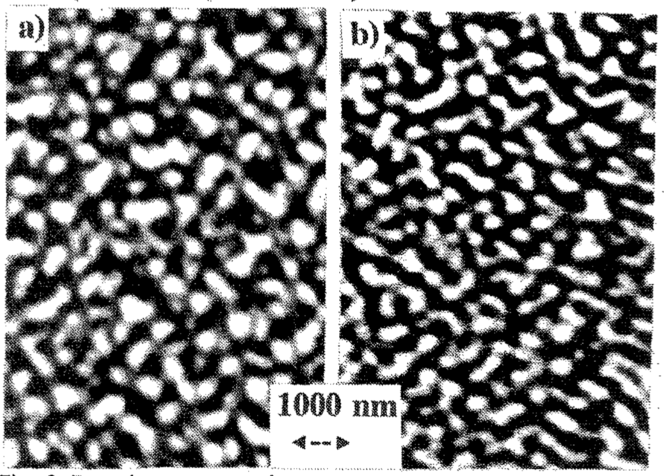

Fig. 2 Domain structure in $BaFe_{10.85}Co_{0.55}Ti_{0.6}O_{19}$ polycrystalline films: a) h=290 nm (above 'critical')
b) h= 30 nm (below 'critical').

Tables 1 and 2 summarize the results of measurements of the domain periods *p* and the sample thickness *h*, along with their magnetic characteristics M_s and H_c.

Tab. 1. $BaFe_{12}O_{19}$ wedges and polycrystalline films

Sample No.	h [nm]	M_s [Gauss]	$H_c^{\perp}$ [Oe]	p [nm]
wedge 1*	400÷ ÷2500	350	< 5	(Fig. 3)
wedge 2	400÷ ÷1600	350	<5	(Fig.3)
1	480	255	1100	640±140
2	280	270	1100	560±50
3	110	-	-	490±60
4	60	310	2260	500±50
5	45	300	2200	600±50
6	30	300	2200	1260±250

*) already published in [2]

Tab. 2. $BaFe_{12-x-y}Co_xTi_yO_{19}$ wedge and polycrystalline films ($x\cong 0.55$; $y\cong 0.6$)

Sample No.	T [nm]	M_s [Gauss]	$H_c^{\perp}$ [Oe]	p [nm]
wedge 2*	600÷ ÷4000	325	< 5	(Fig. 4)
7	290	300	540	560±50
8	30	280	1300	430±40

*) already published in [1]

Figs. 3 and 4 show plots of the measured domain period *p* as function of the film (wedge) thickness *h* in pure and Co,Ti doped hexaferrite samples, respectively. The solid line shows theoretical interpolation (discussed below; the dotted line relates to the earlier simplified theory [4]).

DOMAIN THEORY AND MICROMAGNETICS

Theoretical models interpolating the experimental results facilitate assessment of their compatibility and sample quality, as well as extrapolation to ranges of different sample parameters; this is connected with estimates of material characteristics, like the domain wall energy density σ or the characteristic 'material length'

$$l=\sigma / \mu_o M_s^2 . \qquad (1)$$

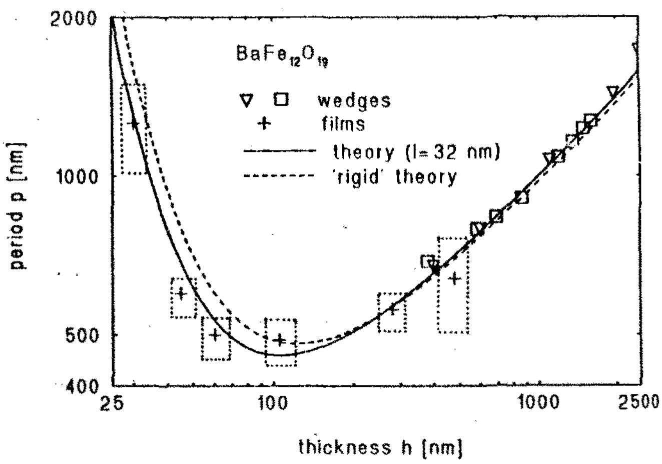

Fig.1 Domain period *p* *vs.* film thickness *h* in $BaFe_{12}O_{19}$ wedges and polycrystalline films, compared with theory.

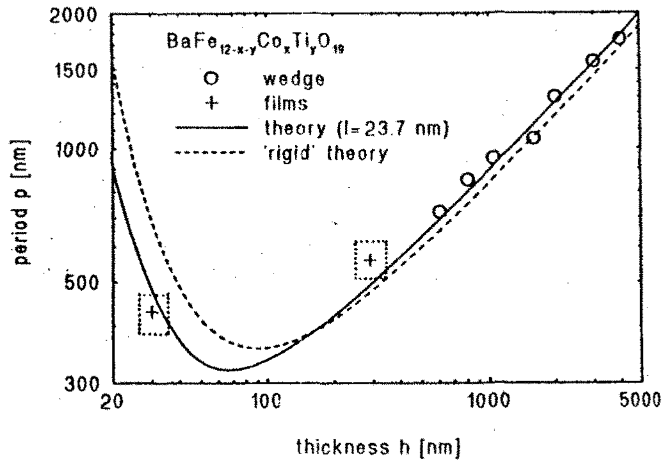

Fig.2 Domain period *p* *vs.* film thickness *h* in $BaFe_{12-x-y}Co_xTi_yO_{19}$ wedges and polycrystalline films, compared with theory.

The simplified model calculation by Kittel [3] giving the half-power law, $p \propto h^{1/2}$ for stripe domain periods in relatively *thick* films was first corrected [4] for magnetic flux closure *through* the thickness in *thin* films, which makes domains less favourable and leads to *increasing* periods at low *h*, and later also for partial flux closing by rotation of magnetization in the surface regions of *domains* [5].

Numerical micromagnetic calculations [8,9] done in the vicinity of the 'critical' thickness (where *p* is a minimum) take into account concentration of the latter process in the *walls* in the *thin* limit; however, these resuts surprisingly seem to *completely* remove the earlier correction [5] in the *thick* limit.

Thus, in spite of the limited accuracy of experimental results, particulary at low film thickness, it appeared necessary to reexamine the calculations before drawing 'theoretical lines' connecting the experimental points. The same need arose in interpretation of analogous experiments on garnets [10] with smaller values of the quality factor $Q=H_K/M_s$.

We have therefore extended the micromagnetic computations to larger arrays representing fine finite-element

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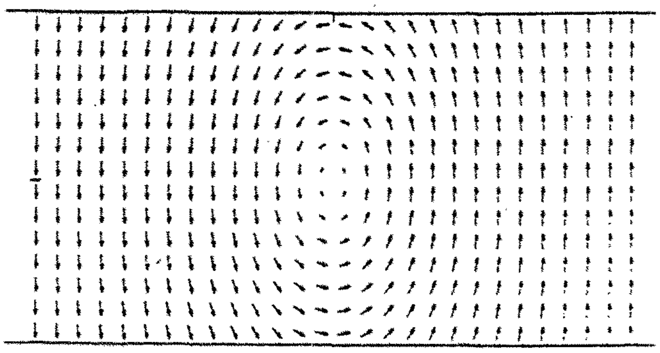

Fig. 5 Relaxed magnetization structure in 1/ 2 period of stripe domain model (Only projections into paper plane, each 3rd cell shown). Thickness h=2.2 l, Q=1.3.

divisions of the cross sections of stripe domains (Fig.5) in a wide range of film thickness (and domain periods). Energy minimization with respect to all local magnetizations in the array representing a fixed period p, and then with respect to p, is of course quite demanding [11]. Fig.5 shows a small array wth a pronounced 'swirl structure' of the wall; arrays for (up to 10x) thicker films show, on the other hand, the surface structures taken into account approximately by Kooy and Enz [5]. The resulting equilibrium p *vs.* h dependence is shown in Fig.6 for a relatively low Q=1.3 [10] (since the differences between 'rigid' domain theory and micromagnetic results *decrease* with increasing Q, as seen comparing Figs. 3 and 4, we use this low Q value in both illustrations, Figs. 5 and 6).

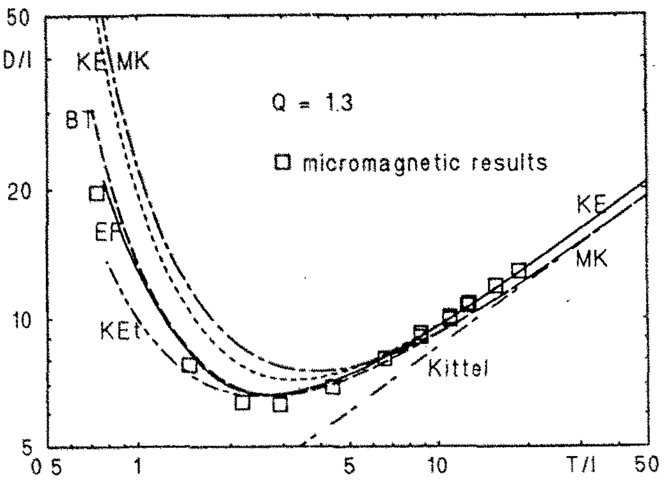

Fig. 6 Domain period p *vs.* film thickness h according to present [10] calculations (points) and previous theories (explained in the text).

Fig.6 also shows a survey of the previous predictions: MK denotes the results [4] for 'rigid' domains (infinite Q; these lines are also plotted in Figs.3 and 4), KE denotes results obtained from the energy approximation by Kooy and Enz [5] while KEt denotes their often quoted final result for the p *vs.* h dependence (which is a *thick* film approximation); BT is a plot of the interpolation fomula by Blake et al.[9] based on earlier micromagnetic results [8], which alone connects upon the Kittel and MK lines at high thickness. Our results shown as open points, on the other hand, lie practically on the KE line in that range. The solid line 'EF' represents an empirically found formula (eqs.2,3) which approximately fits our computations, and connect upon KE in the half-power law region.

While 'rigid' domain theory [4] predicted a 'universal' p/l *vs.* h/l dependence, in the form

$$l/h = (4/\pi q^2)\sum f_n(q)/n^3 \qquad (2)$$

where $q=2\pi h/p$, $f_n(q)=[1-(1+nq)\exp(-nq)]$ and the summation runs over odd n, we find good fitting to the micromagnetic results replacing this $f_n(q)$ by a function also depending on the anisotropy (i., on the quality factor Q), which is a modification of the KE correction [5]:

$$f_n(q) = \frac{2[1-(1+nq\rho)\exp(-nq\rho)]}{\rho+1+(\rho-1)\exp(-2q^2)} \qquad (3)$$

where $\rho=\sqrt{(1+1/Q)}$ is the square root of the rotational permeability [12,5]. The fitting seen in Fig. 6 improves for larger Q values, pertaining to the present experiment.

DISCUSSION AND CONCLUSIONS

For the fitting to experiment in Figs. 3 and 4 we used the average (VSM) values of Q= 4.24 and 1.6 for the samples of $BaFe_{12}O_{19}$ and $BaFe_{10.85}Co_{0.55}Ti_{0.6}O_{19}$, respectively. The results are values of the characteristic length (l) for these two materials, obtained as 32 nm and 23.7 nm, respectively.

Compatibility of the data for single crystals and for the laser deposited films is satisfactory (within experimental uncertainties), indicating rather good quality of the films.

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