EFFECT OF ANISOTROPY DISPERSION ON STATIC REVERSAL PROCESS OF MAGNETIZATION IN Ni-Fe FILMS

TOSHITAKA FUJII, EIZŌ YAMADA, and SUSUMU UCHIYAMA

Department of Electrical Engineering

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Static reversal process of the magnetization in normal permalloy films of about 800 Å in thickness was investigated by means of the Faraday magneto-optic effect. For films with small anisotropy dispersion ($\Delta_{90} \simeq 0.1$), the splitting into band domains of about 100 μ wide was observed. The appearance of these domains is interpreted by Smith's model of labyrinth propagation. For films with medium dispersion ($\Delta_{90} = 0.2 \sim 0.3$), a new type of partial rotation, the splitting into the slender domains of about 20 μ in width was found to precede the appearance of the band domains. The splitting into the slender domains is interpreted by Middelhoek's model of partial rotation. The propagation of the labyrinth domain was clearly observed only in the case of large dispersion ($\Delta_{90} \simeq 0.4$).

§ 1. Introduction

In normal uniaxial ferromagnetic films, the magnetization was thought to be reversed either by the domain wall motion or by the coherent rotation according to the situation that the reversing magnetic field is nearly parallel to the easy axis or not. Previous works, however, reported that the static reversal was not performed by such simple processes, but by various kinds of noncoherent switching such as low stray field type,[1] partial rotation type,[2] and labyrinth propagation type.[3] Since these noncoherent switching processes result from the magnetic anisotropy dispersion in the film, what type of the magnetization reversal really occurs should be dependent upon the degree of the anisotropy dispersion as already suggested by Prutton.[4] The experimental result to this purpose, however, has not yet been published except the work of Cohen.[5] Although his result is very valuable, his interpretation seems to need some corrections in several respects. (This problem will be discussed in §4.) In this paper, we will report our experimental results and the correct interpretation about the influence of the anisotropy dispersion on the static reversal process for normal permalloy films.

§ 2. Apparatus and Samples

The Faraday magneto-optic apparatus, which is used in this experiment to reveal the magnetic domain, is similar to that first reported by Fowler and Fryer,[6] as shown schematically in Fig. 1. The B–H characteristic can be observed simultaneously with the domain observation.

Permalloy films of about 80–20 Ni-Fe were deposited in vacuo in the presence of a magnetic field onto cleaned microscope cover glasses. After the deposition,

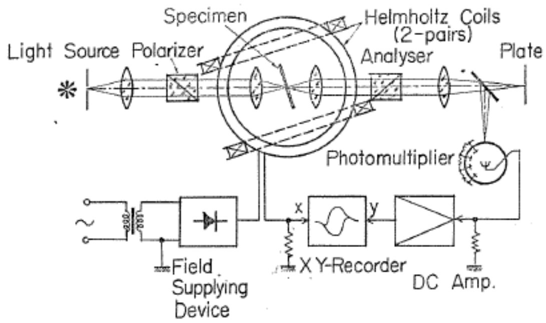

FIG. 1. Schematic diagram of the experimental apparatus, a Faraday magneto-optic device.

the films were coated with a thin SiO layer of about 1000 Å in thickness so as to improve the contrast of the photographs. The temperature of the substrate, the pressure of the residual gas in the vacuum deposition unit, and the rate of the evaporation were changed in various ways in order to obtain the films with various degree of anisotropy dispersion.

Properties of the samples used in this experiment are listed in Table 1. Anisotropy field H_k, angular dispersion α_{90}, and magnitude dispersion Δ_{90} were measured by means of ferromagnetic resonance at 500 kc.[7]

TABLE 1. Magnetic anisotropy field and its dispersion of permalloy films used in this experiment (measured by means of ferromagnetic resonance)

sample	H_k (Oe)	α_{90} (dag)	Δ_{90}
#1	7.0	1.7	0.12
#2	7.5	1.7	0.12
#3	5.5	5.0	0.20
#4	6.7	4.1	0.25
#5	6.5	6.1	0.32
#6	5.7	11	0.39
#7	9.5	10	0.24

§ 3. Observation

3–1. Films with small anisotropy dispersion

First we show the case of small anisotropy dispersion. (Film No. 1 and No. 2) If the angle β between the direction of the reversing field H and that of easy axis is smaller than a certain critical angle β_c, then the reversal of the magnetization is simply performed by the domain wall motion. The critical angle β_c is about 40° for film No. 1 and about 30° for film No. 2. Next in the case where $\beta > \beta_c$, the situation is as follows. If the reversing field H becomes almost as large as the threshold field H_{th} for the coherent rotation,[8] then band domains of about 100 μ in width appear as shown in Fig. 2 a. The increase of the field H by a small amount results in the increase of the number of the band domains. (Fig. 2 b) With further increase of H the width of the band domains becomes broader, *i.e.*

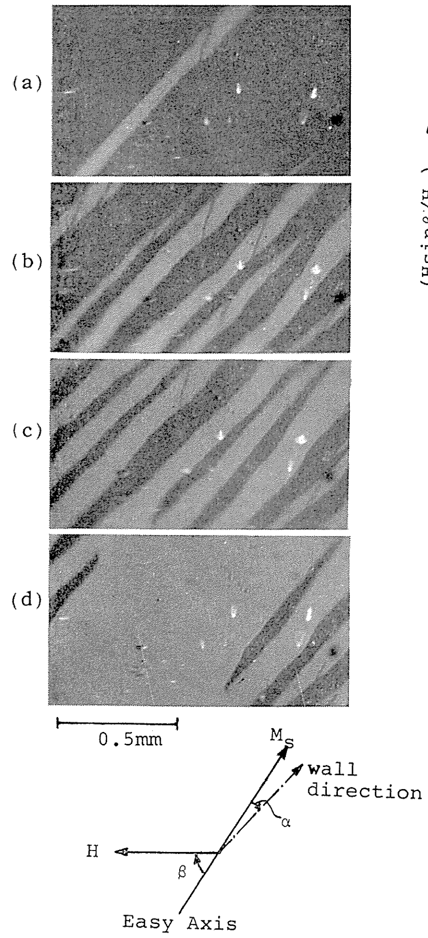

FIG. 2.

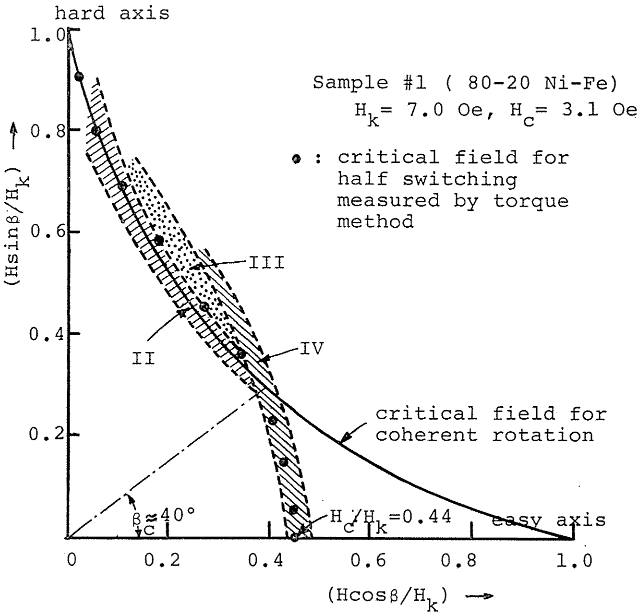

FIG. 3.

Fig. 2. The reversal process at acute angles to the anisotropy axis observed for film with small anisotropy dispersion.
Sample #1 ($\Delta_{90}=0.12$), $\beta=60°$, $\alpha=10°$ (a) $H=3.4$ Oe (b) 3.5 Oe (c) 3.6 Oe (d) 3 9 Oe.

Fig. 3. Representation of regions of various static reversal processes observed in Ni-Fe films: an example of the film with small dispersion.
II : Region of the increase of the band domain number.
III : Region of the broadening of the band domain.
IV : Region of usual wall motion.

the wall motion of the band domain occurs (Fig. 2 c), and finally the magnetization reversal is completed by the wall motion of the very wide domain which is nucleated at the edge of the film.

The type of the reversal process just described is qualitatively the same as that observed by Middelhoek.[2] Fig. 3 shows the result thus obtained in normarized form, using $\bar{H}_k$ measured by the FMR method as normalizing denominator. In the figure, the solid line shows the theoretical switching curve for coherent rotation and the solid circles correspond to the field of half switching (*i.e.* at this field just the half area of the film is switched) which is measured by the torque magnetometer. The agreement of the switching field measured by the Faraday, the torque, and the FMR method indicates that the magnetic anisotropy of the region under observation by the Faraday method is almost the same as the mean anisotropy of the whole film, in other word the film has small dispersion.

3–2. Films with medium dispersion

The aspect of the reversal process becomes somewhat different for films with medium dispersion, No. 3, No. 4, and No. 5. When $90^\circ > \beta > \beta_c$ and $H \simeq H_{th}$, the band domains appear as in the case of small dispersion, but the unswitched band regions show patterns with peculiar fine structure which remind us of something twisted. (Fig. 4b and Fig. 5b) It is noted further that the pattern with fine structure becomes more and more remarkable with the increase of the magnitude dispersion (cf. Fig. 4b of film No. 3 with $\Delta_{90}=0.20$ and Fig. 5b of film No. 4 with $\Delta_{90}=0.25$), and finally comes to the situation where the shape of band domain is no more clear enough and the pattern as a whole resembles that of the labyrinth domain. (Fig. 6b or 6c of film No. 5 with $\Delta_{90}=0.32$) In order to compare more precisely these domains with the labyrinth domain, the field was first applied

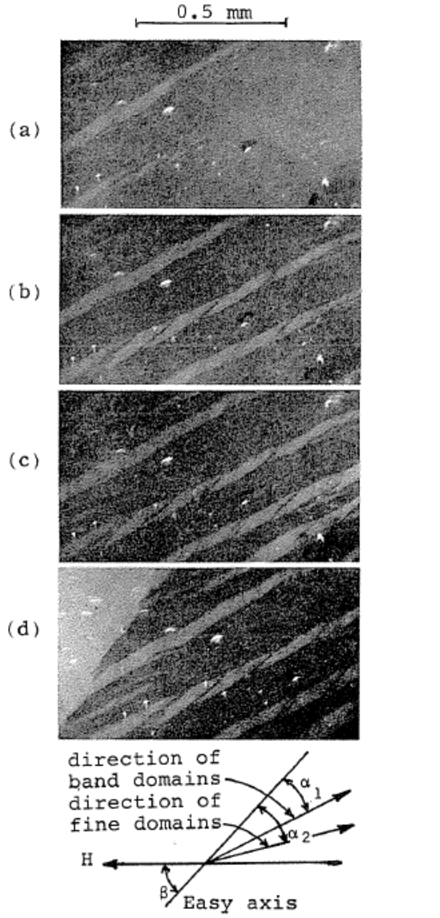

FIG. 4. Acute angle reversal process observed for film with medium dispersion. Smple #3, $\beta=45^\circ$, $\alpha_1=20^\circ$, $\alpha_2=37^\circ$ ($\Delta_{90}=0.20$).

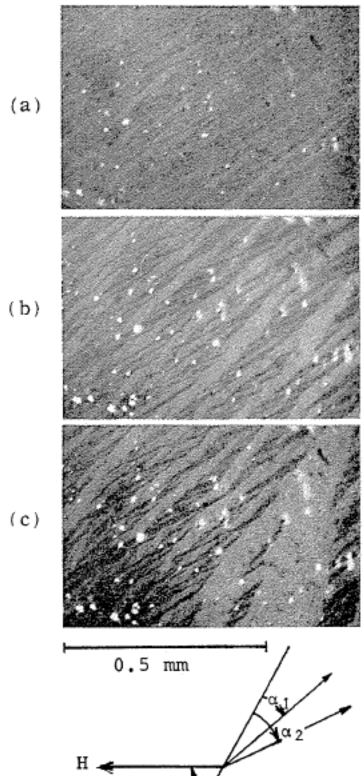

FIG. 5. Acute angle reversal process observed for film with medium dispersion. Sample #4, ($\Delta_{90}=0.25$), $\beta=60^\circ$, $\alpha_1=20^\circ$, $\alpha_2=35^\circ$ (a) $H=2.95$ Oe, (b) 3.2 Oe, (c) 3.25 Oe.

(a)
(b)
(c)
(d)

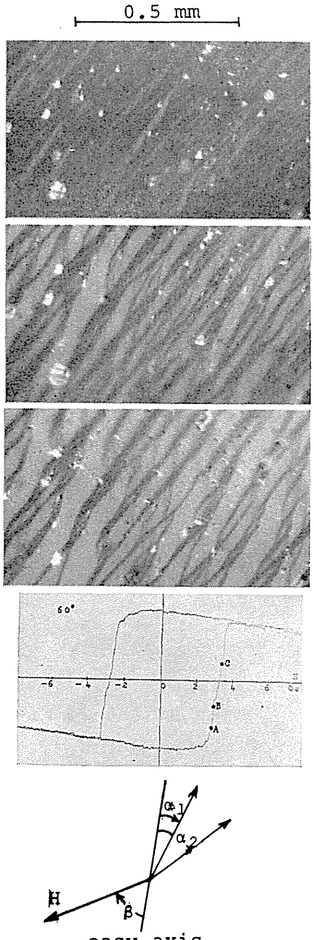

Fig. 6.

(a)
(b)

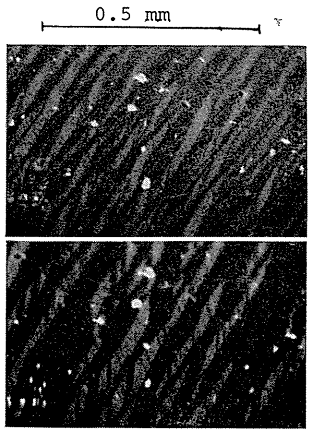

Fig. 7.

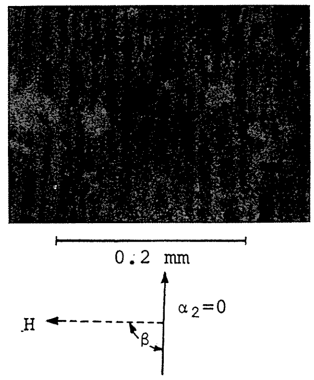

Fig. 8.

FIG. 6. Acute angle reversal process observed for film #5 with medium dispersion ($\Delta_{90}=0.32$). $\beta=60°$, $\alpha_1=20°$, $\alpha_2=45°$
(a) H=2.9 Oe, (b) 3.0 Oe, (c) 3.4 Oe (d) B-H curve of the inspected region. Marks A, B, and C correspond to the photographs (a), (b) and (c) respectively.

FIG. 7. Comparison of the domain structure before (a) and after (b) the removal of the reversing field H. Sample #5, $\beta=55°$, (a) H=3.0 Oe, (b) H=3.0 →0 Oe. Note this domain shape (b) quite resembles the shape of the labyrinth domain.[3]

FIG. 8. Slender domain of hard axis splitting for film #5. $\beta=90°$, H was reduced from 10 Oe to zero, $\alpha_2=0°$.

and then reduced to zero, and both of these domain structures were photographed as shown in Fig. 7a and 7b. It is clearly seen that Fig. 7b resembles the labyrinth domain of Fig. 14 of ref. 3.

If we observe the process more carefully, it is found that the appearance of the fine structure consisting of fine slender domains precedes to that of the ordinary band domains as can be seen in Fig. 4a or 5a. The width of these fine slender domains is about 20μ and is almost the same as that of the slender domain observed in the case of hard axis splitting. (cf. Fig. 8) Increase of the reversing field H results in the increase of the number of the band domains (Fig. 4b→4c) as well as in the broadening of the width of the band domains (Fig. 6b→6c) followed by the wall motion of the domain nucleated at the film edge. (Fig. 4c→4d and Fig. 5b→5c) Fig. 6d is the B-H characteristic of the same region as that of Fig. 6a~c, where B is the flux component in the easy direction. Marks A~C in Fig. 6d indicate the positions where the domain structures of Fig. 6a~c are observed.

When $\beta<\beta_c$, the reversal is usually performed by the wall motion throughout its process. Sometimes, however, the partial rotation, splitting into the fine slender domains, is observed in unswitched region for films with larger dispersion. (Fig. 9)

If the angle β is nearly equal to 90°, then only appear the slender domains indicating the nonuniform rotation.

In Fig. 10, the reversal process described above is summarized for film No. 3.

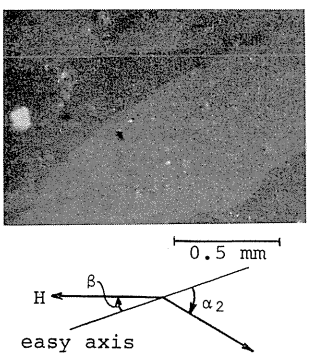

Fig. 9.

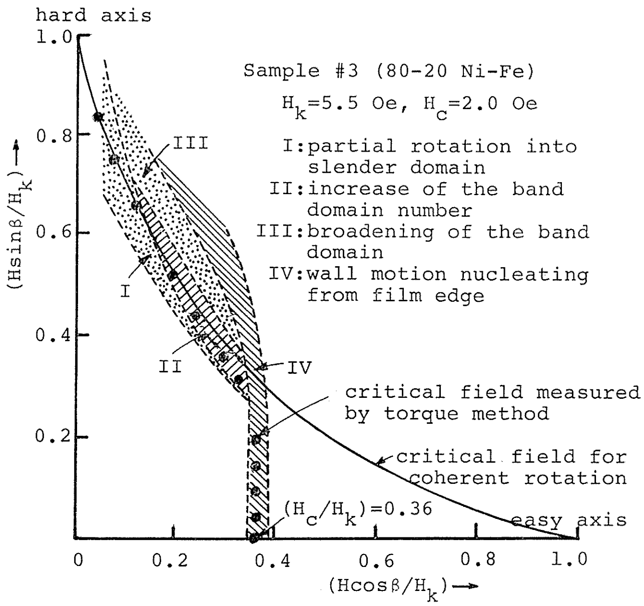

Fig. 10.

FIG. 9. Appearance of slender domain in course of wall displacement from the film edge. Sample #5, $\beta=20°$, $H=2.2$ Oe, $\alpha_2=50°$.

FIG. 10. Representation of regions of various static reversal processes observed in Ni-Fe films: an example of the film with medium dispersion.

3–3. Films with large dispersion

In several examples shown above, the domain splitting on the way of the magnetization reversal occurred almost uniformly in the visual field. In film No. 6, however, which has the largest magnitude dispersion ($\Delta_{90}=0.39$) among the films studied, the domain structure was not uniform in every visual field with the area of the order of 1 mm. As shown in Fig. 11, if we increase the reversing field in the direction $\beta_c<\beta<90°$, then the magnetization reversal starts at one end and extends to the other. (Fig. 11a∼c) Especially, it is noted that the labyrinth like domains with the width of about 100 μ propagate from the upper right to the lower left. If we observe, however, a small selected area in the visual field, one may found that the reversal process is quite similar to that given above for films with medium dispersion.

By changing the magnitude and the direction of the reversing field H, the reversal process was examined as before, and is shown schematically in Fig. 12. It is noted that the switching field obtained with the torque method differs from

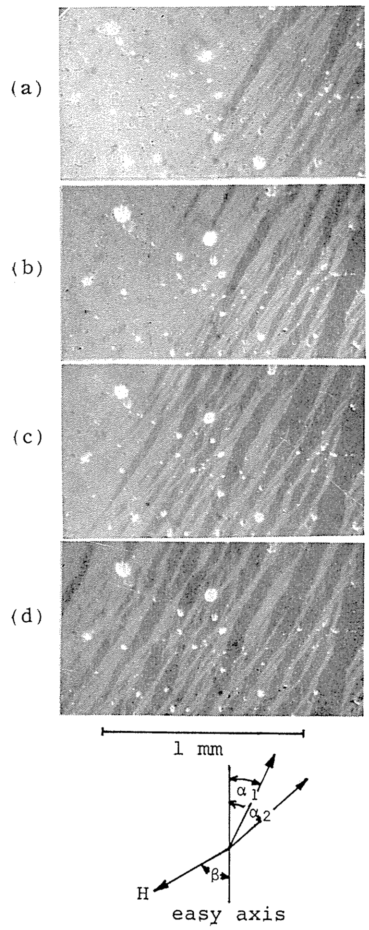

Fig. 11.

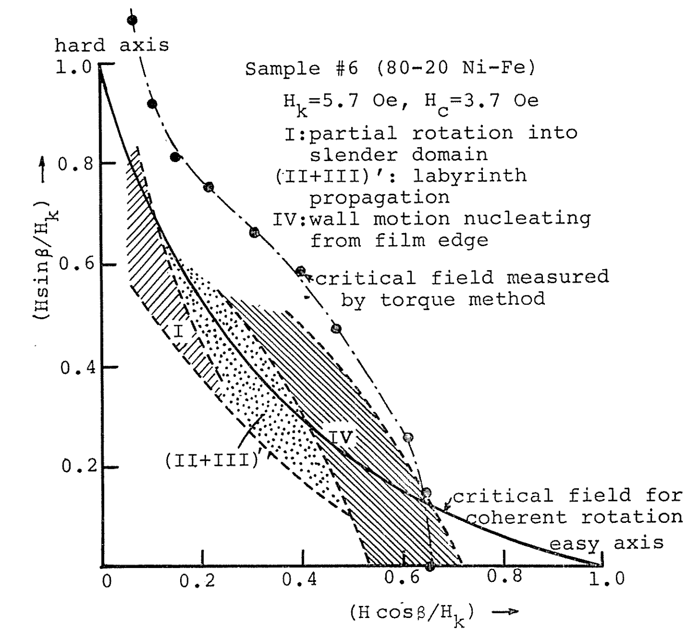

Fig. 12.

FIG. 11. An example of the labyrinth propagation observed in a film with very large magnitude dispersion. Sample #6, $\Delta_{90}=0.39$, $\beta=60°$, $\alpha_1=25°$, $\alpha_2=45°$.
(a) $H=2.5$ Oe, (b) 2.6 Oe, (c) 2.8 Oe, (d) 3.0 Oe.

FIG. 12. Representation of region of various static reversal processes observed in Ni-Fe films: an example of the film with large dispersion.

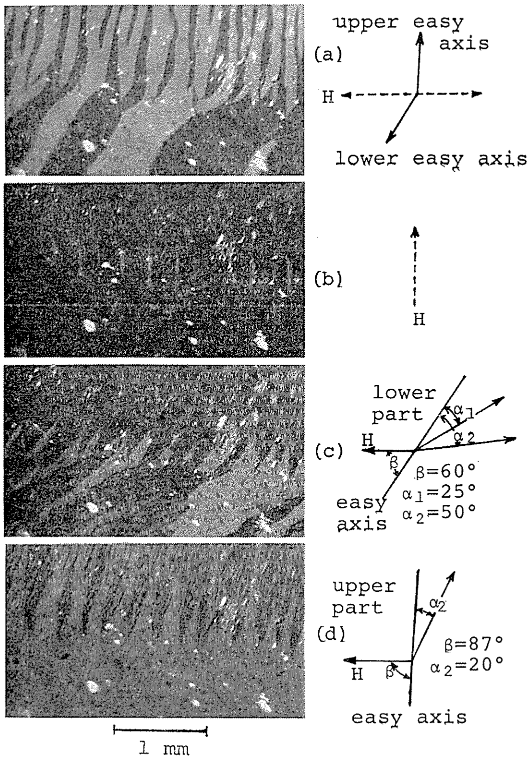

Fig. 13. Magnetization reversal process around some irregular region. Sample #7 (a) demagnetized state (b) remanent state (c) $H=4.7$ Oe (d) 9.5 Oe.

the results of the Faraday or the FMR method. This suggests that the torque method is greatly influenced by the high anisotropy centers thought to be present in the films with large magnitude dispersion.

For film No. 7, which has very large angular dispersion in spite of medium magnitude dispersion, the reversal process is almost the same as that for the films with medium dispersion except some irregular region as shown in Fig. 13. Figure 13a shows the demagnetized state after saturating the film by the horizontal field. It is seen that the easy axis of the upper half region differs in its direction by about 30 degrees from that of the lower half region. Figure 13b is the remanent state after being saturated in the vertical direction. Figures 13c and 13d are the examples of the reversal processes by the horizontal field. The magnetization of the lower half region is reversed first by the partial rotation and then followed by the wall motion, while that of the upper half region is reversed mainly by the nonuniform rotation.

§ 4. Considerations

4–1. Origin of the band and the slender domain splitting

After the method of Smith or Middelhoek, we examined the dependence of

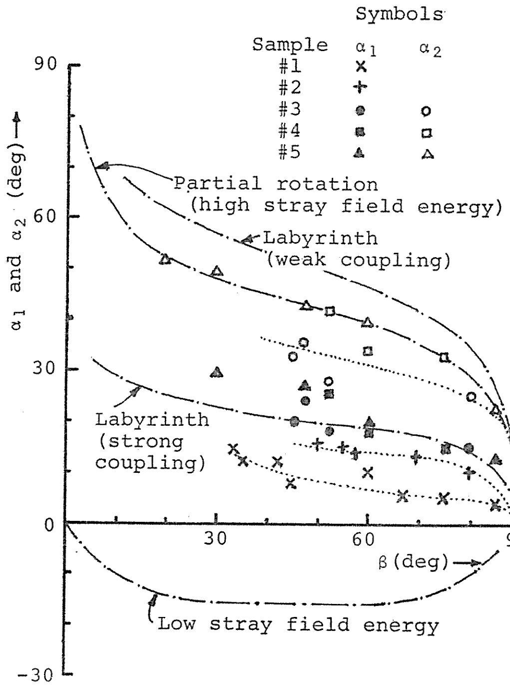

FIG. 14. Dependence of the direction of the band domain (α_1) and the slender domain (α_2) upon the direction of the reversing magnetic field (β)

α_1 or α_2 upon β, where α_1, α_2, and β are the angles between the direction of the easy axis and that of the band domain walls, of the slender domain walls, and of the applied field respectively. The results are summarized in Fig. 14. As we reported before,[9] the direction of the slender domain walls α_2 coincides fairly well with that of the theoretical prediction of Middelhoek which is based on the idea that partial rotation is due to the angular dispersion. On the other hand, the direction of the band domain walls α_1 approximately coincides with the Smith's theory of the labyrinth propagation which originates from the magnitude dispersion. Thus it may be concluded that the band domain comes from the magnitude dispersion while the slender domain from the angular dispersion. This is also supported by the fact that the slender domains are dominant when the reversing field is nearly parallel to the hard axis where the angular dispersion is most essential to the reversal process.

4–2. Change of reversal mechanism with magnitude dispersion

Now we can illustrate the difference of the reversal mechanism between the films with small dispersion and those with medium dispersion. If the angular dispersion is very small and $90° > \beta > \beta_c$, then the noncoherent switching mainly comes from the magnitude dispersion. This fact is easily understood by considering the switching threshold curve of dispersed film.[10] Thus the labyrinth model holds for these films and the band domains result. If the effect of the angular dispersion becomes too large to be neglected, then appears the partial rotation by Middelhoek's mechanism. However, once the partial rotation occurs, then further rotation of the magnetization will be prohibited by the stray field due to the magnetization discontinuity between the switched and unswitched bands, and the magnetization reversal by the labyrinth mechanism will proceed.

4–3. Propagation of the labyrinth domain

As is discussed in the previous section, the band domain is essentially interpreted as a sort of labyrinth domain. The propagation phenomena, however, of this domain could not be observed in films with small or medium dispersion. The reason is as follows: If we expand the uniaxial anisotropy $K_u(x, y)$ into Fourier series, the amplitude of the component whose wave length is of the same order as the diameter of the whole field of view should be very small for the films we are interested in now. Once the reverse domain nucleates at the film edge, it grows and extends itself completely across the whole film as a result of the magneto-static interaction as indicated by Smith. On the other hand, as for film with large dispersion the amplitude of the long wave length component is large, so that it may happen that tips of some reversed domains stop at certain points within the field of view at a value of the reversing field and then move to the points with high anisotropy when the field is increased by a small amount. Thus the propagation of the reversed domain can be observed.

4–4. Comments to the work of Cohen

It was reported by Cohen[5] that the labyrinth domain was observed in a film with small dispersion, while the partial rotation was observed in a film with large dispersion. His conclusion clearly contradicts to our results. In our opinion his results should be interpreted as follows.

Since the Cohen's observation were carried out by means of Lorentz electron microscopy, the partial rotation into the band domains with the width of the order of 100 μ might be taken as the coherent rotation (films with small dispersion). The labyrinth domain, which Cohen observed for film with medium dispersion, seems to correspond to the slender domains of the present paper if we think of the dimension and the shape of the domain. The labyrinth domain first indicated by Smith seems too large to be observed in the electron microscope. Furthermore, the partial rotation domain indicated by Cohen, which was observed in a film of inverted type, is thought to correspond to the locking domain. Thus we can conclude that he made rather inadequate interpretation in correlating the observations by the electron microscope to those by the Kerr or by the Bitter methods.

§ 5. Conclusion

In this paper, it is examined how the anisotropy dispersion influences the static reversal process of the magnetization. The results are summarized as follows.

When β, the angle between the direction of the reversing field and that of the easy axis, is smaller than a critical angle β_c, then the reversal of the magnetization is performed completely by the simple 180° wall motion from the edge.

If the films, however, have very large anisotropy dispersion in the range of normal film, splitting into the fine slender domains (the locking domain) occurs as a result of partial rotation to some extent and then it is followed by the ordinary 180° wall motion.

For film with small anisotropy dispersion ($\Delta_{90} \simeq 0.1$ and $\alpha_{90} \simeq 1°$) and when $\beta > \beta_c$, the band domains are observed which can be interpreted by Smith's labyrinth propagation model.

For films with medium dispersion ($\Delta_{90} \simeq 0.2$ and $\alpha_{90} \simeq 5°$) and when $\beta > \beta_c$, splitting into the fine slender domains precedes to the ordinary partial rotation into the band domains. The former is interpreted by the Middelhoek's theory of the partial rotation which assumes the presence of angular dispersion.

For films with large dispersion ($\Delta_{90} \simeq 0.3$ and $\alpha_{90} \simeq 10°$) and when $\beta > \beta_c$, the labyrinth propagation becomes remarkable, but the initial splitting into the slender domains is limited to the very narrow region and becomes rather ambiguous.

When $\beta \simeq 90°$, only the slender domains are remarkable regardless of the magnitude of the dispersion. This result is quite reasonable because the angular dispersion plays an important role to the reversal of the magnetization near in the hard axis.

Acknoledgement

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