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INFLUENCE OF THE SAMPLE'S CRYSTALLOGRAPHIC ORIENTATION ON THE THICKNESS-DEPENDENCE OF THE DOMAIN WIDTH IN FeSi

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The thickness-dependence of the domain width, $D(T)$, of the modified Landau-Lifshitz (ML) domain structure in FeSi is studied on rectangular-prism-shaped single-crystalline samples with different crystallographic orientation, for a thickness range from 10^{-3} cm to 1 cm. The dependence is shown to obey the power-rule $D = a \cdot T^b$, and the sample's crystallographic orientation is found to affect merely the coefficient a if the thickness T is measured along the direction of domain polarization. In particular, the results obtained for a sample with faces parallel to the crystallographic planes (110), $(\bar{1}10)$ and (001) agree with those obtained in a former paper from measurements on a wedge-shaped FeSi sample.

1. *Introduction*

Recently [1, 2], the thickness-dependence of the domain width of the simple (SL) and modified (ML) Landau-Lifschitz domain structure (see models in Fig. 1) has been studied on two wedge-shaped FeSi single crystals having different crystallographic orientation. The examined thickness range was $2 \cdot 10^{-3}$ cm $< T < 5 \cdot 10^{-1}$ cm. Much like in previous experiments on Co [3,4], the existence of a critical thickness T_0 has been discovered below and above which the dependence of the domain width D on the crystal thickness T is governed by a different power law. According to [1], this law can be written in the general form

$$D_{x;m} = a_{x;m} T^{b_m} \tag{1}$$

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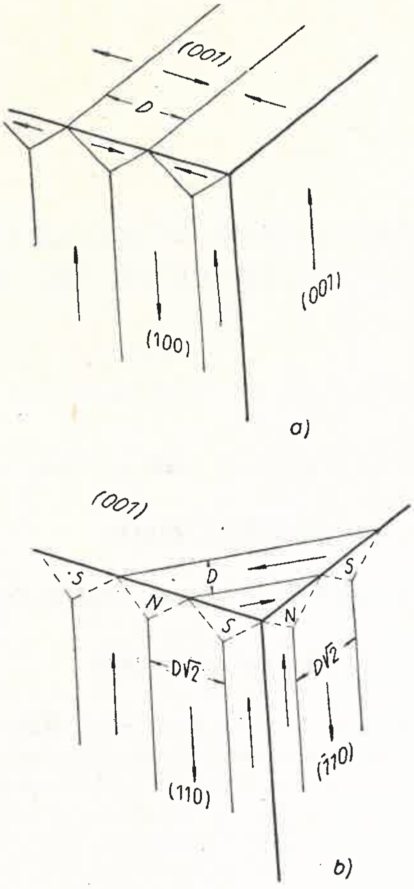


Fig. 1. Models of the simple (*a*) and modified (*b*) Landau-Lifshitz domain structures

where $m = 1$ or 2 according to whether $T \leqslant T_0$ or $T \geqslant T_0$, and the index x denotes the type of domain structure (*e. g.*, $x = SL$ or ML for FeSi). It has been shown in [1–4] that $b_1 = 0.5$ for Co and FeSi whilst $b_2 = 0.57$ for Co and 0.9 for FeSi, regardless of the type of domain structure. The critical thickness T_0 was shown to be about $5 \cdot 10^{-3}$ cm for Co and $4 \cdot 10^{-2}$ cm for Fe—3.25% Si.

The results for Co obtained in [3] from measurements on a single-crystalline wedge-shaped sample have been verified by experiments on a series of rectangular-prism-shaped single crystals [4]. The aim of the present paper is (*i*) to provide a similar verification for the ML domain structure examined in [1], and (*ii*) to study the influence of the sample's crystallographic orientation on the thickness-dependence law.

2. *Observations and measurements*

Three Fe—3.25% Si single crystals have been used in the experiment, having the shape of rectangular prisms with two sides in the (110) plane. The initial dimensions w, t, l and the crystallographic orientation of the samples are shown in Fig. 2; the latter differed by the angle $\Phi = 0°$, $20°$ and $45°$. The single crystals were obtained from a polycrystalline sheet-metal band by the method of secondary recrystallization described in [5] which resides in pulling the band at a certain speed through a heating device with large temperature gradient. The accuracy in determining the crystallographic orientation of the (110) sides of the samples was $\pm 10'$ (Kristalloflex 4, Siemens). The mechanical and electrolytic polishing of the samples and the colloid technique used in determining the domain structure were the same as in [1–4]. For the observations, a Neophot 2 (Zeiss) metallographic microscope was used, and the distance d between the Bloch lines on the (110) surface of the samples was determined from averaged measurements on large photographs of the domain pattern. To account for incidental distortions of the domain structure (local stresses, large vacancies or impurities, *etc.*), the samples were heated above the Curie temperature and cooled off to room temperature several times and the observations and measurements were repeated. The same procedure was repeatedly applied upon lessening the thickness t of the sample, which has been changed step-wise from 1 cm down to $1.5 \cdot 10^{-3}$ cm. In this way a satisfactory accuracy in determining d has been achieved, which is estimated at $\pm 10^{-5}$ cm for small, and $5 \cdot 10^{-4}$ cm for large thicknesses t.

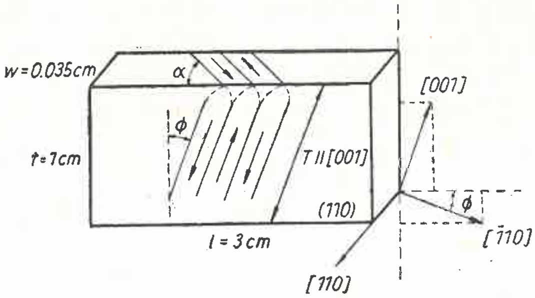


Fig. 2. Shape, initial dimensions, and crystallographic orientation of the samples

As shown in [1], the angle α between the crystal edge and the Bloch lines on the upper crystal surface (cp. Fig. 2) amounts to 45° if this surface lies in the (001) crystallographic plane, in agreement with the theoretical conclusion of [6] according to which the 180° Bloch walls should in this case lie in the plane (100). From Fig. 1b we see that the relation between the distance d as defined above and the domain width D is simply

$$d = D\sqrt{2}. \tag{2}$$

If the upper crystal surface is inclined by the angle $\varnothing$ to the plane (001) but remains perpendicular to the plane (110), the angle α decreases from 45° to 0° as $|\varnothing|$ increases from 0° to 90°, according to the relation

$$\tan \alpha = \cos \varnothing \tag{3}$$

which follows from simple geometric considerations. This, however, has no influence on the relationship (2) from which the domain width D is determined by measuring the distance d between the Bloch lines on the crystal surface (110).

3. *Results of measurements*

The results of our measurements are shown in Fig. 3 where D^0_{ML}, D^{20}_{ML} and D^{45}_{ML} indicate the thickness-dependence curves corresponding respectively to $\varnothing = 0°$, $20°$ and $45°$, and the tilde over those symbols denotes the respective critical domain widths corresponding to the critical thickness T_0 at which the curves change their inclination. The variable T in Fig. 3 is the effective "magnetic" thickness measured along the Bloch lines on the (110) crystal surface (*i. e.*, in the magnetically preferred direction [001]; cp. Fig. 2). It is seen that (*i*) the critical thickness T_0 is the same for all curves, (*ii*) it is equal to $4 \cdot 10^{-2}$ cm which confirms the result obtained in [1,2], (*iii*) the change of inclination at T_0 is the same for all curves, and (*iv*) within the intervals $T \leqslant T_0$ and $T \geqslant T_0$ the curves are parallel to each other. It is also seen that an increase of the angle $\varnothing$ shifts the curve upwards. For comparison the curves D_{SL} and D_{ML} obained in [1] for the SL and ML domain structures are also shown, in Fig. 3. Within the accuracy of our measurements, the latter coincides with the curve D^0_{ML} As for the exponent b_m in the power law (1), the curves obtained here lead to $b_1 = 0.5$ and $b_2 = 0.9$ which agrees with the result of [1,2]. For the coefficients $a_{x;m}$ the curves give the following values:

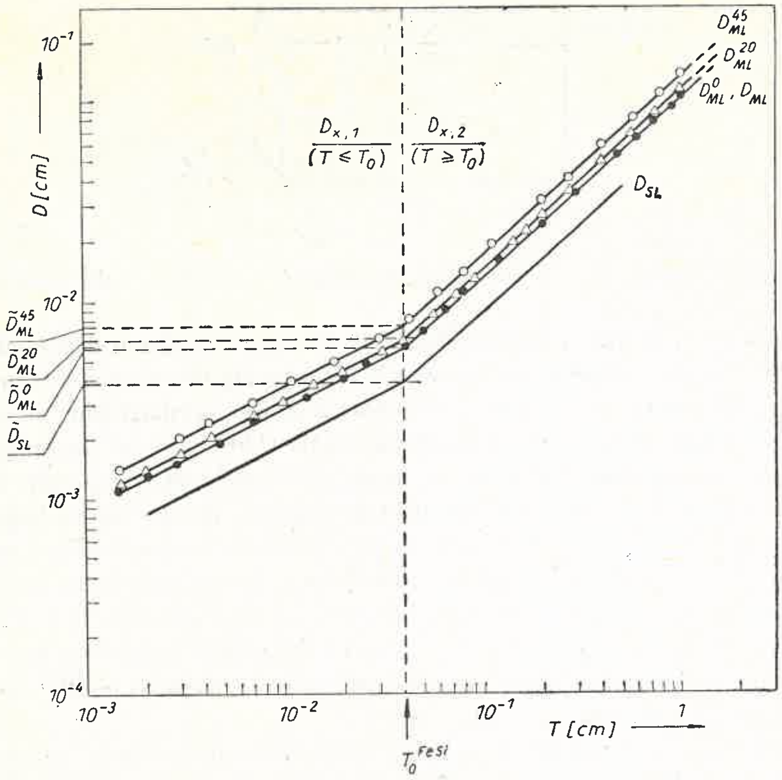


Fig. 3. Thickness-dependence curves of the domain widths for $\varnothing = 0°$, $20°$ and $45°$. Curves D_{ML} and D_{SL} from [1]

$$a^0_{ML;1} = 0.029, \quad a^{20}_{ML;1} = 0.032, \quad a^{45}_{ML;1} = 0.0375 \tag{4}$$

for $m = 1$ $(T \leqslant T_0)$, and

$$a^{0}_{ML;2} = 0.106, \qquad a^{20}_{ML;2} = 0.117, \qquad a^{45}_{ML;2} = 0.137 \tag{5}$$

for $m = 2$ $(T \geqslant T_0)$, the units being cm^{1-b_m}.

The critical thickness $\tilde{D}^{\varnothing}_{ML}$ corresponding to the thickness-dependence curve for the angle $\varnothing$ is given by the formula

$$\tilde{D}^{\varnothing}_{ML} = a^{\varnothing}_{ML;1} T_0^{b_1} = a^{\varnothing}_{ML;2} T_0^{b_2} \tag{6}$$

which leads to

$$T_0 = (a^{\varnothing}_{ML;1}/a^{\varnothing}_{ML;2})^{\frac{1}{b_2-b_1}}, \tag{7}$$

$$\tilde{D}^{\varnothing}_{ML} = [(a^{\varnothing}_{ML;1})^{b_2}\,(a^{\varnothing}_{ML;2})^{-b_1}]^{\frac{1}{b_2-b_1}}. \tag{8}$$

Since formulae (7), (8) hold for any $\varnothing$, they provide a check on the values of the coefficients (4), (5) which have been determined directly from the curves. One easily verifies that each of the three pairs of coefficients leads consistently to the value $T_0 = 4 \cdot 10^{-2}$ cm, and from (8) one obtains

$$\tilde{D}^{0}_{ML} = 58, \quad \tilde{D}^{20}_{ML} = 64, \quad \tilde{D}^{45}_{ML} = 74 \tag{9}$$

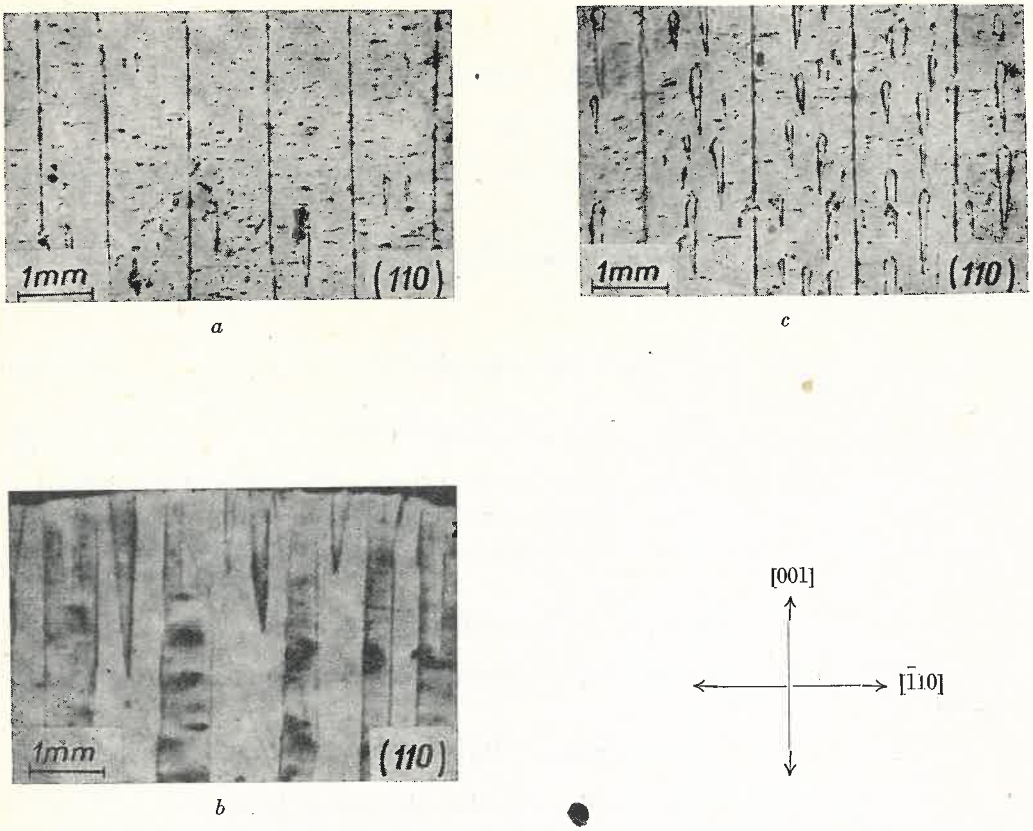
in units of 10^{-4} cm. A further check on the correctness of the values (4), (5) is the value of the ratio

$$a^{\varnothing}_{ML;1}/a^{\varnothing}_{ML;2} = 0.276\ \mathrm{cm}^{0.4} \tag{10}$$

which is independent of $\varnothing$ and coincides with that obtained in [1].

TABLE 1

Critical crystal thickness T_0	400 μm							
Declination ϕ	Rectangular-prism-shaped samples						Wedge-shaped sample in [1] ($\phi = 18°$)	
	0°		20°		45°			
Cristal thickness T	$T \leqslant T_0$ $(m=1)$	$T \geqslant T_0$ $(m=2)$	$T \leqslant T_0$ $(m=1)$	$T \geqslant T_0$ $(m=2)$	$T \leqslant T_0$ $(m=1)$	$T \geqslant T_0$ $(m=2)$	$T \leqslant T_0$ $(m=1)$	$T \geqslant T_0$ $(m=2)$
Exponent b_m	0.5	0.9	0.5	0.9	0.5	0.9	0.5	0.9
Coefficient $a_{ML,m}$ $[\mathrm{cm}^{1-b_m}]$	$0.029\,\mathrm{cm}^{0.5}$	$0.106\,\mathrm{cm}^{0.1}$	$0.032\,\mathrm{cm}^{0.5}$	$0.117\,\mathrm{cm}^{0.1}$	$0.0375\,\mathrm{cm}^{0.5}$	$0.137\,\mathrm{cm}^{0.1}$	$0.030\,\mathrm{cm}^{0.5}$	$0.110\,\mathrm{cm}^{0.1}$
Critical domain width $D^{\phi}_{ML} \equiv D^{\phi}_{ML}(T_0) = a^{\phi}_{ML,m} T_0^{bm}$	58 μm		64 μm		74 μm		60 μm	
$a^{\phi}_{ML,1}/a_{ML,2} = T_0^{b_2-b_1}$ $[\mathrm{cm}^{b_2-b_1}]$	$0.276\ \mathrm{cm}^{0.4}$							
$a^{\phi}_{ML,m}/a^{0}_{ML,m} = \tilde{D}^{\phi}_{ML}/\tilde{D}^{0}_{ML}$	1		1.10		1.27		1.03	
$a^{\phi}_{ML,m}/a^{20}_{ML,m} = \tilde{D}^{\phi}_{ML}/\tilde{D}^{20}_{ML}$	0.91		1		1.16		0.94	
$a_{ML,m}/a_{ML,m} = \tilde{D}^{\phi}_{ML}/\tilde{D}^{45}_{ML}$	0.78		0.85		1		0.81	

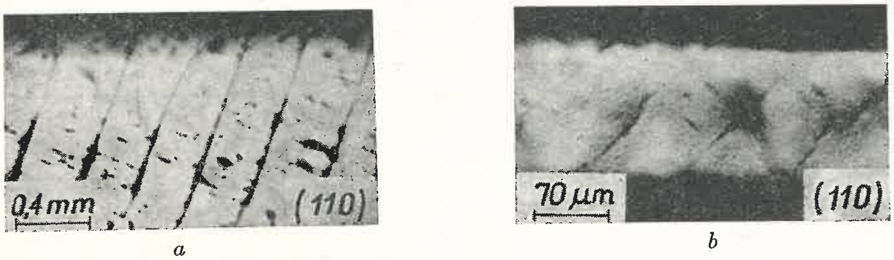


a

c

b

Fig. 4. Domain patterns on the (110) crystal surface for $\Phi = 0°$. In units of 10^{-3} cm, the crystal thicknesses are 725, 500 and 925, and the domain widths D are 110, 75 and 135 in (*a*), (*b*) and (*c*), respectively. In (*b*), weak magnetic field (0.5 Oe) applied in the direction [001]. Bitter technique



a

b

Fig. 5. Domain patterns on the (110) crystal surface for $\Phi = 20°$ and 45° in (*a*) and (*b*), respectively. Bitter technique

We can now write down explicitly the power laws corresponding to the different angles $\varnothing$:

$$D^{0}_{ML;1} = 0.029\ T^{0.5}, \quad D^{20}_{ML;1} = 0.032\ T^{0.5},$$
$$D^{45}_{ML;1} = 0.037\ T^{0.5} \tag{11}$$

for $T \leqslant T_0$, and

$$D^{0}_{ML;2} = 0.106\ T^{0.9}, \quad D^{20}_{ML;2} = 0.117\ T^{0.9},$$
$$D^{45}_{ML;2} = 0.137\ T^{0.9} \tag{12}$$

for $T \geqslant T_0$, where D and T are to be measured in cm (otherwise the coeffients have to be changed appropriately; cp. [1]). The quantitative results are summed up in Table I and compared to those obtained for the *ML* domain structure [1].

Typical domain patterns observed on the crystal surface (110) are shown in Fig. 4 and 5. Fig. 4, 5*a* and 5*b* correspond respectively to $\varnothing = 0°, 20°$ and 45°; Fig. 4*c* shows the characteristic drop-like closure-domains that form at this surface if it is slightly inclined to the direction [001]; Fig. 4*b* demonstrates spike-like closure domains at the edges of the (110) and (001) crystal surfaces (for explanation and model see [1]). In the latter case, a weak (0.5 Oe) magnetic field is applied along the direction [001].

Measurements of the angle α on the upper and lower crystal surfaces confirmed quite satisfactorily the relation (3), supporting evidently the theoretical predictions about the crystallographic orientation of the Bloch walls in this case [6].

4. *Concluding remarks*

The results reported here provide further evidence confirming the general rules that, according to [1], govern the thickness-dependence of the domain width in ferromagnets. They also prove, much like in [4] for Co, that the time-consuming measurements on rectangular-prism-shaped single crystals can reliably be replaced by measurements on wedge-shaped single-crystalline samples, at least in the case of the *ML* domain structure. Futhermore, our experiment shows also that in rectangular-prism-shaped samples the change of the sample's crystallographic orientation as given by the angle $\varnothing$ influences the thickness-dependence curve by merely shifting it upwards with increasing $|\varnothing|$, the inclination of the curve and the critical thickness remaining unchanged, provided the thickness T is being measured in the direction of domain polarization. (Note that it would be inadequate to choose the "geometric" thickness t of the sample as variable; besides shifting the curves in Fig. 3 farther apart, this would result in different critical thicknesses for different angles $\varnothing$). However, the reason for the existence of T_0 for FeSi still remains a mystery, as no essential difference could be established between the *ML* domain structure below and above T_0. As shown in [3, 4], the difference in uniaxial Co resides in the disappearance of the spike-like closure domains at the basal crystal surface below T_0, and recent theoretical investigations gave a satisfactory explanation of this phenomenon [7].

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