OBSERVATION OF INTERNAL DOMAIN STRUCTURE OF BARIUM FERRITE IN INFRARED

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The results of studies on the domain structure of barium ferrite crystals of thickness up to 3 mm are presented. The structure was observed simultaneously by the powder patterns technique and Faraday effect technique using the infrared part of the optical spectrum. Strong correlation between the surface and internal domain structure has been found. The dependence of the domain width on the crystal thickness found experimentally is compared with the existing theories of domain structures of uniaxial ferromagnetics.

In thin barium ferrite crystals in which the hexagonal axis is normal to plane of the plates the domain structure has the shape of plane-parallel plates and can be described by the model of Kittel [1]. With increasing plate thickness L this structure becomes more complicated. In the thickness range $8\ \mu m < L < 50\ \mu m$ a wavy domain structure is observed [2÷5]. For thicknesses greater than 50 μm the wavy structure is accompanied by dagger-like domains [2÷4]. Changes in the surface domain structure are associated with a tendency to a decrease in the magnetostatic energy of the crystal which however rapidly increases with plate thickness (the Kittel model predicts the magnetostatic energy to be proportional to $\sqrt{L}$).

There are two main methods of experimental investigation of the domain structure: the powder patterns technique and the technique which makes use of the magnetooptical Faraday effect. The first method can be used for studies of the surface structure only, while the latter supplies information about the internal structure. Strong absorption od light in magnetic crystals, however, restricts the Faraday method to thin crystals only. Indeed, the Faraday method has been used with the help of a polarization microscope to the study of barium ferrites with thickness not exceeding 15 μ [15], *i.e.*, in the thickness range for which the domain structure is still comparatively simple.

The purpose of the present work was the study of the structure of barium ferrite crystals with thickness greater than 50 μm. This structure has been studied using both the

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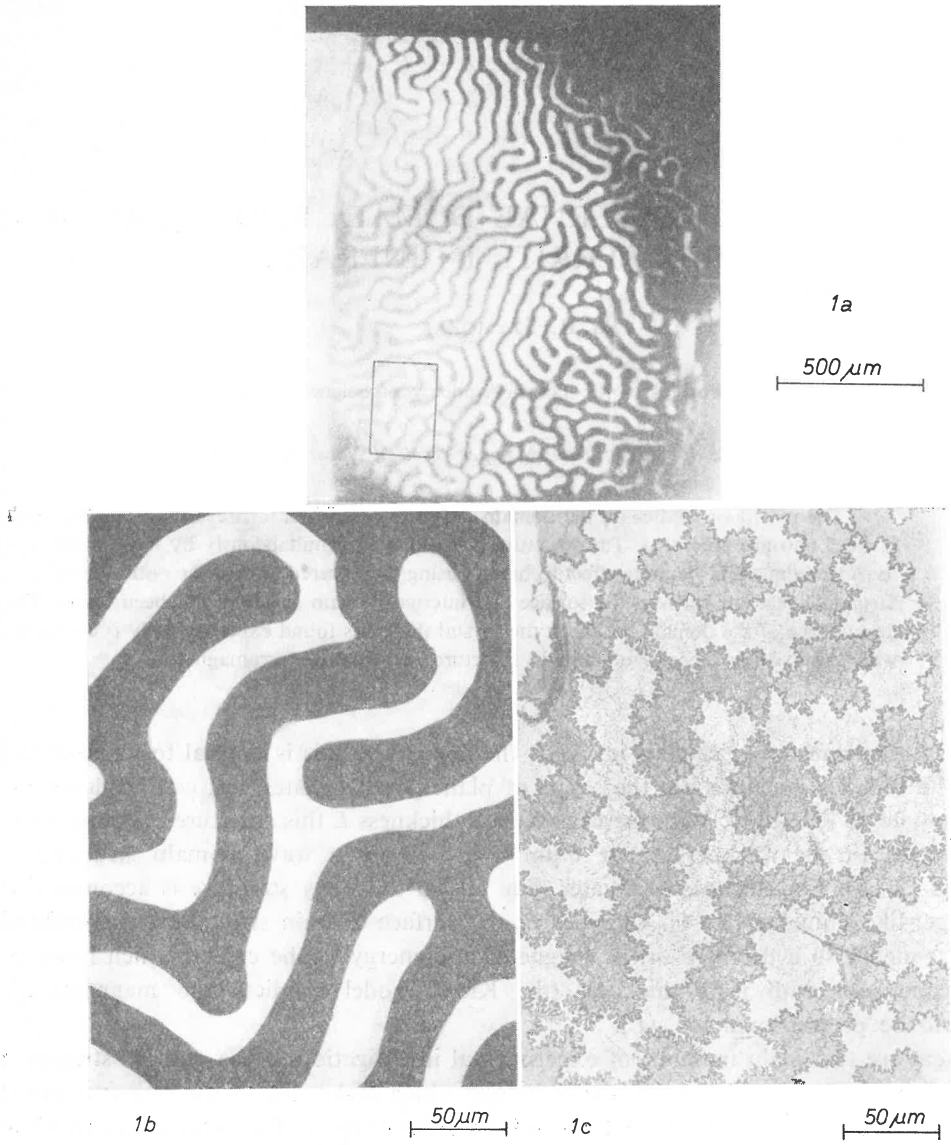
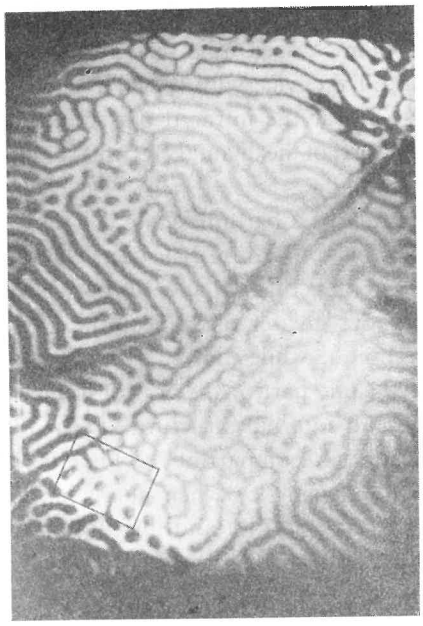


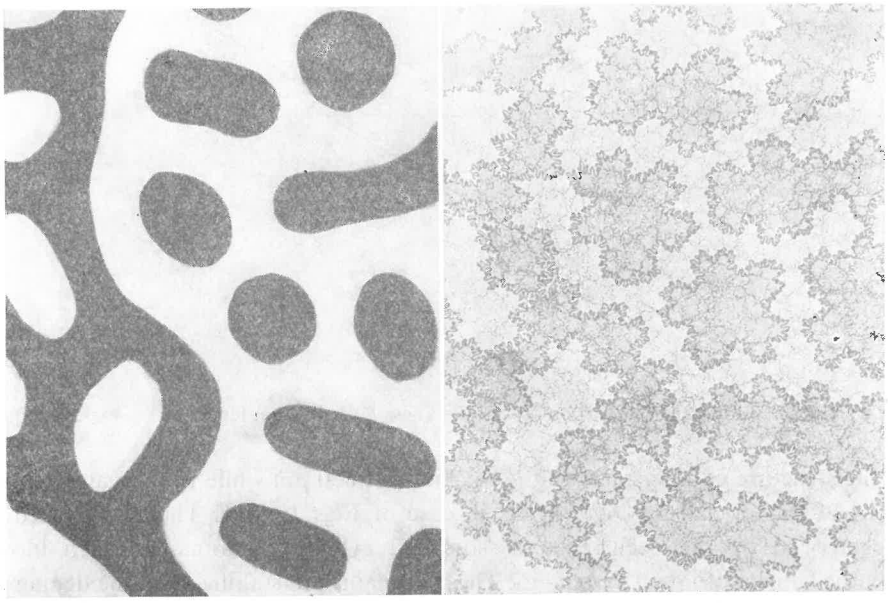
Fig. 1. Domain structure of a barium ferrite single crystal with the thickness of 0.08 cm. Microphotographs a) and b) have been obtained by means of the Faraday effect technique, c) by means of the powder patterns technique

powder patterns technique and the Faraday method to check whether the highly complicated surface structure is correlated with the internal domain structure or whether it has only a local character. This problem is of importance inasmuch that the information about the internal domain structure of such ferrites is extracted only from observations of the surface structure. In order to study the structure of thick crystals (3–5 mm) by means



2a

500 μm



2b

50 μm

2c

50 μm

Fig. 2. Domain structure of a barium ferrite single crystal with the thickness of 0.085 cm. Microphotographs a) and b) have been obtained by means of the Faraday effect technique, c) by means of the powder patterns technique

of the Faraday technique, the infrared part of the spectrum has been used. In this wavelength range the majority of the ferrites is characterized by a relatively small absorption. A polarization microscope connected with a TV device with an RFT endicon type F 2.5 M1UR has been used in the present work. So far the infrared part of the spectrum has been used in the study of the domain structure of hexagonal ferrites only in Ref. [6] in case 43 μm thick magnetoplumbite crystals.

Fig. 1a shows the internal domain structure of a barium ferrite crystal with the thickness of 800 μm under a comparatively small magnification. It is seen that this structure is similar to that described by the model of Kittel. Figs 1b and 1c illustrate the structure of a part of the crystal from Fig. 1a but under greater magnification; Fig. 1b has been obtained by means of the Faraday effect technique while Fig. 1c by means of the powder patterns technique. Both 1b and 1c show the same part of the crystal to enable the observation of correlations between the surface and internal structures. It is seen in Fig. 1c that the surface structure is quite complicated. A comparison of Fig. 1c with 1b shows that the complicated domain structure becomes simpler when going inside the crystal, there is however, a strong correlation between the surface and internal structure. Fig. 2a

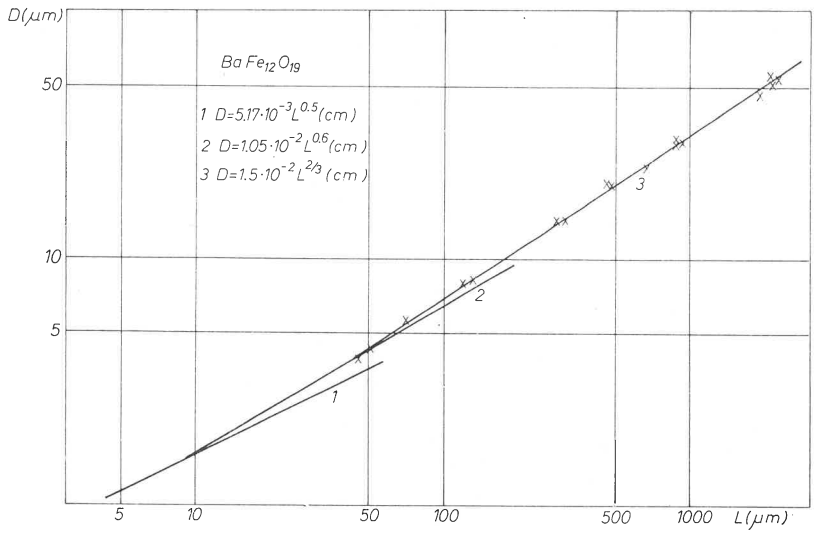


Fig. 3. Dependence of domain witdh D on crystal thickness L for barium ferrite, × — experimental results

shows the structure of a crystal with the thickness of 850 μm while Figs 2b and 2c the same fragment of this crystal analogously as in case of Figs 1a, b, c. The investigated crystal is characterized by the occurrence of so-called cylindrical domains which have been recently the subject of intensive studies. These domains are stabilized by the demagnetizing field of neighbouring domains in accordance with the results of the analysis made in Ref. [7]. It is characteristic that the diameter of a cylindrical domain is always slightly greater (about 4%) than the width of a stripe domain. Analogous photographs have been made in case of barium ferrite crystals with thickness ranging from 50 μm to 3000 μm. This

permitted the study of the dependence of the width of the domain structure on crystal thickness. The results fo these measurements for the investigated crystal thickness range are shown in Fig. 3. To determine the dependence $D = D(L)$ only those crystals have been used which had practically noncylindrical domains. It follows from the figure that the experimental dependence $D(L)$ in case of barium ferrite can be described by the formula:

$$D = 1.5 \cdot 10^{-2} L^{2/3} \text{ (cm)}. \tag{1}$$

For the sake of comparison the figure also shows the *D versus L* dependences derived from the Kittel model [1]: $D = 5.17 \cdot 10^{-3} L^{1/2}$ cm) (curve *1*) and the wave domain structure model [3, 9]: $D = 1.05 \cdot 10^{-2} L^{0.6}$ cm (curve *2*). There is at present no theory which would describe correctly the domain structures investigated in the present paper, *i.e.*, wavy structures supplemented with spike-like domains. The theoretical models which give predictions comparatively closest to the experiment are those derived for pure wavy structure. Here are some of them:

1. The model of Goodenough [8] which assumes the decay of the wavy structure inside the crystal. Owing to numerous approximations, however, this model does not offer the possibility of numerical calculations, in particular of the dependence $D = D(L)$.

2. The model presented in Ref. [9] which is a generalization of the model of Goodenough obtained by taking into account the pole energy at the domain walls and the changes in the shape of the domains with crystal thickness. In case of barium ferrite this model predicts the following relationship

$$D = 1.05 \cdot 10^{-2} L^{0.6} \text{ (cm)} \tag{2}$$

and it has been confirmed by the studies of the domain structure as a function of thickness [3] and temperature [10].

3. In the model of Kaczér [11] both pure wavy structures and the more complex wavy structures with spike-like domains considered in the present paper are described by one model. It is assumed that the magnetostatic energy of poles on the surface does not depend on crystal thickness. This model predicts the relationship

$$D = \left(\frac{3}{8M} \sqrt{\frac{\sigma_w \mu}{\pi}} \right)^{2/3} L^{2/3} \tag{3}$$

where M is the saturation magnetization, σ_w the domain wall energy density, $\mu = 1 + 2\pi M^2/K$, K the magnetocrystalline anisotropy constant. This yields in case of barium ferrite:

$$D = 1.34 \cdot 10^{-2} L^{2/3} \text{ (cm)}. \tag{3a}$$

4. A similar model to model 2) has been considered in Ref. [12] for the case of cobalt crystal. The difference consists in the assumption that the surface structure has rectangular and not trapezoidal wave shape so that it is easier to take into account the interaction of magnetic poles at the domain walls with the poles on the surface of the sample (this inter-

action is neglected in the models 1–3). This model[1] predicts the dependence $D \sim L^{0.6}$ both for wavy domain structure and wavy structure with spike-like domains.

The studies of the internal domain structure of thick barium ferrite crystals made in the present paper confirm the fundamental assumption contained in all the above models, namely, that the domain structure inside the crystal has the shape of plane-parallel plates. Unfortunately the quantitative analysis of the $D = D(L)$ dependence yields that none of these models gives a correct description of the observed wavy structure supplemented by spike-like domains. The dependence (3) obtained by Kaczér fits best the observed $D = D(L)$ dependence, however, the assumption that the magnetostatic energy E_m of the poles on the surface of the crystal *vs* independent of the crystal thickness seems to be too fargoing. The acceptance of this assumption in case of the pure wavy structure model considered in Refs [3] and [9] leads to the following expression for the energy of the system:

$$E = \frac{\sigma_w L}{D} + \theta \sqrt{D} \tag{4}$$

where θ is a constant which depends on the shape of the domain and is given in Refs [3, 9], while σ_w is the domain wall energy density.

It follows from Eq. (4) that

$$D = \left(\frac{2\sigma_w}{\theta}\right)^{2/3} L^{2/3} \tag{5}$$

which in case of barium ferrite yields

$$D = 2.73 \cdot 10^{-2} L^{2/3} \text{ (cm)}. \tag{6}$$

It is obviously difficult to assume that the energy E_m does not depend on the crystal thickness, similarly as it also seems highly improbable that this energy depends so strongly on the domain width as, *e.g.*, in the model of Kittel, where $E_m \sim D$.

Since a rigorous calculation of E_m is impossible it seems reasonable to consider a dependence weaker than that in the model of Kiittel, *e.g.*

$$E_m = B(\sqrt{D} + C) \tag{7}$$

where the constants B and C can be determined from the condition that E_m calculated for the model with spike-like domains under consideration and E_m for the pure wavy domain structure $\left(\text{as well their derivatives } \frac{\partial E_m}{\partial D}\right)$ must be equal for this crystal thickness at which the first spike-like domains appear (which is $L \approx 50$ μm in case of barium ferrite). Making use of Eqs (4), (7) and the expression for the magnetostatic energy for pure wavy structure

$$E_m = \xi D$$

[1] The author of [12] did not take into account the influence of the μ-effect on the magnetostatic energy. The μ-effect plays a significant role in case of cobalt which is considered in his paper.

where ξ is a constant given in Refs [3, 9] we obtain the relationship $D = D(L)$ for the thickness range characterized by spike domains:

$$D = \left(\frac{2\sigma_w}{B+\theta}\right)^{2/3} L^{2/3} \tag{8}$$

which in case of barium ferrite yields

$$D = 1.52 \cdot 10^{-2} L^{2/3} \text{ (cm)}. \tag{9}$$

The above result and its consistency with the experimental dependence (1) prove the validity of the assumption about the character of changes in the magnetostatic energy E_m. In order to check whether the semi-empirical model of domain structure has a more general character or the above consistency is accidental, it is necessary to study the domain structure of other uniaxial crystals. The same role is of course played by studies of barium ferrite as a function of temperature since the parameters of a ferrite change with the latter. Such investigations has been made in case of a barium ferrite crystal with the thickness $L = 850$ μm, at room temperature and at 515°K. The experimental results have been compared with the theoretical predictions according to the relationship (3), (5) and (8) and are listed in the Table I.

TABLE I

T°K	D (μm)			
	Eq. (3)	Eq. (5)	Eq. (8)	exper.
295	25.9	52.8	29.4	29.0
515	30.1	61.2	36.6	36.1
D_{515}/D_{295}	1.16	1.16	1.24	1.24

It should be pointed out that in the temperature range 295°K÷515°K the particular ferrite parameters change rather strongly, *e.g.*, $M_{295}/M_{515} \approx 1.7$ and $\sigma_{w295}/\sigma_{w515} \approx 1.7$.

This indicates that the studies of the temperature dependence are a good criterion for checking various models of domain structure. This criterion has confirmed the usefulness of the semi-empirical model in the description of domain structure in comparatively thick uniaxial crystals.

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