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EFFECT OF INHOMOGENEOUS RADIALLY DIRECTED MECHANICAL STRESSES ON THE DOMAIN STRUCTURE OF A $FeBO_3$ SINGLE CRYSTAL

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The effect of inhomogeneous radially directed mechanical stresses on the domain structure of a FeBO3 single crystal is studied by a magnetooptical method. It was found that in the magnetic field applied in the $FeBO_3$ basal plane along the direction of the compressive force, a system of wedge-shaped domains appears in the process of magnetization in the crystal, which exists in a certain temperature-dependent interval of fields in the $\boldsymbol{H_0}$ range of $\boldsymbol{H_c}$ values. The discussion of the results obtained was carried out within the framework of the thermodynamic theory of the domain structure. It is shown that the theoretical model used well allows one to describe the experimentally observed relative change in ***d*** *as a function of the magnetic field and temperature.*

Keywords**:** single crystal, domain structure, magnetic field, temperature, thermodynamic theory, magneto-optics, mechanical stresses.

Introduction

Iron borate ($FeBO_3$) is an easy-plane weak ferromagnet transparent in the visible spectral region, which makes it a convenient object for visual study of the magnetic state and magnetization process of this class of magnetically ordered crystals by the magneto-optical method. For example, in [1, 2], using a polarization microscope using the Faraday method, the domain structure (DS) of $FeBO_3$ was studied, as well as the influence of compressive mechanical stress and an external magnetic field applied in the basal plane of the crystal. As a result of the studies performed in [1, 2], it was found, in particular, that both the relative orientation of the spontaneous magnetization vector **m** in adjacent domains and the direction of domain walls (DW) in $FeBO_3$ are extremely sensitive to the presence of mechanical stresses in the crystal.

In contrast to [1, 2], where the experiments were carried out under conditions of uniform uniaxial crystal voltage, the results of studies of the effect of heterogeneous mechanical stresses on the $FeBO_3$ DS are presented below.

1. Samples and experimental technique

A sample of a single crystal of $FeBO_3$ (space group - D_{3d}^6) used in the experiments was a flat-parallel plate of almost regular hexagonal shape with a thickness of ~ 45 μm with transverse dimensions of 3 mm. The developed faces of the crystal coincided with the plane of easy magnetization (with the basal plane). The crystal surfaces had a sufficiently high optical quality and were not subjected to any additional processing.

DS studies were carried out in the region of maximum transparency of $FeBO_3$ (in the region of wavelengths of 0.52 μm) “to the light”. The image of the domains was observed visually in a polarizing microscope and recorded with a digital camera docked with the computer. The magneto-optical contrast of the DS image was due to the difference in the sign of the Faraday effect in the neighboring domains. Since the magnetic structure of $FeBO_3$ makes it possible to observe the

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Faraday effect only at an angle to the optical axis (axis C_3) of the crystal (magneto-optical rotation occurs due to the projection of the vector **m** on the direction of light propagation appearing with this crystal orientation) [3, 4], in the experiment the sample was oriented so that the normal to its basal plane (axis C_3) was made with the direction of the incident light angle 10^0.[1]

The sample was placed in a nitrogen optical cryostat, providing observations in the temperature range of $90 \le T \le 290$ K. The magnetization system, consisting of two pairs of Helmholtz coils, made it possible to create in the sample location region along two mutually perpendicular directions a uniform magnetic field of strength $H \le 50$ Oe (in all experiments the vector **H** lies in the plane of the sample).

To reveal the effect of mechanical stresses on the magnetic state of $FeBO_3$, all experiments were duplicated on an "unstressed" crystal and a crystal subjected to a non-uniform voltage, and the results were compared with each other.

In the second case, the sample was glued with one of its corners (glue BF - 2) to the copper washer (see below Fig. 1c), which was attached to the cryostat cooler. As the temperature decreased from room temperature, as the temperature cooled, a washer deformed, which was transferred to the sample, causing its non-uniform stress.

2. Experimental results and discussion

At room temperature in the demagnetized state, the sample under study had a two-layer DS with orientation of the domain walls in the basal plane along directions close to the directions of the C_2 axes (the orientation of which was determined by the natural faceting of the crystal), which are the light axes of the intra plane hexagonal anisotropy [5, 6] (Fig. 1a). Such a DS is characteristic of stress-free thin $FeBO_3$ plates [1, 2]. It is known [1, 2, 6] that in this case the azimuth of the spontaneous magnetization vector **m** in adjacent domains in the sample plane differs by approximately 180^0, and the boundaries between the domains are Neel-type domain walls (the boundary between the domain layers is the Bloch domain wall, the plane of which parallel to the basal plane of the crystal). As experiments have shown, the DS of the crystal, observed in the case of a "non-stressed" sample, is practically independent of temperature in the entire investigated range of $90 \le T \le 290K$. The DS of the "glued" sample behaves differently: as the temperature decreases, starting at approximately T = 270 K, the Neel walls gradually become bent, and the DS turns from a two-layer into through, taking the form of sectors of concentric rings of approximately equal thickness, (fig.1 b).

Referring to fig. 1b, it can be noted that the maximum contrast of the image of the DS is observed in the central part of the sample, with the degree of clarity of the image of the domains practically unchanged throughout the sample area along the vertical Y axis (the orientation of the axes of the selected coordinate system is shown in Fig. 1 c). This non-uniformity of the image contrast is not the result of the defocusing of the microscope optical system, but arises as a result of a change in the azimuthal angle of the vector **m** in the basal plane of the crystal.

Indeed, as already noted, the angle of the Faraday rotation at a given point of the sample plane with the x and y coordinates is determined by the projection of the local vector m to the direction of light propagation, i.e.

$$F \infty m \sin\varphi \sin\theta ,$$

where φ = const $\approx 10^0$ - angle of light on the sample plane, θ - the azimuth of the vector m at the point (x, y) about an axis perpendicular to the plane of incidence, and it is considered that **m** does not go out of the base plane (the image of the DS, shown in fig. 1b, was obtained when the sample

[1] At large angles of deflection of the direction of light propagation from the optical axis, the influence of natural crystalline birefringence on the polarization of light becomes noticeable, which leads to a decrease in the contrast of the obtained DS images.

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was rotated by an angle φ around the Y axis, i.e. θ - azimuth **m** relative to the same axis). This shows that the observed change in the magneto-optical contrast is associated with a smooth change in the angle θ along the X axis in the direction from the center of the sample to its periphery (in the Y direction — the $\theta \approx const$ axis).

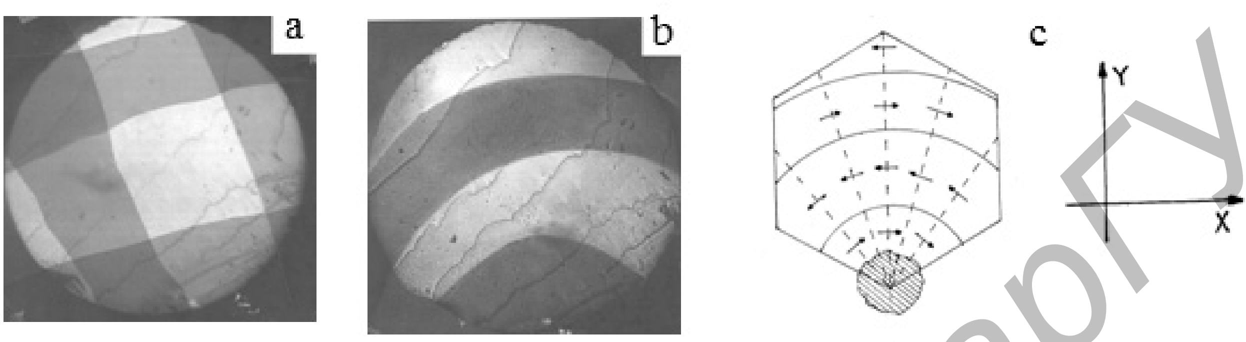

Fig.1. Images of the domain structure of the "glued" $FeBO_3$ crystal, obtained at H = 0:
a - T = 290 K, b - T = 90 K; **c** is the spatial distribution of the spontaneous magnetization vector (arrows) in the basal plane of a stressed crystal: dashed lines indicate the directions of acting mechanical stresses, the hatched area is a drop of glue that the crystal is glued to the sample holder. On the right - the orientation of the axes of the laboratory coordinate system (the X axis coincides with the direction of one of the three C_2 axes, the Z axis — with the direction of the C_3 axis).

Since the intra plane magnetocrystalline anisotropy in $FeBO_3$ is not large (at $T = 77K$, the field of intra plane anisotropy $H_A < 1\,Oe$ [7]), according to [1,2,4], in the stressed state of the crystal at $H = 0$, the vector **m** is oriented in the basic plane mostly perpendicular to the direction of compression. Obviously, when the mechanical stresses are distributed nonuniformly throughout the crystal, the orientation **m** in the basal plane will change from point to point. Based on this, the spatial distribution of the vector **m** in the DS of a stressed crystal (shown in Fig. 1b) can be schematically represented as shown in Fig. 1c (it is assumed that **m** does not vary in thickness of the crystal). From which it follows that the temperature deformations of the sample holder create in the crystal radially directed non-uniform stresses from the point of its gluing, while the DC of the crystal remains 180-degree.

The process of technical magnetization of a "non-stressed" sample proceeded in the usual way: when a magnetic field is applied along any direction in the basal plane, the area of domains in which m makes an acute angle with H increases due to neighboring domains with opposite orientation of magnetization until the crystal passes in monodomain (homogeneous) state. Similarly, a stressed ("glued") crystal is magnetized upon orientation $H \parallel X$.

Of interest is the evolution of the DS of a stressed crystal, observed at $H \perp X$. In a magnetic field, the DW is under pressure [8]:

$$P = mH(\cos\theta_1 - \cos\theta_2),$$

where θ_1, θ_2 are the angles that the vector **m** makes with **H** on both sides of the DW. Since the angles θ_1 and θ_2 change along the DB direction (see Fig. 1b, c), the field action in this case leads to the fact that the "dark" domains to the right of the central part of the sample grow due to the "light" domains, and to the left of center — on the contrary, the areas of "light" domains increase (visually "dark" domains are perceived as brown, and "light" - as green).

The process of displacement of the domain walls proceeds most rapidly along the edges of the sample, where the pressure P is maximal (while in its central part along the Y - axis $P = 0$). As a

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result, in some field H_0 ($H_0 = 3Oe$ at $T = 90K$), only two ("bright" and "dark") so-called counter domains, separated by one zigzag domain wall, remain in the crystal (fig.2 a, b).[1]

The resulting domain configuration is obviously determined mainly by the competition between the magnetostatic energy of the E_M crystal and the energy of the DW. From the energy point of view, a flat domain wall having a minimal length is advantageous. However, the maximum will be the magnetostatic energy. Indeed, if on both sides of the DW the vector **m** is with the normal to this boundary angles γ_1 and γ_2, then $E_M \propto m^2(\cos\gamma_1 - \cos\gamma_2)^2$ [8], i.e. The energy E_M is maximum at perpendicular orientation **m** to the plane of the DW. Therefore, in this case, the zigzag DW, reducing the angles γ_1 and γ_2, ensures a minimum of the free energy of the crystal.

With a further increase in H, the areas of wedge-shaped domains that are separated by DW decrease, but the zigzag shape of DW persists up to the fields of transition of the crystal to a uniform state. Fig. 2 a, b illustrates the change in the DS of a stressed crystal in the process of its magnetization at $H \perp X$, and Fig. 2c shows schematically the resulting spatial distribution of **m** in the basal plane of the crystal.

The system of wedge-shaped domains, which occurs in the central part of a stressed crystal when it is magnetized along the Y axis, exists up to some field dependent Hs (at $T = 90K$, $H_c \approx 45Oe$). It is significant that with the growth of H and/or T the average width of the wedge-shaped domains *D* and their length *L* (determined, as shown in Fig. 2c), however, the areas of the "light" and "dark" domains remain equal to each other. At the same time, as the field increases from H_0 to $H \sim 0{,}8H_c$, a smooth decrease in the contrast of the image of the wedge-shaped domains is observed, after which the system of wedge-shaped domains disappears visually by degrading its image clarity, and at $H = H_c$, the sample surface will evenly colored throughout its area.

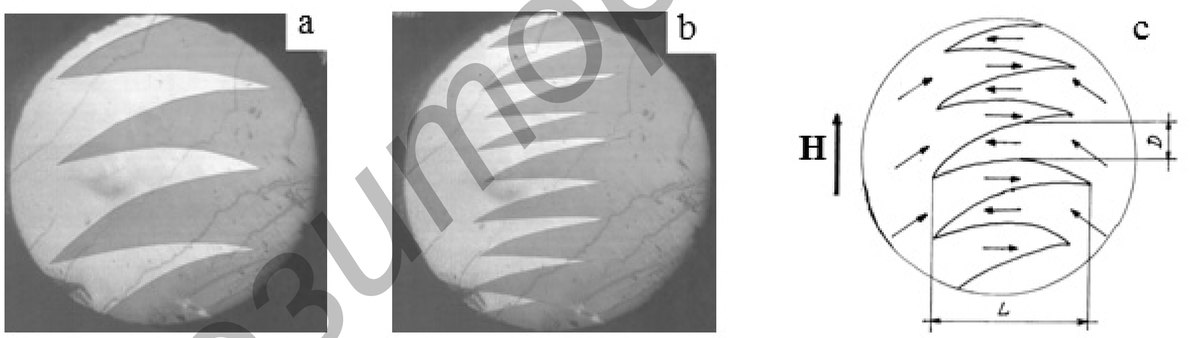

Fig.2. Images of the domain structure of a stressed $FeBO_3$ crystal, observed at T = 90K: a - H = 3 Oe, b - H = 20 Oe ($H \perp X$); c - spatial distribution of the spontaneous magnetization vector (arrows inside the circle) in the emerging domain configuration. An arrow outside the circle indicates the direction of the applied field. *D* - is the average width of the wedge-shaped domain, *L* -is its length.

Experimental dependences of the average width and length of the wedge-shaped domains on the external magnetic field and temperature are shown in Fig.3 and Fig.4 (the values of *D* and *L* were obtained by averaging over the entire number of wedge-shaped domains that exist with the data H and T). Note that, both with the inversion of the direction of magnetization and with the cyclic change of the heating – cooling mode, there was no noticeable hysteresis in the dependences D (H, T) and L (H, T). To interpret the results obtained, we turn to the thermodynamic theory of DS s without closure domains. According to [9, 10], the free energy of a crystal per one wedge-shaped domain is represented as

[1] When the temperature changes from 90 to 270 K, the field H_0 decreases by about 1.5 times.

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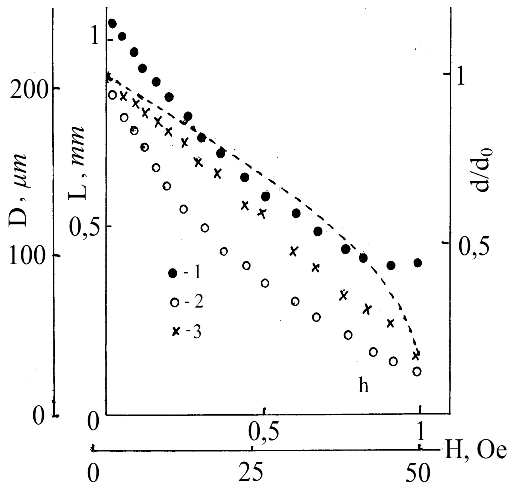
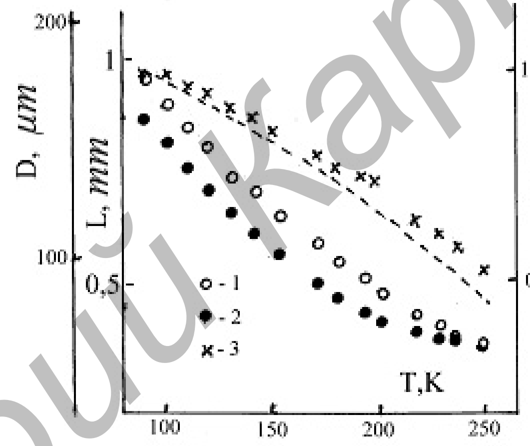
$$E = \frac{\varepsilon L}{D} + NI^2 D, \qquad (1)$$

here ε - is the DW energy density, N - is the coefficient determined by the domain configuration and the shape of the domains, I - is the density of the magnetic poles appearing at the end of the domain, L and D are the characteristic size of the domain respectively along and across the direction of the easy axis of magnetization; the first term describes the energy of domain walls of the Neel type, the second one describes the density of the magnetostatic energy (we neglected the Zeeman and magnetoelastic contributions to E, assuming that, in general, the emerging system of wedge-shaped domains is $m \perp H$ and $m \perp \sigma$, where σ - is the longitudinal component of the stress tensor).



a

Fig.3. The field dependences of the average width (1) and length (2) of the wedge-shaped domains, as well as the values $d = D/\sqrt{L}$, normalized to their maximum value d_o (3), obtained at T = 90K. The dashed line is the theoretical dependence $d/d_o(h)$ [9].



b

Fig.4. The temperature dependences of the average width (1) and length (2) of the wedge-shaped domains, as well as the values $d = D/\sqrt{L}$, normalized to their maximum value do (3), obtained at H = 7 Oe (**H⊥X**). The dashed line is the temperature dependence of the ratio d/d_o, calculated by the formula (5).

In the general case of an arbitrary form of domains, the calculation of the N coefficient is a rather complicated task. At present, such calculations are performed only for the simplest domain configurations. For example, for the simplest regular structure of rectangular domains with $L >> D$, the coefficient is $N = 1.7$ [9, 10]. Although in our experiments the observed shape of the domains differs noticeably from the rectangular one and the condition $L >> D$ is fulfilled poorly (in all cases $\frac{L}{D} \sim 5$), for definiteness we take the value N in formula (1) to be 1.7.

In an external magnetic field, the vector m in a strained crystal is deflected from the direction given by the anisotropy induced in the basal plane by stresses. In this case, the direction m is with the direction $H(H \perp X)$ angle $\theta = \arccos\left(m\frac{H}{2K}\right) = \arccos(h)$ (K is the magnetic anisotropy constant) [8]. Taking into account that the magnetic poles arise in the process of magnetization inside the crystal (along the zigzag DB), the density of the magnetic poles is defined as:

$$I = \xi m \sin\theta, \qquad (2)$$

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where $\xi = \dfrac{2}{(1+\mu)}$ - coefficient taking into account (the so-called μ - correction [8]) magnetic permeability of the medium, which in the field of fields $H_0 \le H \le H_c$ has the form [8]:

$$\mu = 1 + \frac{\pi m^2}{K}$$

Since in the calculation of the magnetostatic energy, the distribution of the vector **m** in the crystal region near the DB is relevant, by θ in (2) we will understand the angle between the vectors **m** and **H** averaged over the entire area of the wedge-shaped domain (i.e., we assume that the angle A does not depend on from spatial coordinates). Then, in view of the above, formula (1) can be rewritten in the form:

$$E = \frac{\varepsilon L}{D} + 1{,}7\xi m^2(1-h^2)D\,. \qquad (3)$$

A similar expression for E with $\xi = 1$ (i.e., without μ - correction) was used in [11] in interpreting the results of observations of the surface DC of cobalt and magnethoplumbite. A formula describing the change in the energy of a non-Neile-type domain wall in a magnetic field directed perpendicular to its plane was also obtained there. Using the results of [9] and assuming that in our case the vector ***H*** is approximately perpendicular to the DH plane along its entire length, the energy density of the DWs will be represented as:

$$\varepsilon = 8\sqrt{A(K+2\pi m^2)}\left(\sqrt{1-h^2} - h\arccos(h)\right), \qquad (4)$$

where A - is the exchange constant.

Under the condition $\dfrac{\partial E}{\partial D} = 0$, which determines the minimum of the free energy, from (3) we obtain:

$$D = \frac{1}{m}\sqrt{\frac{\varepsilon L}{1{,}7\xi(1-h^2)}}. \qquad (5)$$

If we assume that the anisotropy constant in the basal plane of a stressed crystal is $K = -\dfrac{3}{2}\Lambda\sigma\cos^2(\Psi)$ (Λ - is the magnetostriction constant, Ψ - is the angle between **m** and the longitudinal component of the effective voltage tensor **σ**), then for $\xi = 1$ and $H = 0$, the formula (5) coincides with the expression for D, which follows from the theory of equilibrium DS of rhombohedral weak ferromagnets, taking into account the mechanical stresses of the crystal [6].

We note an important consequence of formula (4): according to the calculations performed in [9], for $h \to 1$, the value of D in (5) tends to some finite limit, and the width of the Neel domain wall goes to infinity. This means that, at $h \to 1$, the DS disappears by an unlimited increase in the width of the DW. The latter is consistent with the visually observed process of the disappearance of wedge-shaped domains at $H \to H_c$ as a result of a decrease in the sharpness of their image (see above).

Since the energy density of the DB decreases with increasing h faster than the function $(1-h^2)$ (the dependence $\varepsilon(h)$ calculated by (4) is given in [9]), then, as follows from formula (3), to maintain the energy balance in the process of magnetization at $H \to H_c$, the value of the ratio $\dfrac{L}{D^2}$ should increase, which is observed experimentally. In Fig. 3, the results of the calculation of

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the field dependence of $d = \frac{D}{\sqrt{L}}$ normalized to its maximum value d_0, obtained in [9] on the basis of formulas (4) and (5), are compared with the experimental dependence $\frac{d(H)}{d_0}$. It can be seen that although the form of the calculated and experimental $\frac{d(H)}{d_0}$ dependences is somewhat different, formula (5) allows us to describe the fivefold change in the $\frac{d}{d_0}$ ratio observed in the interval of fields of existence of wedge-shaped domains (But ($H_0 \le H \le H_c$)).

Conclusion

From the previous it follows that formula (5) quite well allows us to describe the experimentally observed relative change in the value of $\frac{D}{\sqrt{L}}$ depending on H and T. Thus, despite the relative simplicity of the theoretical model used, on the basis of formulas (4) and (5), it is possible to describe the main features of the DS behavior of a $FeBO_3$ crystal subjected to heterogeneous radially directed mechanical stresses observed with a change in the external magnetic field and temperature.

Acknowledgments

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