can be used to determine the Hermitian components of the diffusion tensor with the aid of the relation

$$\langle \delta j_\alpha{}^t \delta j_\alpha{}^t \rangle_\omega = \frac{n_{el} e^2}{\pi V} \Delta_{\alpha\alpha}.$$

[1)] For the sake of convenience we shall write p_n in place of p_z in the transformations that follow.

[1] P. M. Tomchuk and A. A. Chumak, Ukr. Fiz. Zh. **18**, 1818 (1973).
[2] Yu. L. Klimontovich, Kineticheskaya teoriya neideal'nogo gaza i neideal'noĭ plazmy (Kinetic Theory of Nonideal Gas and Nonideal Plasma), Nauka, Chap. 3, §18, 1975.
[3] P. M. Tomchuk and A. A. Chumak, Preprint No. 9, Phys. Inst. Ukr. Acad. Sci., 1971.
[4] P. M. Tomchuk and A. A. Chumak, Phys. Tver. Tela (Leningrad) **15**, 1011 (1973) [Sov. Phys. Solid State **15**, 697 (1973)].
[5] S. S. Rozhkov, Zh. Eksp. Teor. Fiz. **77**, 170 (1979) [Sov. Phys. JETP **50**, 86 (1979)].
[6] A. A. Tarasenko and A. A. Chumak, ibid. **73**, 625 (1977) [**46**, 327 (1977)].
[7] S. D. Beneslavskiĭ and N. A. Polevaya, Fiz. Tverd. Tela (Leningrad) **20**, 2687 (1978) [Sov. Phys. Solid State **20**, 1553 (1978)].
[8] A. A. Zlobin and P. S. Zyryanov, Proc. Symp. on Plasma Physics and Electric Instabilities in Solids, Vilnius, 1971.
[9] V. S. Gantsevich, V. L. Gurevich, and R. Katilius, La Rivista del Nuovo Cimento **2**, 5 (1979).
[10] S. V. Gantsevich, V. L. Gurevich, and R. Katilius, Phys. Cond. Matter **18**, 165 (1974).
[11] Sh. M. Kogan and A. Ya. Shul'man, Fiz. Tverd. Tela (Leningrad) **9**, 2259 (1967) [Sov. Phys. Solid State **9**, 1771 (1968)].
[12] V. A. Bareikis, A. P. Gal'dikas, and Yu. K. Pozhela, Fiz. Tekh. Poluprovod. **11**, 365 (1977) [Sov. Phys. Semicond. **11**, 210 (1977)].

Translated by J. G. Adashko

Domain structure of uniaxial ferrimagnets with a compensation point in strong magnetic fields

I. E. Dikshteĭn, F. V. Lisovskiĭ, E. G. Mansvetova, V. V. Tarasenko, V. I., Shapovalov, and V. I. Shcheglow

Institute of Radio Engineeing and Electronics, Academy of Sciences, USSR

(Submitted 6 November 1979)
Zh. Eksp. Teor. Fiz. **79**, 509–527 (August 1980)

Results are presented of theoretical and experimental investigations of the domain structure of uniaxial ferrimagnets of finite dimensions during second-order phase transitions in the vicinity of the magnetic compensation point. The theoretical analysis is carried out for the magnetic-field range from zero to the "flip" field of the magnetization vectors of the sublattices. Domains in fields above 100 kOe were observed on the "Solenoid" installation at the P.N. Lebedev Physical Institute of the Academy of Sciences, USSR.

PACS numbers: 75.50.Gg, 75.60.Ch

INTRODUCTION

Investigation of orientational second-order phase transitions induced in uniaxial magnetic materials by a magnetic field H perpendicular to the axis of easy magnetization (AEM) is of great interest both for physics and for applications. In theoretical papers[1,2] devoted to the analysis of the nucleation of a domain structure in the vicinity of such transitions in plates of uniaxial ferromagnets (with **n**‖AEM, where **n** is the normal to the plate surface), it was shown that because the static susceptibility of the crystal increases on approach to the phase-transition point (line), the effect of the demagnetizing field on the distribution of magnetization within the plate is considerably enhanced. Nevertheless, in the vicinity of lines of second-order phase transition the presence of a small parameter (the amplitude of the magnetization within a domain) makes it possible to find all the parameters of the domain structure directly from the equations of state and the equations of magnetostatics, with allowance for the boundary conditions on the magnetization and on the magnetic field, without resorting to any model-type assumptions. It should be noted that allowance for the nonuniformity both along the length and along the thickness of the plate is in principle important both for determination of the type of phase transition and for calculation of the temperature and field dependences of the parameters that characterize the nonuniform state. In other theoretical papers in this direction, the authors have determined the limits of stability of the uniform magnetic state[3-6] and have also, on the basis of model representations of the nature of the nucleating domain structure, similar to those of Ref. 7, calculated certain parameters of the structure. Obviously, according to the considerations indicated above, the last-mentioned results are correct only at a sufficient distance from the transition point.

In the present paper, we carry out a theoretical and experimental investigation of the domain structure of uniaxial ferrimagnets with a compensation point. In such magnets, as was first shown in Ref. 8 (see also Ref. 9), for an infinite medium a noncollinear state originates at arbitrarily small fields; this shows up especially clearly in the vicinity of the magnetic com-

0038-5646/80/080256-05$02.40

pensation point. Therefore allowance for noncollinearity of the magnetization vectors of the sublattices is in principle necessary in analysis of the domain structure near lines of second-order phase transition in ferrimagnets when H⊥ AEM; this was not taken into account in Refs. 10–16. In contrast to Ref. 17, the theoretical treatment in the present paper relates to the vicinity of lines of second-order phase transition, separating regions of existence of the noncollinear phase and of the high- and low-temperature collinear phases. It is shown that a thermodynamically stable domain structure exists in strong magnetic fields, up to the flip field of the magnetization vectors of the sublattices. The objects of experimental investigation were quasiuniaxial epitaxial films of magnetic garnets, in which a domain structure was observed in fields above 100 kOe.

1. Theory

We consider a uniaxial ferrimagnet in the form of a plane-parallel plate of thickness l, with the AEM directed along the normal $\mathbf{n} \parallel \mathbf{e}_z$ to the developed surface, in an external magnetic field $\mathbf{H} \parallel \mathbf{e}_y$. The free energy of the plate, for a two-sublattice model of the magnet, can be written in the form

$$F=\int dv[{}^1/_2\alpha_{ij}(\nabla\mathbf{M}_i)(\nabla\mathbf{M}_j)+\delta\mathbf{M}_1\mathbf{M}_2-{}^1/_2\beta_{ij}M_{iz}M_{jz}-M_yH-{}^1/_2\mathbf{M}\mathbf{H}_D], \qquad (1)$$

where i and j are the indices of the magnetic moments of the sublattices, $\mathbf{M}=\mathbf{M}_1+\mathbf{M}_2$ is the resultant magnetization vector, α_{ij} and δ are the constants of nonuniform and of uniform exchange interaction, respectively, β_{ij} are the anisotropy constants, $\mathbf{H}_D$ is the dipole-dipole interaction field, and the integration extends over the whole volume of the magnet V. In the vicinity of points of phase transition of the second kind, the vectors $\mathbf{M}_1$ and $\mathbf{M}_2$ are almost collinear with H, and $|\mathbf{M}_{jx}|$ and $|\mathbf{M}_{jz}| \ll |\mathbf{M}_j|$; therefore the free energy can be expanded as a power series in M_{jx} and M_{jz} to the second and fourth orders, respectively. We further transform to the variables M and $\mathbf{L}=\mathbf{M}_1-\mathbf{M}_2$. Then, minimizing (1) with respect to L for given M, we write the effective free energy in the form

$$F_{eff}=F_0+\int dv[{}^1/_2\alpha(\nabla M_z)^2+{}^1/_2\tilde{\alpha}(\nabla M_x)^2-{}^1/_2aM_z^2+{}^1/_2a'M_x^2+{}^1/_4bM_z^4-{}^1/_2\mathbf{M}\mathbf{H}_D], \qquad (2)$$

where

$$\begin{gathered}
\alpha=\alpha_M+\alpha_L(A')^2/A_L^2-2\alpha'A'/A_L, \quad \tilde{\alpha}=\alpha_M+\alpha_L(B')^2/B_L^2-2\alpha'B'/B_L,\\
a=-A_M+(A')^2/A_L, \quad a'=B_M-(B')^2/B_L,\\
b=C_M[1+(A')^4/A_L^4]+2C'(A')^2/A_L^2-4D'A'/A_L[1+(A')^2/A_L^2],\\
\alpha_M={}^1/_4(\alpha_{11}+2\alpha_{12}+\alpha_{22}), \quad \alpha_L={}^1/_4(\alpha_{11}-2\alpha_{12}+\alpha_{22}),\\
\alpha'={}^1/_4(\alpha_{11}-\alpha_{22}), \quad A_M=B_M-{}^1/_4(\beta_{11}+2\beta_{12}+\beta_{22}),\\
B_M=(4M_1M_2)^{-1}[-\delta(M_1-M_2)^2+H_0(M_1+M_2)],\\
C_M=C_L=(32M_1^3M_2^3)^{-1}[-\delta(M_1^2-M_2^2)^2+H_0(M_1^3+M_2^3)],\\
A_L=B_L-{}^1/_4(\beta_{11}-2\beta_{12}+\beta_{22}), \quad B_L=(4M_1M_2)^{-1}(M_1+M_2)[-\delta(M_1+M_2)+H_0],\\
A'=B'-{}^1/_4(\beta_{11}-\beta_{22}), \quad B'=(4M_1M_2)^{-1}(M_1-M_2)[\delta(M_1+M_2)-H_0],\\
C'=3C_M-\delta(M_1M_2)^{-1}, \quad D'=(32M_1^3M_2^3)^{-1}[\delta(M_1^4-M_2^4)-H_0(M_1^3-M_2^3)].
\end{gathered} \qquad (3)$$

In formulas (3), M_1 and M_2 are the projections of the magnetic moments of the sublattices on the y axis for the uniform state of the magnet; they may be either positive or negative (to denote the modulus of these projections, we shall use the index 0). The values of M_{10} and M_{20} are functions of the temperature and of the magnetic field. It follows from (2) that the problem under consideration formally reduces to analogous problems concerning a phase transition in ferromagnets.[1]

The condition for vanishing of the coefficient a determines the equation that describes the lines of phase transition in an infinite crystal,

$$\begin{aligned}
H_0={}&{}^1/_2[\delta(M_1+M_2)+\beta_{11}M_1+\beta_{22}M_2\mp{}^1/_2\{\delta^2(M_1+M_2)^2\\
&-2\delta[(\beta_{11}M_1-\beta_{22}M_2)(M_1-M_2)+4\beta_{12}M_1M_2]+(\beta_{11}M_1-\beta_{22}M_2)^2\\
&+4\beta_{12}^2M_1M_2\}^{1/2}.
\end{aligned} \qquad (4)$$

To make the subsequent discussion specific, we suppose that the ferrimagnet possesses a magnetic compensation point and that at low temperatures ($T \lesssim T_c$) $M_{10} < M_{20}$, while at high temperatures ($T \gtrsim T_c$) $M_{10} > M_{20}$. A typical phase diagram of a two-sublattice uniaxial ferrimagnet for this case, first obtained in Ref. 8, is shown in Fig. 1. The lines $P_0Q_0R_0$ and $G_0W_0U_0S_0$, which separate the regions of existence of the low-temperature collinear phase (LTC) ($\mathbf{M}_1\downarrow\uparrow\mathbf{M}_2\uparrow\uparrow\mathbf{H}$), the noncollinear (NC) phase ($\mathbf{M}_1$ nonparallel to H, $\mathbf{M}_2$ nonparallel to H), and the high-temperature collinear (HTC) phases ($\mathbf{M}_2\downarrow\uparrow\mathbf{M}_1\uparrow\uparrow\mathbf{H}$ below the dashed-dotted line W_0I_0, and $\mathbf{M}_2\uparrow\uparrow\mathbf{M}_1\uparrow\uparrow\mathbf{H}$ above W_0I_0) are simultaneously lines of second-order phase transition in an infinite crystal. It is evident that to each fixed value of the temperature, there in general correspond three critical values of the magnetic field intensity, $H_0^{(1)} < H_0^{(2)} < H_0^{(3)}$, where

$$H_0^{(1)}=|(\beta_{11}M_{10}^2+\beta_{22}M_{20}^2-2\beta_{12}M_{10}M_{20})(M_{10}-M_{20})^{-1}|, \qquad (5)$$

$$H_0^{(2)}=|\delta(M_{10}-M_{20})-(\beta_{11}+\beta_{22}-2\beta_{12})M_{10}M_{20}(M_{10}-M_{20})^{-1}|, \qquad (6)$$

$$H_0^{(3)}=\delta(M_{10}+M_{20})+(\beta_{11}+\beta_{22}-2\beta_{12})M_{10}M_{20}(M_{10}+M_{20})^{-1}. \qquad (7)$$

The position of the points Q_0 and U_0 of the diagram is determined by the system of equations

$$\begin{gathered}
M_{10}(T_0^{(Q_0,U_0)},H_0^{(Q_0,U_0)})[1\pm2(\beta_{11}+\beta_{22}-2\beta_{12})^{1/2}\delta^{-1/2}]\\
=M_{20}(T_0^{(Q_0,U_0)},H_0^{(Q_0,U_0)}),\\
H_0^{(Q_0,U_0)}=[\delta^{1/2}(\beta_{11}+\beta_{22}-2\beta_{12})^{1/2}\\
\pm2(\beta_{22}-\beta_{12})]M_{10}(T_0^{(Q_0,U_0)},H_0^{(Q_0,U_0)}),
\end{gathered} \qquad (8)$$

and that of the point W by the system of equations

$$M_{20}(T_0^{(W_0)},H_0^{(W_0)})=0, \qquad H_0^{(W_0)}=\delta M_{10}(T_0^{(W_0)},H_0^{(W_0)}). \qquad (9)$$

The curve W_0I_0 in the diagram of Fig. 1, which corresponds to vanishing of the magnetization M_{20} by vir-

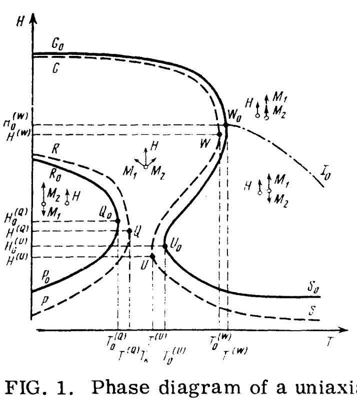

FIG. 1. Phase diagram of a uniaxial two-sublattice ferrimagnet when $H\perp$ AEM.

tue of the paraprocess, is not a line of phase transition.

In order to determine the form of the nonuniform distribution of the resultant magnetization in the vicinity of the lines of phase transition of the second kind for a specimen of finite dimensions (a plate of thickness l), we shall carry out a minimization of (2) with respect to M and shall solve the resulting equations of state

$$H_D^x=a'M_x, \quad H_D^z=-\alpha\nabla^2 M_z - aM_z + bM_z^3 \tag{10}$$

simultaneously with the equations of magnetostatics for the field H_D

$$\mathrm{rot}\, \mathbf{H}_D=0, \quad \mathrm{div}\, (\mathbf{H}_D+4\pi\mathbf{M})=0. \tag{11}$$

From (10) and (11) we get the equation that describes the spatial variation,

$$\frac{\partial^2}{\partial x^2}\left(\alpha\frac{\partial^2 M_z}{\partial x^2}+aM_z-bM_z^3\right)-4\pi\frac{\partial^2 M_z}{\partial z^2}=0. \tag{12}$$

In the derivation of Eq. (12) we have restricted ourselves to consideration of plates that are thick enough so that the inequality $\alpha(1+4\pi/a')\ll l^2$ is valid. In this case the contribution of the surface solutions of Eq. (12) to the total energy of the crystal may be neglected, since their depth of penetration is proportional to $\alpha^{1/2} \ll l$, and since the characteristic scale of the nonuniformity along the plate considerably exceeds the corresponding scale through its thickness ($|\partial M_z/\partial z| \ll |\partial M_x/\partial x|$). In the approximation adopted, the boundary conditions reduce to

$$4\pi M_z|_{z=\pm l/2}=(H_D^{(e)})_z|_{z=\pm l/2}, \quad (H_D)_x|_{z=\pm l/2}=(H_D^{(e)})_x|_{z=\pm l/2}, \tag{13}$$

where $\mathbf{H}_D^{(e)}$ is the dipole field in a vacuum.

The solution of the nonlinear Eq. (12) with the boundary conditions (13) simplifies considerably in the vicinity of a line of phase transition. In fact, it was shown in Ref. 1, on the basis of general considerations, that in finite crystals the dipole energy does not change the type of phase transition. Therefore on approach to lines of second-order phase transition from the side of the noncollinear phase ($M_z \neq 0$), the magnetization distribution approaches the form that is obtained by solution of Eq. (12) without the cubic nonlinear term:

$$M_z=A\cos kx\cos qz, \tag{14}$$

where $k=2\pi/D$ is the reciprocal period of the domain structure, and where $q\approx\pi/l$. Since for small departures from a phase-transition line the spatial distribution of the magnetization should not differ appreciably from the distribution (14), we write the solution of Eq. (12) in the form

$$M_z=\sum_{n=0}^{\infty}\lambda^{2n+1}A_{2n+1}(z)\cos(2n+1)kx, \tag{15}$$

where λ is a formal small parameter that determines the degree of closeness to lines of phase transition in the plate; these in general differ from the lines of phase transition in an infinite ferrimagnet. It is evident from the expressions (14) and (15) that the magnetization distribution near lines of phase transition is significantly nonuniform. It should be noted that the domain structure being studied is thermodynamically in equilibrium, since it corresponds to an absolute minimum of the free energy of the ferrimagnet.

Using the method developed in Ref. 1 for ferromagnets, we find the period D of the domain structure, the critical domain dimension D_c, and the amplitude of the nonuniform component of the magnetization:

$$D=D_c+\frac{l}{16\pi^2}\Delta a, \quad D_c=(4\pi\mu\alpha l^2)^{1/4}, \quad M_z(x=0;\,z=0)={}^4/_3(\Delta a/b)^{1/2}, \tag{16}$$

where

$$\mu=1+4\pi/a', \quad \Delta a=a-(4\pi^3\alpha/\mu l^2)^{1/2}. \tag{17}$$

The lines of phase transition of the second kind for a ferrimagnetic plate of thickness l, which bound the regions of existence of the states of uniform magnetization and of nonuniform (with a domain structure), are denoted by the letters PQR and $SUWG$ in the diagram of Fig. 1. They are located in the region of noncollinearity of the magnetization vectors of the magnetic sublattices near the lines of second-order phase transition, $P_0Q_0R_0$ and $S_0U_0W_0G_0$, for an infinite medium. The displacement of the position of the lines of phase transition because of finite dimensions of the magnet, for specimens in the form of plates, is inversely proportional to l:

$$H^{(1)}=H_0^{(1)}-\frac{4\pi^{3/2}}{l\mu^{1/2}}(\alpha_{11}M_{10}^2+\alpha_{22}M_{20}^2-2\alpha_{12}M_{10}M_{20})^{1/2},$$

$$H^{(2,3)}=H_0^{(2,3)}\pm\frac{2^{5/2}\pi^{3/2}}{\delta l}\left\{\frac{M_{10}M_{20}}{M_{20}-M_{10}}[(\beta_{22}-\beta_{12})M_{20}\pm(\beta_{11}-\beta_{12})M_{10}](\alpha_{11}+\alpha_{22}-2\alpha_{12})\right\}^{1/2},$$

where

$$\mu=1+4\pi(M_{10}-M_{20})^2(\beta_{11}M_{10}^2+\beta_{22}M_{20}^2-2\beta_{12}M_{10}M_{20})^{-1}.$$

It is seen that in the upper part of the diagram, the displacement of the lines of second-order phase transition with respect to the field, in a plate of finite thickness, is smaller than in the lower part by a factor $\delta^{-1}(\max\beta_{ij})$.

At point Q of the diagram,

$$\Delta T^{(Q)}=T^{(Q)}-T_0^{(Q)}=\frac{\pi^{3/2}}{l}(T_0^{(U)}-T_0^{(Q)})\left[\frac{\alpha_{11}+\alpha_{22}-2\alpha_{12}}{\delta(\beta_{11}+\beta_{22}-2\beta_{12})}\right]^{1/2},$$

$$\Delta H^{(Q)}=H^{(Q)}-H_0^{(Q)}=-M_{10}\frac{4\pi^{3/2}}{l}(\alpha_{11}+\alpha_{22}-2\alpha_{12})^{1/2}.$$

In the vicninity of line PQ in Fig. 1,

$$D_c^{(1)}=\left\{4\pi l^2\frac{\alpha_{11}M_{10}^2+\alpha_{22}M_{20}^2-2\alpha_{12}M_{10}M_{20}}{(M_{10}-M_{20})^2}\left[1+\frac{4\pi(M_{10}-M_{20})^2}{\beta_{11}M_{10}^2+\beta_{22}M_{20}^2-2\beta_{12}M_{10}M_{20}}\right]\right\}^{1/4}, \tag{18a}$$

$$M_z(x=0;\ z=0)=\frac{4}{3}\left[\frac{2(H^{(1)}-H)(M_{20}-M_{10})^3}{\beta_{11}M_{10}^2+\beta_{22}M_{20}^2-2\beta_{12}M_{10}M_{20}}\right]^{1/2}. \tag{18b}$$

Near the point Q we have

$$D_c^{(Q)}\approx\left[4\pi\delta l^2\frac{\alpha_{11}+\alpha_{22}-2\alpha_{12}}{\beta_{11}+\beta_{22}-2\beta_{12}}\right]^{1/4}, \tag{19a}$$

$$M_z(x=0;\ z=0)=\frac{4}{3\sqrt{5}}\frac{|H-H^{(Q)}|}{\delta}. \tag{19b}$$

For the lines QR and GW we get, respectively,

$$D_c^{(2,3)}\approx\left\{8\pi\delta^2 l^2\frac{(M_{10}\mp M_{20})^2(\alpha_{11}+\alpha_{22}-2\alpha_{12})}{[(\beta_{22}-\beta_{12})M_{20}\pm(\beta_{11}-\beta_{12})M_{10}]^2}\right\}^{1/4}, \tag{20a}$$

$$M_z(x=0;\ z=0)=\frac{4}{3}\cdot\frac{(\beta_{22}-\beta_{12})M_{20}\pm(\beta_{11}-\beta_{12})M_{10}}{M_{20}\mp M_{10}}\left[\frac{\pm M_{10}M_{20}(H-H^{(2,3)})}{\delta(M_{20}\mp M_{10})}\right]^{1/2}. \tag{20b}$$

In formulas (18b), (19b), and (20b), $H^{(i)}$ ($i=1,2,3,Q$, or W) represents the transition field for a magnet in the form of a plate of finite thickness. Analogous formulas can also be obtained for lines of the phase diagram when $T > T_c$.

The dependence of the domain dimension on the magnetic field intensity is described by an expression of the form

$$D^{(i)}=D_c+C_1|(H/H^{(i)})-1|+C_2|(H/H^{(i)})-1|^2, \tag{21}$$

where C_1 and C_2 are constants, dependent on the temperature and on the plate parameters (C_1 and C_2 are quantities of the same order everywhere except in the vicinity of the points Q_0, U_0, and W_0, where $C_1 \to 0$). The value of $D_c^{(i)}$ increases with increase of the magnetic field intensity; and in the upper part of the diagram of Fig. 1, $D_c^{(i)}$ is larger than in the lower by a factor of about $\{\delta(\text{mas}\beta_{ij})^{-1}\}^{1/2}$. Therefore experimental detection of domain structure in the vicinity of lines of second-order phase transition in strong magnetic fields is facilitated in materials with strong anisotropy and with weakened exchange interaction.

2. Experiment

In the experiments, we investigated epitaxial films of magnetic garnets $(YGdYbBi)_3(FeAl)_5O_{12}$, of thickness 5–15 μm, grown on substrates of $Gd_3Ga_5O_{12}$ cut in a {111} plane. The domain structure of the films was observed in polarized light, by means of a microscope, on the basis of the Faraday effect. The films, in a thermostat, were placed in a magnetic field directed approximately parallel to the developed plane (along the axis y in Fig. 2); the light was propagated along the axis z. The anisotropy of films of magnetic garnets differs from uniaxial (cubic and rhombic components are also present; see, for example, Refs. 13 and 18); therefore a second-order phase transition, for a chosen position of the film with respect to azimuth (φ = const), occurs within a narrow interval of angles ψ between H and the developed surface of the film (in general $\psi \neq 0$). The source of the magnetic field was an electromagnet of the "Solenoid" installation of the P.N. Lebedev Physical Institute of the Academy of Sciences, USSR, which enabled us to perform the experiments in stationary magnetic fields up to 150 kOe.[19]

The results of the experiments are shown in Figs. 3 and 4 for one of the films investigated, of thickness ~5 μm, with compensation point $T_c \approx 310$ K and Curie

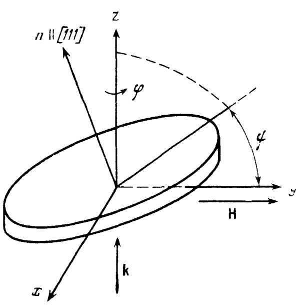

FIG. 2. Geometry of the experiment.

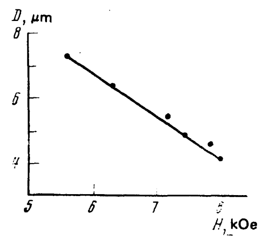

FIG. 3. Variation of the period D of the domain structure with the biasing field H in a film of $(YGdYbBi)_3(FeAl)_5O_{12}$ of thickness 5 μm, at $T = 212$ K.

temperature $T_C \approx 420$ K. The AEM in the film was inclined to the normal (the {111} axis) at an angle ~1°; the uniaxial anisotropy field, at any temperature $0 < T < T_C$, exceeded the saturation magnetization $4\pi M$, and therefore the domain structure that existed in the film was of the "open" type.[20] At $H=0$, within the temperature intervals $T < 250$ K and $375\text{ K} < T < 420$ K, an ordinary maze domain structure was observed in the film. With increase of the magnetic field, which was so oriented that the disappearance of the domain occurred via a second-order phase transition, the period of the domain structure decreased according to a linear law (see Fig. 3); at the instant of disappearance of the Faraday constant between domains with opposite signs of M_z, the period $D=D_c$ remained finite. Near the compensation point T_c when $H=0$, a single-domain interval.[21,22] was observed ($250\text{ K} < T < 375$ K); but with increase of H, a domain structure originated anew[1)] near the critical values of the magnetic field $H=H_1$ (see Fig. 4). In Fig. 4 are plotted the temperature variations of the critical field H_1 and of the reciprocal critical dimension D_0^{-1} of the domains in zero field. It is evident that the form of the $H_1(T)$ curves agrees well with the form of the branches PQ and SU in the theoretical diagram of Fig. 1. With approach to the compensation point, D_c and H_1 increase; the single-domain interval with respect to "high-field" domains is $290\text{ K} < T < 335$ K. For $T \leq 290$ K, coarse domains ($D_c \approx 100$ μm) were observed at magnetic field strength $H_1 \approx 110$ kOe.

For observation of a domain structure in strong magnetic fields, it is necessary carefully to maintain the conditions necessary for occurrence of a second-order phase transition (or of a first-order transition close to it). For chosen values of the temperature T and of the angle φ, this takes place only within a very narrow in-

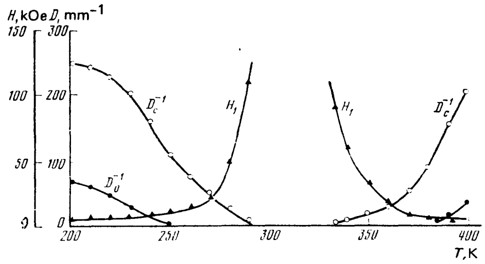

FIG. 4. Temperature variation of the inverse period D_0^{-1} of the domain structure in zero field, of the inverse critical period D_c^{-1} of the domain structure, and of the critical field H_1, in a film of $(YGdYbBi)_3(FeAl)_5O_{12}$ of thickness 5 μm.

terval (≲1°) of variation of the angles ψ of inclination of the film and of the magnetic field intensity H. Within the permissible interval of variation of the angle ψ, there is a certain critical value ψ_c for which the field for vanishing of the domain structure is a maximum (it is this field that was taken as H_1 in Fig. 4). At $H=H_1$ the Faraday constant between domains vanishes; the width of the magnetic-field interval for existence of these domains is a maximum. On departure from the critical value φ_c, the transition field decreases abruptly; the process of disappearance of domains acquires a tendency to proceed by squeezing out of one phase by the other, and the Faraday constant between neighboring domains persists up to the transition point itself.[2)] At appreciable departures of ψ from ψ_c (>1°), a domain structure is not observed at all, and increase of the field leads only to a replacement of one phase by the other by motion of the interphase boundaries. On change of T or φ or both, the values of ψ_c and H_1 also change; this is due to the different temperature dependences of the constants of uniaxial, rhombic, and cubic anisotropy.

It is known that many-sublattice magnetic materials have the capacity to form a thermodynamically stable domain structure in strong magnetic fields, up to the "flip" field of the magnetization vectors of the sublattices (~10^6 Oe).[26-30,9] In the experiments performed, a domain structure in uniaxial ferrimagnets in strong magnetic fields was observed during second-order phase transitions of the second kind, which are not accompanied by a jump of the resultant magnetization. Thus in many-sublattice magnets, the presence of a first-order transition is not a necessary condition for existence of a domain structure.

The authors express their gratitude to V.G. Veselago, V.E. Makhotkin, and L.P. Maksimov for help in the organization and conduct of the experiments on the "Solenoid" installation, and to I.G. Avaeva for growing the films.

[1)]In Ref. 23 it was shown that in an ideal crystal in the form of an infinite plate, there is no single-domain interval, but the domain dimension increases without limit on approach to the compensation point. But in practice, near T_C there is always either a single-domain interval (if the specimen is subjected to magnetic "shaking"; see, for example, Ref. 22) or (in the absence of magnetic "shaking") a temperature interval within which the domain dimension remains unchanged. This is due to the fact that because of the abrupt decrease of the magnetostatic energy ($M\to 0$) near T_C, the role of the coercive force increases greatly, and it prevents the establishment of a thermodynamic-equilibrium domain structure in real crystals.

[2)]We note that in epitaxial films of magnetic garnets, layers are often observed that differ in their parameters (for example, in the compensation temperature[24]); therefore the possibility is not excluded that the domains observed in strong magnetic fields are ones that do not run all the way through (see Ref. 25).

[1]V. V. Tarasenko, E. V. Chenskiĭ, and I. E. Dikshteĭn, Zh. Eksp. Teor. Fiz. **70**, 2178 (1976) [Sov. Phys. JETP **43**, 1136 (1976)].
[2]V. G. Bar'yakhtar and B. A. Ivanov, Zh. Eksp. Teor. Fiz. **72**, 1504 (1977) [Sov. Phys. JETP **45**, 789 (1977)].
[3]M. W. Muller, Phys. Rev. **122**, 1485 (1961).
[4]W. F. Brown, Jr., Phys. Rev. **124**, 1348 (1961).
[5]A. Holz and H. Kronmüller, Phys. Status Solidi **31**, 787 (1969).
[6]R. M. Goldstein and M. W. Muller, Phys. Rev. **B2**, 4585 (1970).
[7]M. Ya. Shirobokov, Zh. Eksp. Teor. Fiz. **15**, 57 (1945).
[8]A. K. Zvezdin and V. M. Matveev, Zh. Eksp. Teor. Fiz. **62**, 260 (1972) [Sov. Phys. JETP **35**, 140 (1972)].
[9]K. P. Belov, A. K. Zvezdin, A. M. Kadomtseva, and R. Z. Levitin, Orientatsionnye fazovye perekhody v redkozemel'nykh magnetikakh (Orientational Phase Transitions in Rare-Earth Magnetic Materials), Nauka, 1979.
[10]A. J. Kurtzig and F. B. Hagedorn, IEEE Trans. Magn. **7**, 473 (1961).
[11]P. W. Shumate, D. H. Smith, and F. B. Hagedorn, J. Appl. Phys. **44**, 449 (1973).
[12]W. F. Druyvesteyn, J. W. F. Dorleijn, and P. J. Rijnierse, J. Appl. Phys. **44**, 2397 (1973).
[13]A. P. Malozemoff and J. C. De Luca, J. Appl. Phys. **45**, 4586 (1974).
[14]Y. Shimada, H. Kojima, and K. Sakai, J. Appl. Phys. **45**, 4598 (1974).
[15]M. W. Muller, J. Appl. Phys. **45**, 5050 (1974).
[16]M. W. Muller and S. K. Chung, AIP Conf. Proc. **24**, 588 (1975).
[17]V. I. Khalturin, Fiz. Met. Metalloved. **41**, 271 (1976) [Phys. Met. Metallogr. (USSR)].
[18]F. V. Lisovskiĭ, E. G. Mansvetova, and V. I. Shapovalov, Preprint, IRÉ, Acad. Sci. USSR, No. 14 (256), 1978, p. 43.
[19]V. G. Veselago, L. P. Maksimov, and A. M. Prokhorov, Vest. Akad. Nauk SSSR **12**, 58 (1968).
[20]L. D. Landau and E. M. Lifshitz, Élektrodinamika sploshnykh sred (Electrodynamics of Continuous Media), M., Gostekhizdat, 1957, p. 532 (translation, Pergamon Press and Addison Wesley, 1960).
[21]V. G. Bar'yakhtar and D. A. Yablonskiĭ, Fiz. Tverd. Tela **16**, 3511 (1974) [Sov. Phys. Solid State **16**, 2282 (1975)].
[22]F. V. Lisovskiĭ, E. G. Mansvetova, and V. I. Shapovalov, Zh. Eksp. Teor. Fiz. **71**, 1443 (1976) [Sov. Phys. JETP **44**, 755 (1976)].
[23]A. N. Bogdanov and D. A. Yablonskiĭ, Summaries of Reports at the All-Union Conference on the Physics of Magnetic Phenomena, Kharkov, 1979, p. 442.
[24]I. G. Avaeva, V. B. Kravchenko, F. B. Lisovskiĭ, E. G. Mansvetova, and V. I. Shapovalov, Mikroélektronika **7**, 444 (1978).
[25]F. B. Lisovskiĭ, E. G. Mansvetova, and A. Ya. Chervonenkis, Summaries of Reports at the All-Union Conference on the Physics of Magnetic Phenomena, Kharkov, 1979, p. 438.
[26]V. G. Bar'yakhtar, A. E. Borovik, and V. A. Popov, Pis'ma Zh. Eksp. Teor. Fiz. **9**, 634 (1969) [JETP Lett. **9**, 391 (1969)].
[27]A. I. Mitsek, N. P. Kolmakova, and P. F. Gaĭdanskiĭ, Fiz. Tverd. Tela **11**, 1258 (1969) [Sov. Phys. Solid State **11**, 1021 (1969)].
[28]V. G. Bar'yakhtar, A. A. Galkin, S. N. Kovner, and V. A. Popov, Pis'ma Zh. Eksp. Teor. Fiz. **10**, 292 (1969) [JETP Lett. **10**, 184 (1969)].
[29]V. V. Eremenko, N. F. Kharchenko, and S. L. Gnatchenko, Digests Intermag Conf., Toronto, 1974, 7–7.
[30]F. V. Lisovskiĭ and V. I. Shapovalov, Pis'ma Zh. Eksp. Teor. Fiz. **20**, 128 (1974) [JETP Lett. **20**, 55 (1974)].

Translated by W. F. Brown, Jr.