Zinatne, Riga, 1966, p. 71.
[151]V. V. Antonov-Romanovskiĭ, Kinetika fotolyuminestsentsii kristallov (Kinetics of Photoluminescence of Crystals), Nauka, M., 1966.
[152]V. Ya. Grabovskis, Uch. zap. Latv. GU **245**, 73 (1975).
[153]I. Tale, D. Millers, and E. Kotomin, J. Phys. **C8**, 2366 (1975).
[154]I. Fabrikant and E. Kotomin, J. Luminescence **9**, 502 (1975).
[155]R. Balzer, Zs. Phys. **234**, 242 (1970).
[156]A. A. Vorob'ev, E. K. Zavadovskaya, and A. V. Kuz'mina, Zapasennaya énergiya v shchelochnogaloidnykh soedineniyakh (Stored Energy in Alkali-Halide Compounds), TGU, Tomsk, 1969.
[157]V. I. Gotlib, Ya. Zh. Kristapson, K. K. Shvarts, and Yu. A. Ékmanis, see Ref. 62, p. 143.
[158]É. L. Andronikashvili and N. G. Politov, in Radiation Damage in Solids, Vol. 3, Vienna, 1963, p. 147.
[159]L. W. Hobbs, A. E. Hughes, and D. Pooley, Proc. Roy. Soc. **A332**, 267 (1973).
[160]D. I. Vaĭsburd and I. N. Balychev, Pis'ma Zh. Eksp. Teor. Fiz. **15**, 537 (1972) [JETP Lett. **15**, 380 (1972)].
Translated by M. V. King

Synthesis and physical properties of single-crystal films of rare-earth iron garnets

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Usp. Fiz. Nauk **122**, 253–293 (June 1977)

The synthesis conditions, certain problems of epitaxial growth, and methods of controlling the quality of single-crystal iron-garnet films are discussed. The main physical properties of garnet films are considered, such as optical absorption, Faraday rotation, the characteristic length, the saturation magnetization, the coercive force, the magnetic anisotropy, the mobility, and the dynamic transformation of domain walls. Measurement methods and some results of the investigation of these properties are described. The reproducibility and the temperature dependence of the principal parameters of the films are discussed.

PACS numbers: 68.55.+b, 75.70.–i, 78.65.Jd, 75.30.Cr

CONTENTS

1. INTRODUCTION

Interest in the investigation of thin magnetic films is due both to the singularities of their structure and physical properties, which promise to cast light on many fundamental problems of solid state physics, and to the prospects of the practical utilization of these films in electronic technology. Among the trends that lead to advanced devices for automation and computer technology is development of memory and logic devices based on the motion of domains in magnetically uniaxial materials.[1–6] Research is also being carried out on magneto-optical devices for the reduction and storage of information in ferrites.[4]

Principal attention is being paid to ferrites with garnet structure $R_3Fe_5O_{12}$ (where R is an yttrium or rare-earth ion),[7,8] a distinctive magnetic structure—cylindrical magnetic domains (CMD) bubble (Fig. 1)—is produced in films of this material, with the easy magnetization axis normal to the plane of the film, when a constant magnetic field is applied in the same direction.

Among the advantages of domain devices for computer logic and memory over their semiconductor analogs we can single out the following:

a) the small (micron and submicron) dimensions of the bubble make it possible to obtain a binary information recording density 10^6–10^9 bit/cm^2;

b) low power consumption (0.04 W to perform 10^{12} binary operations per second);

c) possibility of storing the information without consuming energy;

d) ability of circuits using domain interactions in a homogeneous magnetic medium to perform multiple functions;

e) the possibility of producing these circuits by the

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FIG. 1. Domain structure in an iron garnet film of the system $(YSmCa)_3(FeGeSi)_5O_{12}$ in different bias fields normal to the plane of the film.

known methods of integral and thin-film technology.

An analysis of the distinguishing features and capabilities of domain structures for the reduction and storage of information points to the feasibility of developing bubble memory devices with capacity 10^6–10^9 bits, a repetition frequency on the order of several hundred kHz, and an access time from several dozen microseconds to milliseconds, so that preliminary logical reduction of the information to be stored can be effected in one crystal.[5] The tendency to attain maximum information density by decreasing the size of the bubble has made it necessary to use single-crystal rare-earth garnet films approximately 6 μ thick. The most widely used method of obtaining such films is liquid-phase epitaxy, whose principal superiority lies in the possibility of obtaining compositions with varied properties by using isomorphic substitutions, and in the ability to form continuous solid solutions.[9,10]

Observation of giant Faraday rotation in garnet films containing bismuth,[11–18] in conjunction with the possibility of magnetic and thermal recording of arbitrary symbols with the aid of the domains[19–21] and the existence of a color contrast between domains of opposite sign[22,23] in these films, is of practical interest for the development of optical memory devices, tunable optical transparencies, and reversible media for the registration of holographic images.

We consider in this paper synthesis conditions and procedures, and some problems in the kinetics of epitaxial growth of single-crystal films of iron garnets. We describe the physical properties of garnet films and methods of their investigations. The reproducibility and temperature stability of the principal magnetic parameters of these films are investigated.

2. IRON-GARNET FILM GROWTH METHODS

The best reproducibility of the properties of single-crystal iron-garnet films is obtained when the films are grown by the method of liquid-phase epitaxy from a molten solution.[24–28]

The substrates used as a rule are crystals of nonmagnetic garnets.[29,30] Figure 2 shows the lattice constants for a number of substrates of nonmagnetic garnets and iron-garnet films.[30] The film and the substrate must have close lattice parameters, so that the film can grow without cracking. On the other hand, the difference Δa between the lattice parameters should be large enough to produce in the film uniaxial anisotropy with an easy axis normal to its plane. The value of Δa in epitaxial iron-garnet films with CMD is 0.01–0.02 Å. The best substrates for growing iron garnets are crystals of gadolinium–gallium garnet (GGG) $Gd_3Ga_5O_{12}$ with a lattice constant 12.383 Å. Substrates in the form of plates 0.3–1 mm thick and diameter 5–38 mm, oriented as a rule along the ⟨111⟩ direction, are cut from GGG crystals grown by the Czochralski method in an iridium crucible.[31]

When single crystals are grown by liquid-phase epitaxy, the solvent must satisfy the following principal requirements[32–34]:

1) high solubility (10–15%) of the garnet-forming components;

2) high melting temperature and low viscosity;

3) the dissolved substance should be a stable solid phase under the growth conditions;

4) low vapor tension and low chemical activity at the working temperatures, and absence of chemical interaction with the crucible material;

5) low solubility of the solvent in the grown crystals;

6) temperature invariance of the distribution coefficients of the garnet-forming elements, which should be close to unity;

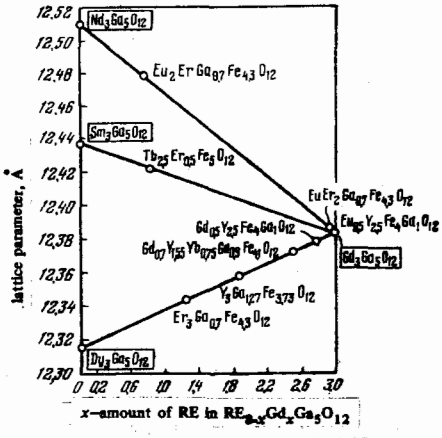

FIG. 2. Lattice constants of substrates of nonmagnetic garnets and iron-garnet films.[30]

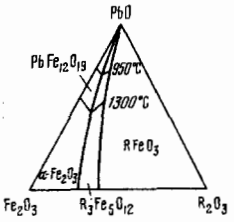

FIG. 3. Phase diagram of the system $PbO-Fe_2O_3-R_2O_3(Y_2O_3)$.[91]

7) the possibility of controlling the supercooling with a high degree of accuracy.

The solvents most widely used for the growth of garnets by the liquid-epitaxy methods are the binary melts $PbO-B_2O_3$,[26,28,35-74] $BaO-B_2O_3$,[24,75-80] and the ternary melts $PbO-B_2O_3-PbF_2$[81-86] and $BaO-B_2O_3-BaF_2$.[87-90] A feature of melts based on PbO and BaO, containing garnet-forming oxides, is that they can be strongly supercooled (by approximately 100 °C) and remain in this state for a considerable time.[33,41,68] This makes it possible to grow epitaxial iron-garnet films under isothermal conditions.

Introduction of substitutes into the structure of the iron garnet results in a multicomponent system in the melt solution. Figure 3 shows the main features of the pseudotriple diagram of $PbO-Fe_2O_3-R_2O_3$ (Y_2O_3).[91] Depending on the position on the diagram, one of the following four principal phases will be crystallized: hermatite (Fe_2O_3), magnetoplumbite ($PbFe_{12}O_{19}$), garnet ($R_3Fe_5O_{12}$), or orthoferrite ($RFeO_3$). A detailed investigation of the phase diagrams of $PbO-Ba_2O_3-FeO_3-Y_2O_3$ is reported in[92]. When the charge is prepared, an important role is played by the following molar ratios[68,93]

$$M_1=\frac{Fe_2O_3}{\sum R_2O_3}, \quad (1)$$

$$M_2=\frac{Fe_2O_3}{Ga_2O_3\ (\text{or}\ Al_2O_3)}, \quad (2)$$

$$M_3=\frac{PbO}{B_2O_3}, \quad (3)$$

$$M_4=\frac{\sum R_2O_3+Fe_2O_3+Ga_2O_3}{\sum R_2O_3+Fe_2O_3+Ga_2O_3+PbO+B_2O_3}. \quad (4)$$

To obtain the garnet phase, it is best to use $M_1=14$, $M_2=16$, $M_3=15.6$, $M_4=0.08$. The saturation temperature T_{sat} of the molten solution depends on M_3 and changes by 8.49 °C for each unit of its change.[28,41]

Typical apparatus used to grow garnet films by liquid-phase epitaxy from the solution in the melt is described in detail in[28-28,47,52,53,69,70]. Figure 4 shows a block diagram of the installation and the construction of the heating furnace used in the Physics Department of the Moscow State University to grow epitaxial single-crystal iron-garnet films.[69,70]

The principal stages in the epitaxial growth of garnet films are the following: thorough mixing of a batch consisting of approximately 9 percent by weight of the garnet-forming oxides and a solvent with a weight ratio $PbO:B_2O_3=50:1$, and melting the mixture in a platinum crucible at a temperature 1100–1150 °C; homogenization of the melt in the furnace for 2–18 hours at 1050–

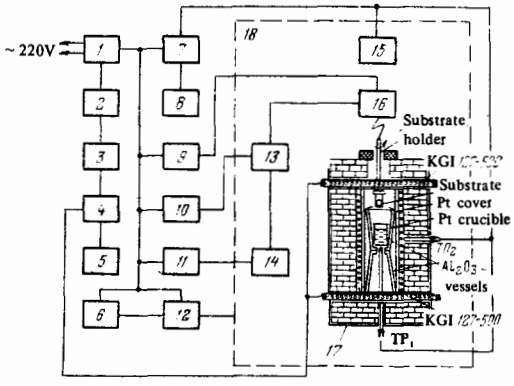

FIG. 4. Block diagram of installation for the growth of single-crystal garnet films.[69,70] 1—voltage stabilizer, 2,3—blocks for regulating and setting the temperature-lowering program, 4,5—instruments that control and record the current and the voltage, 6,12—automatic temperature control system, 7,8—instruments for the control and continuous recording of the temperature, 9—system for the control of the substrate rotation, 10,11—blocks for the control of the velocities of the lifting devices, 13,14—lifting devices, 15—thermostat for the cold junctions of the thermocouples, 16—substrate-rotation blocks, 17—resistance furnace, 18—hermetic blocks. (Platnum melting crucible).

1200 °C; lowering the temperature to a value T_{growth} which is 10–50 °C lower than T_{sat} and thus supercooling the melt by an amount $\Delta T=T_{sat}-T_{growth}$; heating the substrate to the temperature T_{growth} by holding it at the surface of the melt for ~5 minutes; growth of the films under isothermal conditions while the substrate is rotated at ~100 rpm. The growth cycle is terminated by abruptly jerking the substrate out of the melt, drawing it slowly from the heating zone, and treating it with a 50-percent solution of HNO_3 at 80 °C.

The composition of the melt, the saturation temperature, and the growth conditions for a number of iron-garnet film compositions grown with the aid of the described installation are given in Table I.

3. CERTAIN PROBLEMS IN THE GROWTH KINETICS OF GARNET FILMS

The principal mechanisms of epitaxial growth of crystals have been considered in detail in[32,41,54,68,94-102]. The growth from the solution can be divided into four principal stages: 1) transport of the dissolved substance to the surface of the crystal; 2) volume diffusion through the depleted zone at the phase separation boundary; 3) surface diffusion; 4) joining of the growth particles to form a crystal. The mechanism whereby the dissolved substance is transported depends on the growth conditions and includes diffusion, convection, or forced flow (stirring).[32,101] The growing surface serves as a sink for the crystal-forming components. The solvent and the reaction products, which do not take part in the construction of the crystal, are pushed away from the phase-separation boundary, and a concentration gradient is produced in the melt near this boundary.[32] With increasing distance from the phase-separation boundary, the concentration of the absorbed substance increases and that of the expelled components decreases. As a

TABLE I.

Composition of melt	Composition of components, mol.%							
	Y_2O_3	Sm_2O_3	Er_2O_3	Eu_2O_3	Ga_2O_3	Fe_2O_3	PbO	B_2O_3
$Y_3Fe_5O_{12}$	0.72					9	84.84	5.4
$Y_3Ga_{0.75}Fe_{4.25}O_{12}$	0.72				0.54	8.46		
$Y_3Ga_{0.5}Fe_{4.5}O_{12}$					0.96	8.64	" "	" "
$Y_3Ga_{1.0}Fe_{4.0}O_{12}$	" "				0.72	8.28	" "	" "
$Y_3Ga_{1.2}Fe_{3.8}O_{12}$	" "				0.864	8.136	" "	" "
$Y_3Ga_{1.25}Fe_{3.75}O_{12}$	" "				0.9	8.1	" "	" "
$Y_{2.8}Sm_{0.2}Ga_{1.0}Fe_{4.0}O_{12}$	0.7145	0.0565			0.78	6.65	85.72	6.07
$Y_{2.8}Sm_{0.4}Ga_{1.0}Fe_{4.0}O_{12}$	0.658	0.113			0.78	6.65		
$Y_{2.8}Sm_{0.4}Ga_{1.1}Fe_{3.9}O_{12}$					0.857	6.579	" "	" "
$Y_{2.8}Sm_{0.4}Ga_{1.2}Fe_{3.8}O_{12}$	" "	" "			0.995	6.495	" "	" "
$Er_{2.0}Eu_{0.1}Ga_{0.7}Fe_{4.3}O_{12}$	" "	" "	0.48	0.24	0.51	8.47	84.86	5.44

Composition of melt	T_{sat} °C	Δa, Å	ΔT, °C	f_{av} μ/min	M_1	M_2	M_3	M_4	$4\pi M_s$, G
$Y_3Fe_5O_{12}$	940	0.006	20	0.8	12.5	∞	15.6	0.097	1750
$Y_3Ga_{0.75}Fe_{4.25}O_{12}$	960	0.009	20	0.7	11.75	15.68			750
$Y_3Ga_{0.5}Fe_{4.5}O_{12}$	970	0.011	20	0.75	12	24	" "	" "	1070
$Y_3Ga_{1.0}Fe_{4.0}O_{12}$	978	0.012	15	0.8	11.5	11.5	" "	" "	450
$Y_3Ga_{1.2}Fe_{3.8}O_{12}$	985	0.014	15	0.8	11.3	9.42	" "	" "	280
$Y_3Ga_{1.25}Fe_{3.75}O_{12}$	990	0.018	15	0.75	11.24	9	" "	" "	220
$Y_{2.8}Sm_{0.2}Ga_{1.0}Fe_{4.0}O_{12}$	935	0.01	20	0.8	8.63	8.54	14.12	0.082	290
$Y_{2.8}Sm_{0.4}Ga_{1.0}Fe_{4.0}O_{12}$	955	0.011	20	0.7	8.63	8.54			190
$Y_{2.8}Sm_{0.4}Ga_{1.1}Fe_{3.9}O_{12}$	960	0.011	20	0.75	8.59	7.66	" "	" "	175
$Y_{2.8}Sm_{0.4}Ga_{1.2}Fe_{3.8}O_{12}$	965	0.012	20	0.7	8.425	6.94	" "	" "	160
$Er_{2.0}Eu_{1.6}Ga_{0.7}Fe_{4.3}O_{12}$	950	0.014	20	0.8	11.77	16.62	15.6	0.097	248

result, the diffusion flux of the dissolved substance is directed towards the growing surface.

The growth rate is determined mainly by volume diffusion through a depleted boundary layer of thickness δ at the film surface and the unification of the growth particles into a single crystal.

The relative motion of the crystal and of the solution decreases the thickness δ and leads to an increase in the growth rate.[103]

Assuming equality of the growth rate and the rate of diffusion flux through the depleted layer (the volume-diffusion model) and assuming constancy of the concentration gradient in the entire volume, we find from the material balance equation that the film growth rate is proportional to the square root of the angular velocity of the substrate ω. This relation presupposes that there

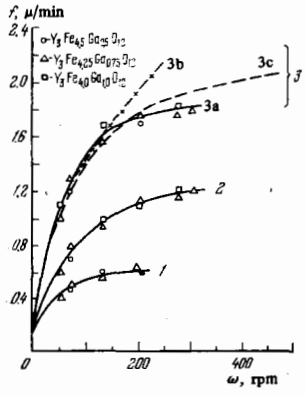

FIG. 5. Dependence of the film growth rate on the substrate rotation velocity in the melt for different values of the supercooling ΔT. 1—10 °C, 2—20 °C, 3—30 °C; 3a—experimental curve, 3b, 3c—theoretical curves calculated with the aid of the volume-diffusion model and the model that takes into account the mechanisms of diffusion and depletion of the particles, respectively.[72]

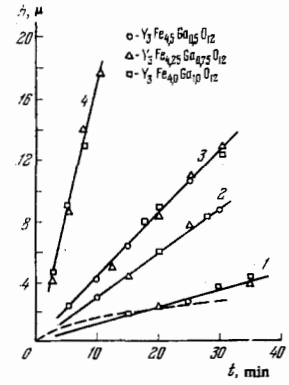

FIG. 6. Dependence of the film thickness on the growth time for different supercooling temperatures and for different substrate-rotation velocities. 1—ΔT = 30 °C, ω = 0; 2—10 °C, 70 rpm; 3—20 °C, 120 rpm; 4—25 °C, 300 rpm. The dashed line shows the theoretical dependence.[72]

is no film growth in the absence of rotation, and that when the speed of rotation increases the growth rate increases without limit.

Experiment has shown, however, that the film growth also in the absence of rotation, at a rate $f_0 = 0.1$–0.5 μ/min,[44,71,72] and when ω is increased the growth rate reaches saturation.[52,71,72,93,94] In addition, the initial growth goes through a transient stage in which the growth of the film is more intense.[94] To interpret the experimental data within the framework of the volume-diffusion model it is therefore necessary to subtract beforehand f_0 from each point of the $f(\omega)$ curve.

The epitaxial-growth process is more completely described by a model that takes into account the volume diffusion through a depleted boundary layer of thickness δ as well as the joining together of the growth particles to form a single crystal on the surface of the film, via a kinetic reaction of first order.[72,94] Figure 5 shows experimental plots of $f(\omega)$, and also curves 3b and 3c, theoretically calculated, respectively, with the aid of the volume-diffusion model and a model that takes into account both the diffusion and the joining of the particles.[72] A difference between the results obtained with the aid of the models and the experimental data sets in at $\omega \approx 140$ rpm. The lower experimental value of the upper limit of the growth rate, compared with the theoretical value, is attributed to the finite value of the volume of the melt in the crucible, a factor not accounted for in the calculation.

Figure 6 shows the experimental plots of the film thickness h against the growth time t.[72] The dashed

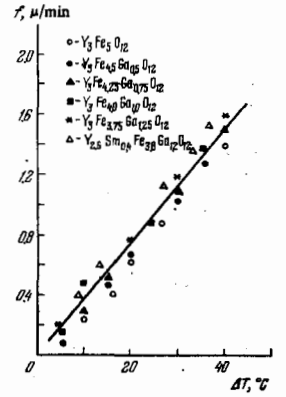

FIG. 7. Dependence of the film growth rate on the supercooling temperature (ω = 50 rpm).[72]

line shows a plot of $h(t)$ calculated in accordance with the second model.

An investigation of the dependence of the growth rate on the degree of supercooling (Fig. 7) has shown that it is linear and is approximately the same for films with different compositions of the system $(YSm)_3(FeGa)_5O_{12}$.[72]

4. QUALITY CONTROL OF PRODUCED FILMS

The quality of epitaxial garnet films depends primarily on the perfection of the substrates. Various inhomogeneities and defects on the substrate are inherited by the film, and give rise to local changes in the magnetic properties.[104] Defects are produced in the substrates during the course of the crystal growth or during the subsequent working (cutting, grinding, polishing, etc.). Work-induced defects, which constitute surface damage of varying types (scratches, etc.), are revealed by direct observation of the substrate surface. Growth defects (stresses, inclusions, growth striae and dislocations) can be observed by optical methods. Observation of an uncut crystal between crossed polaroids reveals the stress distribution. Examination of substrates under a polarization microscope in transmitted and reflected light makes it possible to observe impurities and dislocations.

Observation of substrates under a microscope, using phase contrast, makes it possible to observe the growth striae.

Another source of defects in epitaxial films is the absorption by the growing film, from the melt, of dissolved components from the solvent or from the substrate and the crucible. It is practically impossible to use in bubble devices films with defects, since the defects impede the motion of the domain walls. The interaction, observed with the aid of the Faraday effect, between domain walls and magnetic defects serves as the basis for a number of methods of their detection.[105–116]

To measure the "coercivity" of individual defects in materials with bubbles, a gradient field in the form $H_z = \beta x$ is used and is produced with a pair of electromagnets or a system of permanent magnets, which magnetizes two parts of the film to saturation perpendicular to its surface.[105–111]

If the inhomogeneous field gradient exceeds a certain critical value β_c, a flat domain wall aligns itself along the axis in the film and occupies a position corresponding to zero field.[106]

At $\beta = \beta_c$, a sinusoidal deflection from a straight wall becomes energywise favored. At $\beta < \beta_c$, a region with strip domains is produced.

If a defect is present in the film, then the domain is stopped by this defect when the sample is moved relative to the electromagnets and is lengthened by an amount ΔL_c (Fig. 8a). The "coercivity" of the defect is defined as

$$\Delta H_c = \frac{\Delta L_c}{L} H_{c0}, \qquad (5)$$

where L is the half-width of the region with the strip

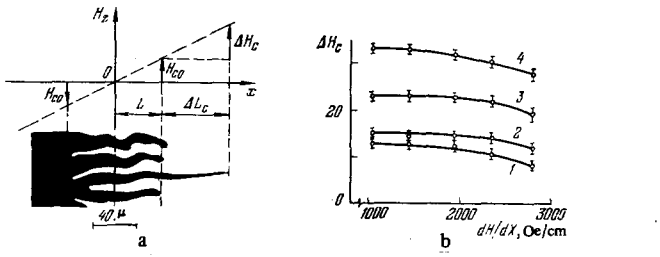

FIG. 8. A method of determining the "coercivity" of the defect[111] (a) and dependence of the "coercivity" of the defects on the field gradient in a film of composition $Y_{2,6}Sm_{0,4}Ga_{1,2}Fe_{3,8}O_{12}$ (b).

domains and H_{c0} is the field that must be applied in order to detach the domain from the defect.[109]

A typical dependence of the "coercivity" of defects in garnet films on the magnetic field gradient is shown in Fig. 8b.

The constancy of ΔH_c in the gradient interval 1000–2800 Oe-cm^{-1} attests to the fact that each defect is characterized by its own value of the "coercivity." The decrease of ΔH_c at large gradients can be due to inhomogeneity of the magnetic field.

Extensively used methods for revealing defects in garnets are based on visual observation of the domain motion in alternating bias fields.[108,112,113] The defects are identified as localized regions in which the domain walls are either pinned or their motion undergoes local changes. A more sensitive method was proposed in[114–118] and is based on continuous generation and propulsion of bubbles by an inhomogeneous field across the field of view of the microscope. The defects either stop the bubbles or change the character of their motion. Since the bubbles can be set in motion by a sufficiently low gradient field this method makes it possible to reveal weak defects.

For a complete understanding of the physical properties of epitaxial iron-garnet films it is necessary to know their chemical composition. Problems connected with a determination of the composition of garnet films are discussed in[117]. The principal difficulties are due to the small thickness of the films and to the fact that the same elements (Ga, Gd) are present in both the film and the substrate.

The best method of determining the chemical composition of garnet films is electronic microanalysis,[118] which makes possible local measurements, since the effective volume that emits the characteristic x radiation amounts to several cubic microns. The element content is determined from the characteristic FeK_α, GaK_α, CuK_α, YL_α, SmL_α, GeL_α, PbM_α, PbM_β and other emission lines. Pure rare-earth elements, Fe, G, Pb, and others serve as the standard, as well as various compounds $Y_3Fe_5O_{12}$, CaF_2, GaSb, GaP, etc. In first-order approximation, the content of the elements in a given sample region is defined as

$$C = \frac{(I_L - I_b)_{\text{sample}}}{(I_L - I_b)_{\text{stand}}}, \qquad (6)$$

where I_L is the intensity of the characteristic radiation and I_b is the intensity of the background. For a more accurate determination of the concentration, the following corrections are introduced:

$$C_i^* = C_i f(\tau) f(Z) f(\nu), \tag{7}$$

where C_i^* is the true concentration of the i-th element, $f(\tau)$ is the correction due to absorption of the x-rays in the sample, $f(z)$ is the correction for the atomic number, and $f(\nu)$ is the correction for the fluorescence. The absolute accuracy is ± 5% for all elements except Pb, for which the accuracy is ± 50%.[39]

For films containing not more than substituting ions, the composition can be determined by measuring the difference Δa between the film and the substrate lattice parameters, as well as the Neel temperature T_N, and by using the plots of Δa and T_N against the content of the substituting elements as calibration curves.[39,46,119,120] Account must be taken here, however, of the fact that the films contain Pb and Pt, which alter the lattice parameter and the Neel temperature.[46,55,93,121]

Since the magnetic properties of a garnet film are quite sensitive to its composition, it is important to know not only the basic elements contained in the film, but also the impurities, slight amounts of which can also be contained in the film. Such an analysis of the garnet films or of the initial materials can be carried out by emission spectroscopy, mass spectroscopy, chemical spectrophotometry, and fluorometry.[122,123]

The exact values of the lattice parameters of the film and of the substrate must be known in order to grow high-grade epitaxial films and to interpret their magnetic properties. An estimate of the degree of perfection of the crystal axis of the film and substrate, and measurements of their parameters, are carried out by standard x-ray structure analysis methods.[124,125] Such investigations were carried out in the Physics Department of the Moscow State University by the two-crystal-spectrometry method using a DRON-0.5 diffractometer CuK_α radiation, and a perfect Si crystal as a monochromator.[73] The half-width of the rocking curves for garnet films, indicated in Table I, was 10–17". Figure 9 shows by way of example the rocking curves for a film with composition $Y_{2.6}Sm_{0.4}Ga_{1.2}Fe_{3.8}O_{12}$ at different points of the surface. The curve of Fig. 9a has a half-width 15", while the curve of Fig. 9b reveals a superposition of reflections from two blocks with transverse dimension ~ 35 μ and a disorientation ~ 10" between the planes.

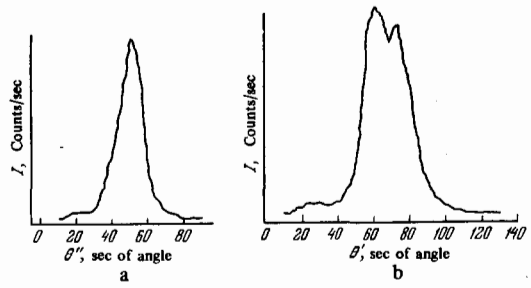

FIG. 9. Diffraction pattern of garnet film of composition $Y_{2.6}Sm_{0.4}Ga_{1.2}Fe_{3.8}O_{12}$ from different sections of the surface, obtained with DRON-0.5 diffractometer.

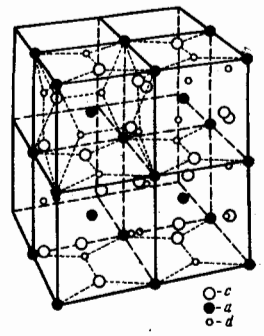

FIG. 10. Arrangement of the cations in the c, a, and d sites of four octants of the unit cell of the garnet.[126]

The difference Δa between the lattice parameters of the film and the substrate, measured with the aid of the DRON-0.5 diffractometer with accuracy 0.001 Å, is listed in Table I for the investigated compositions.

The crystallographic orientation of the films, determined with the URS-50I x-ray installation accurate to 15', agreed with the crystallographic orientation of the substrate.

5. BASIC PROPERTIES OF SINGLE-CRYSTAL GARNET FILMS AND METHODS OF THEIR INVESTIGATION

Iron garnets have a cubic structure and are characterized by a general formula $\{R_3^{3+}\}[A_2^{3+}](B_2^{3+})O_{12}$, where R^{3+} are the rare-earth and yttrium ions, while A^{3+} and B^{3+} are the ions Fe, Al, and Ga. The unit cell contains eight molecules (Fig. 10). The ions R are located in the dodecahedral interstices of the oxygen lattice, the A in the octahedral interstices, and the ions B in the tetrahedral interstices (in the c, a, and d positions, respectively). In the general case the garnet structure contains three crystallographically nonequivalent magnetic-ion sublattices, and the crystals are characterized by ferrimagnetic ordering.[7,126]

Although the iron garnets, being cubic crystals, do not have uniaxial anisotropy, when films of these garnets are epitaxially grown, uniaxial anisotropy is induced in them in the course of the growth or as a result of elastic stresses, because of the difference between the film and substrate lattice parameters. If the uniaxial anisotropy is large enough, then the magnetization in such films is directed normal to the plane of the film.

In the absence of an external magnetic field, materials with bubbles are in a demagnetized state, inasmuch as a structure of oppositely magnetized domains is produced in them. The configuration of the domain structure in the absence of external fields depends on the prior history of the sample and can constitute a labyrinth or herringbone structure made up of strip domains of equal thickness, a structure of linear strip domains, a hexagonal bubble lattice, an amorphous bubble of variable diameter, a lattice of elliptic and strip domains of finite thickness, etc. The most favored energywise,

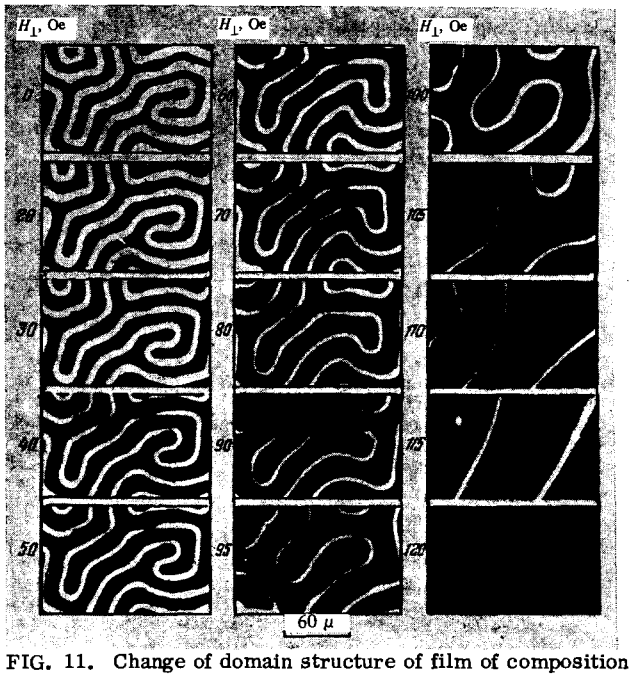

FIG. 11. Change of domain structure of film of composition $Y_{2.6}Sm_{0.4}Ga_{1.2}Fe_{3.8}O_{12}$ in a constant bias field perpendicular to the sample surface.[73]

in the absence of an external field, is the labyrinth domain structure (see Figs. 1 and 11). If a homogeneous quasistatic external field is applied to the sample normal to its plane, then the domains magnetized in the direction of the external field will increase in size at the expense of the "unfavorably" magnetized domains. With further increase of the field, the "unfavorably" magnetized domains will unbend and their number per unit area will decrease. At a certain critical field, the bubble structure becomes energywise more favored. However, no contraction of the strip domains into bubbles will take place if the ends of the strip domains are fastened to the edges of the sample. At the second critical value of the field, the domain structure vanishes, and a uniformly magnetized single-domain sample is produced.

The theory of the isolated bubble was developed in[1,127,128] on the basis of an analysis of the expression for its total energy, which consists of the domain-wall energy E_w, the energy E_H of interaction with the external field, and the magnetostatic energy E_M of the internal demagnetizing fields. The effective field of the wall H_w and the external field H_H tend to decrease the dimensions of the domain, while the demagnetizing field H_M increases the dimensions of the domain. The stable dimension of the domain is determined by the balance between these opposing tendencies. A detailed analysis[127,128] shows that a stable bubble exists in the range of external fields $H_e < H_b < H_0$, where H_0 is the bubble collapse field and H_e is the field of the elliptical instability of the bubble.

Single-crystal iron-garnet films are characterized by the following principal parameters: the absorption coefficient α, the specific Faraday rotation φ_F, the thickness h, the characteristic length l, the saturation

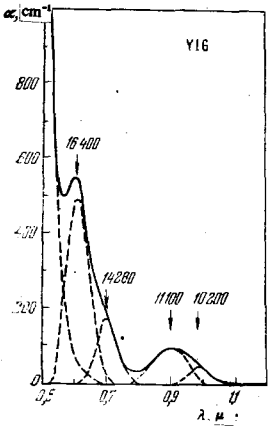

FIG. 12. Absorption coefficient for $Y_3Fe_5O_{12}$ in the visible and near infrared regions of the spectrum.[138]

magnetization $4\pi M_s$, the domain-wall energy σ_w, the uniaxial anisotropy constant K_u, the Neel temperature T_N, the coercive force H_c, the material quality factor q, the exchange constant A, and the domain-wall mobility μ.

The optical absorption is determined as a rule with the aid of standard two-beam spectrometers.[129] Investigations of the optical properties of garnets of different compositions were carried out in[18,19,130–144]. If no account is taken of the linear structure of the spectrum, which is connected with the rare-earth ions, the dependence of the absorption coefficient α on the wavelength is in the main the same for all garnets (Fig. 12).

The Faraday rotation can be measured most accurately with the aid of systems with polarization modulation.[145,146] The investigation of the singularities and the nature of the Faraday effect in garnets has been the subject of[131,140,143,144,147–166]. The specific Faraday rotation φ_F in non-substituted iron garnets, measured at a wavelength 1.15 μ, ranges from 20 deg/cm in $Y_3Fe_5O_{12}$ to 440 deg/cm in $Tb_3Fe_5O_{12}$.[165] The value of φ_F is influenced by both magnetic and diamagnetic substitutions.[18,144,158,166] Thus, introduction of Bi into the garnet greatly increases the Faraday effect,[11–16] which reaches 5×10^4 deg/cm in the visible band.

Giant Faraday rotation in Bi-containing garnet films is explained within the framework of the molecular-orbital model as being due to enhancement of the magneto-optical activity of the transitions under the influence of the Bi.[13,143,144,163] Figure 13 shows the values of the

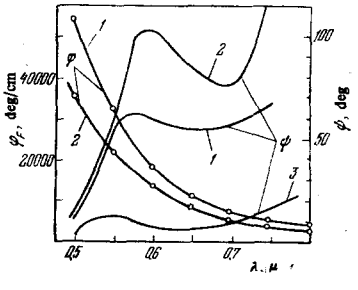

FIG. 13. Specific Faraday rotation φ_F and magneto-optical quality ψ in the visible region.[18] 1—$Y_{2.35}Bi_{0.65}Fe_{4.25}Al_{0.75}O_{12}$, 2—$Y_{2.05}Bi_{0.95}Fe_{3.9}\cdot Al_{1.1}O_{12}$, 3—$Y_3Fe_5O_{12}$.[18]

specific Faraday rotation φ_F and of the magneto-optical quality factor $\psi = 2\varphi_F/\alpha$ in the visible region for films with compositions $(YBi)_3(AlFe)_5O_{12}$ and $Y_3Fe_5O_{12}$.

The thickness h of garnet films is an important parameter, since in films having the same compositions the value of h determines the dimension of the bubble and the region of its stability with respect to a bias field normal to the plane of the sample.[127,128] In bubble devices containing several films, their thickness must not differ by more than 1 percent.[167] In addition, the value of h must be known for many magneto-optical methods of measuring other parameters of the films.

The most accurate method of measuring the thickness of garnet films is the interference method.[116,168–170] The interference pattern is produced by light reflected from the surface of the film and from the film–substrate interface (the refractive indices of the film and the substrate in the red part of the spectrum are respectively[168] 2.35 and 1.70). The motion of the interference fringes that pass through a fixed point on the film in succession is controlled by varying the wavelength λ of the incident light with the aid of a monochromator. The film thickness is calculated from the formula

$$h = \frac{N}{2}\left(\frac{n_1}{\lambda_1} - \frac{n_2}{\lambda_2}\right)^{-1}, \qquad (8)$$

where N is the number of fringes passing through a given point in the wavelength interval from λ_1 to λ_2; n_i is the refractive index of the film at the wavelength λ_i. The dispersion curves for a number of garnet films are given in[171].

The interference method is used to monitor the homogeneity of the film thickness. If h varies over the sample, then the interference pattern is observed in normally incident monochromatic illumination. The difference over the film thickness at points where neighboring dark fringes pass amounts to 0.1–0.15 μ in the visible region.

The characteristic length l, first introduced by Thiele[127,128] and defined as

$$l = \frac{\sigma_w}{4\pi M_s^2}, \qquad (9)$$

is a parameter connected with the characteristic dimensions of the domains in the given material. On the other hand, to determine the value of l it suffices to measure a certain domain dimension and the sample thickness.

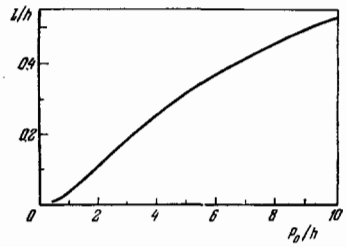

FIG. 14. Ratio of the characteristic length to the sample thickness vs. the ratio of the strip-domain-structure period in a zero field to the sample thickness.[175]

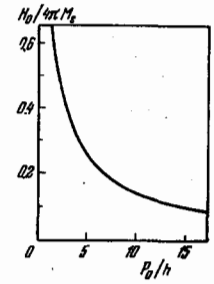

FIG. 15. Ratio of the bubble collapse field to the saturation magnetization vs. the ratio of the strip-domain-structure period to the sample thickness.[173]

The first method of determining the characteristic length[172] is based on measuring the diameter of the bubble in different bias fields and using the results of Thiele's theory.[127,128]

In the second method, the measured quantity is the period P_0 of the equilibrium strip domain structure in a zero bias field.[173–175] The value of l is calculated by using the results of the theory of strip-domain structures,[176,177] where the characteristic length l is a function of only the measured quantities P_0 and h. The results of the numerical calculation are shown in Fig. 14. The structure of straight-line domains that make it possible to measure P_0 with greater accuracy is produced with the aid of an alternating field in the plane of the film, the field amplitude being slowly decreased.

The saturation magnetization $4\pi M_s$ can be measured by a number of well developed methods,[178–181] many of which can be used to investigate garnet films. The main difficulty in the use of these methods is that the film occupies a much smaller volume than the bulky paramagnetic substrate.

The current induced in a coil by the motion of the magnetized sample was used by Geller *et al.*[126,182,183] to study garnets. In view of the superiority of resonance methods of signal amplification, a vibration magnetometer[184–187] is used to investigate garnet films.[188] A magnetized sample placed in a magnetic field whose direction does not coincide with the easy-magnetization axis is subjected to torsion. This effect is used in the torsion anisometer[189–191] to measure the magnetization and the magnetic anisotropy, particularly in garnets.[192–197] To determine the magnetization of thin garnet films, the most convenient are magneto-optical methods.[146,172–175,198–206] On the basis of Thiele's theory[127,128] the magnetization $4\pi M_s$ can be obtained, knowing l and h, for each pair of values of the applied bias field and of the diameter of the bubble situated in this field.[172]

Fowlis and Copeland[173] have proposed a simpler but less accurate method of calculating $4\pi M_s$, wherein the experimentally measured quantities were only the equilibrium period P_0 and the bubble collapse field H_0. The results of the numerical calculation are shown in Fig. 15. A simple analytic expression approximating this curve was obtained by Callen and Josephs.[105,206] A number of workers[146,174,201–204] determined $4\pi M_s$ by using hysteresis loops obtained with a Faraday hysteriograph.[146,198–200] The interpretation of the hysteresis loops in terms of $4\pi M_s$ is based on the theory of strip

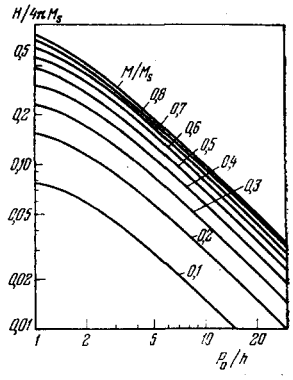

FIG. 16. Dependence of the relative value of the magnetic field $H/4\pi M_s$ on the ratio that must be applied to magnetize the sample to a definite value of M/M_s on the ratio P_0/h.[175]

domains.[176,177] The results of the numerical calculation are shown in Fig. 16. The determination of the saturation magnetization when P_0 and h are known reduces to a measurement of the fields corresponding to several fixed values of M/M_s and averaging the obtained data.

The magnetization $4\pi M_s$ can also be determined by a ferromagnetic resonance method.[207] A number of models have been proposed to explain the magnetic properties of iron garnets.[208–218] The magnetization of iron garnets with a general formula $\{R_3^{3+}\}[Fe_2^{3+}](Fe_3^{3+})O_{12}$ can be explained by extending the Neel molecular-field theory to include a ferrimagnet[219] with three sublattices.[208,209] The total magnetic moment per g-mole can be expressed in the form

$$M(T) = M_a(T) - M_d(T) + M_c(T), \tag{10}$$

where $M_a(T)$, $M_d(T)$, and $M_c(T)$ are the magnetization of the octahedral, tetrahedral, and dodecahedral sublattices, respectively.

Expression (10) presupposes that an antiferromagnetic interaction exists between the magnetic moments of Fe^{3+} in the d and a sites, and also between the magnetic moments of the resultant iron and rare-earth sublattices. Neel's 3-sublattice model was confirmed by neutron-diffraction investigations[220–222] and in experiments where the Mössbauer effect was used.[223]

In the general case we have

$$M_i(T) = M_i(0)\,B_{s_i}(z_i), \tag{11}$$

where $M_i(0)$ is the moment of the i-th sublattice at $T = 0$ °K, $B_{s_i}(2i)$ is the Brillouin function and

$$z_i = \frac{S_i g \mu_B}{kT} \sum_j N_{ij} M_j; \tag{12}$$

here N_{ij} are the molecular-field coefficients that describe the interaction between the i-th and j-th sublattices, μ_B is the Bohr magneton, k is the Boltzmann constant, $S_a = S_c = 5/2$ for Fe^{3+}, and $S_c = 7/2$ for Gd^{3+}.[218]

At $T = 0$ °K, the sublattice magnetizations can be expressed in the form:

$$\left.\begin{aligned} M_a(0) &= 2gS_a\mu_B N, \\ M_d(0) &= 3gS_d\mu_B N, \\ M_c(0) &= 3gS_c\mu_B N, \end{aligned}\right\} \tag{13}$$

where N is the Avogadro number. The values of the coefficients of the molecular fields for a number of garnets were determined in[209,217,218,224–228]. This model, however, does not explain the properties of garnets with more complicated composition. Geller[126,210] has proposed that in a substituted yttrium iron garnet the iron sublattices are not collinear. A statistical model that takes this effect into account has been developed in[211–216].

Dionne[217,218] used a semi-empirical analysis of the experimental $M_s(T)$ curves for garnets of the system $\{Y_zGd_{3-z}\}[R_xFe_{2-x}](Q_yFe_{3-y})O_{12}$, where R and Q are diamagnetic ions (Sc^{3+}, In^{3+}, Ga^{3+} and Al^{3+}) that replace the Fe ions in the a and d sites respectively ($0 \leq z \leq 3$, $x \leq 0.70$, $y \leq 1.95$), to determine the dependence of the molecular-field coefficients on the value of the diamagnetic substitution. Brandle and Blank[228] have extended the results of Dionne's calculations to include garnet systems with other rare-earth ions. Figure 17 shows the temperature dependence of the saturation magnetization for garnets of the system $Y_3[Fe_{2-x}Ga_x](Fe_{3-y}Ga_y)O_{12}$, as obtained by Hansen *et al.*[229] The solid lines show the theoretical curves calculated for the molecular-field coefficients taken from[217].

The domain-wall energy σ_w is one of the parameters that determine the dimension of the domains in a given magnetic material. The breakup of the sample into domain terminates when the gain in the magnetostatic energy due to the formation of smaller domains becomes less than the energy necessary to produce new domain walls. The energy density σ_w and the width Δ_w of a domain wall are determined by the value of the uniaxial anisotropy and by the exchange interaction in the given sample. The simplest domain wall realized in an iron garnet film is of the Bloch type, in which the spin flip on going from one domain to the neighboring one occurs in the plane of the domain wall. For such a domain wall we have

$$\sigma_w = 4\sqrt{AKu} \tag{14}$$

and

$$\Delta_w = \pi\sqrt{\frac{A}{K_u}}. \tag{15}$$

In practice, σ_w can be determined from (9) if l and $4\pi M_s$

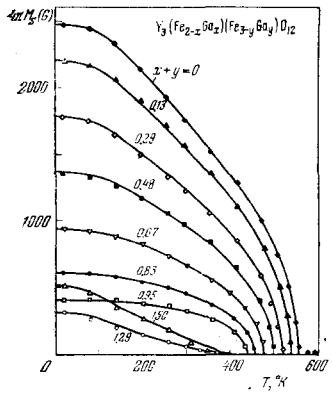

FIG. 17. Temperature dependence of the saturation magnetization $4\pi M_s$ of garnets of the system $Y_3[Fe_{2-x}Ga_x](Fe_{3-y}Ga_y)O_{12}$. The solid lines show the theoretically calculated curves.[229]

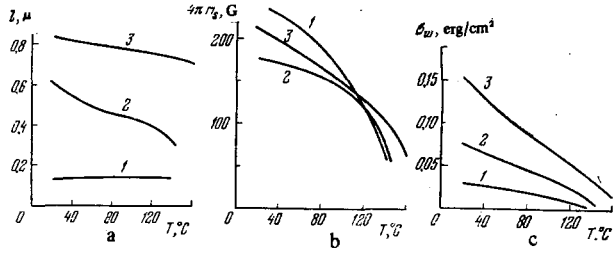

FIG. 18. Temperature dependence of the characteristic length l (a), of the saturation magnetization $4\pi M_s$ (b), and of the domain-wall energy σ_w (c) for garnet films of the systems $Y_3(FeGa)_5O_{12}$ (1), $(YGdYbBi)_3$ $(FeAlGa)_5O_{12}$ (12) and $(YSmGa)_3(FeGeSi)_5O_{12}$ (3).

are known. Other methods of calculating σ_w are considered in[230–232].

It should be noted that the theory of domain structures[127,128,176,177] has been developed for the case of strong anisotropy $H_K \gg 4\pi M_s$ ($\Delta_w = 0$) and for a homogeneous wall energy density σ_w. The influence of the finite anisotropy is discussed in[175,233–235]. The structure of the domain walls, with allowance for the effect exerted on it by the stray fields of surface charges, has been considered in[235–239].

Figure 18 shows by way of example the temperature dependences of the characteristic length l, the saturation magnetization $4\pi M_s$, and of the domain-wall energy σ_w in iron garnet films of the systems $Y_3(FeGa)_5O_{12}$, $(YGdYbBi)_3(FeAlGa)_5O_{12}$, and $(YSmGa)_3(FeGeSi)_5O_{12}$.

The Neel temperature T_N is assumed to be equal to the temperature at which the domain-structure contrast vanishes. T_N is determined more accurately from the abrupt change in the signal from a Faraday loop scope.[200,240]

The coercive force H_c has historically been defined as the half-width of the complete hysteresis loop. In garnet films, the most convenient method of measuring H_c is to plot the displacements S of the domain walls against the amplitude H of the alternating quasistatic magnetic field applied along the easy-magnetization axis,[116,206,241] since this method benefits from the advantages of using a selective amplifier. The value of H_c is obtained by linear extrapolation of the $S(H)$ curves to the intercept with the abscissa axis. Typical values of H_c for films with compositions $Y_{2.6}Sm_{0.4}Ga_{1.2}Fe_{3.8}O_{12}$, $Y_3Ga_{1.2}Fe_{3.8}O_{12}$, and $Y_3Ga_{1.0}Fe_{4.0}O_{12}$ are 0.35, 1.1, and 1.8 Oe respectively (Fig. 19). X-ray spectral investigations have shown that H_c is connected with the defect density in the film.[73]

Magnetic anisotropy. Since garnets are cubic-crystals, the dependence of the energy on the direction of the magnetization, in the absence of other factors, is described by the expression[242]

$$E = K_1(\alpha_1^2\alpha_2^2 + \alpha_2^2\alpha_3^2 + \alpha_3^2\alpha_1^2) + K_2\alpha_1^2\alpha_2^2\alpha_3^2 + \ldots; \quad (16)$$

here α_i are the direction cosines of the magnetization, and K_1 and K_2 are the crystallographic anisotropy constants. Pearson[192,194] measured K_1, and where possible K_2, for a number of garnets. Since usually $K_1 < 0$, the easy magnetization direction is ⟨111⟩.

In single-crystal garnet films one observes a uniaxial anisotropy of considerably larger magnitude than the crystallographic anisotropy. This noncubic anisotropy is produced in the growth process[48,243–252] or as a result of stresses due to the disparity between the lattice parameters of the film and the substrate.[168,199,253–255] This anisotropy can be expressed in the form

$$E = K_{u1}\sin^2\theta + K_{u2}\sin^4\theta + \ldots; \quad (17)$$

here θ is the angle between the magnetization and the easy axis. The total anisotropy energy of garnets is described in the general case by the sum of expressions (16) and (17). Of practical importance is the energy difference, designated K_u, between the direction of the normal to the film plane and the direction of the lowest energy in the plane, since this difference determines the stability of the bubble. Associated with the uniaxial anisotropy constant is the anisotropy field H_K:

$$H_K = \frac{2K_u}{M_s}. \quad (18)$$

The magnetic anisotropy can be investigated with a torsion anisometer,[84,256–259] with a magnetometer with rotating sample,[260–262] and by the ferromagnetic resonance method.[168,207,255,263–269] A number of magneto-optical methods, based on direct observation of the domain structures[270–275] or on the measurement of the Faraday rotation,[208,276–280] are also employed. The theoretical basis of these methods is an analysis of the expression for the energy of a sample with a strip-domain structure, written down for the case when the plane of the film coincides with the (111) crystallographic plane, and when the magnetic field in the plane is applied along one of the directions ⟨110⟩ or ⟨112⟩.

Kurtzig and Hagedorn[270] have observed the domain structure following application of a constant field $H_\perp$ in the plane of the film. The value of H_K was assumed equal to the value $H_\perp^*$ at which the domain-structure con-

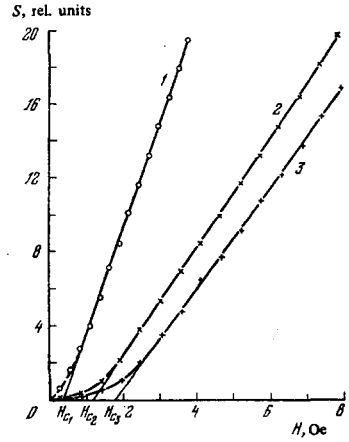

FIG. 19. Dependence of the displacement of the domain walls on the amplitude of the alternating magnetic field in films with compositions: 1—$Y_{2.6}Sm_{0.4}Ga_{1.2}Fe_{3.8}O_{12}$, 2—$Y_3Ga_{1.2}Fe_{3.8}O_{12}$, 3—$Y_3Ga_{1.0}Fe_{4.0}O_{12}$.[241]

trast vanishes. It was shown in[271,273] that $H_\perp^*$ is always smaller than H_K, and nonlinear relations between these quantities were derived. The value of $H_\perp^*$ depends on the orientation of the field in the film plane, this being due to the influence of the cubic anisotropy[272-274] or to inclination of the magnetic-anisotropy axis.[63,274,275,281,282] The error in the determination of H_K by this method, due to the cubic anisotropy, is negligible if the field in the plane of the film is directed along the ⟨110⟩ axis and $K_1/K_u < 1$.[273]

Hubert *et al.* (see[274,275]) have developed a procedure that makes it possible to determine the cubic, uniaxial inclined, and orthorhombic components of the anisotropy by measuring the azimuthal dependence of the critical fields of homogeneous nucleation in garnet films. The nucleation was regarded as homogeneous if the residual domain structure left after the saturating field in the $H_\perp$ plane and the bias field $H_\parallel$ are decreased to zero, consists of an equal number of bubbles of both polarities.

Krumme *et al.*[276-277] have proposed a method for the local measurement of K_u and K_1 in garnet films. They registered in the experiment the dependence of the Faraday rotation φ_F on the external fields $H_\perp$ and $H_\parallel$. The direction of $H_\perp$ coincides with the $\langle 11\bar{2}\rangle$ axis, so that the magnetization was always in the (110) plane. Josephs[206] measured the longitudinal susceptibility $\chi_\parallel$ at $H_\parallel = 0$ in strong fields $H_\perp$. If $H_\perp$ is directed along the ⟨110⟩ axis, then[278]

$$\chi_\parallel = \frac{M_s}{H_\perp - H_K''} \quad (H_\perp > H_K''), \tag{19}$$

where

$$H_K'' = \left(\frac{2K_u + K_1}{M_s}\right) - 4\pi M_s \equiv H_K - 4\pi M_s. \tag{20}$$

The shape of the $\chi_\parallel(H_\perp)$ curves depends strongly on the accuracy with which the sample plane is oriented relative to the direction of the field $H_\perp$.

Shumate *et al.*[278,279] measured $\chi_\parallel(H_\perp)$ in the presence of a constant bias field $H_\parallel$ sufficient to saturate the sample. The field $H_\perp$ at which the susceptibility $\chi_\parallel$ is maximal was identified as $H_K - 4\pi M_s$. The position of the maximum of $\chi_\parallel(H_\perp)$ depends actually on the value of $H_\parallel$. Shumate *et al.*[278,279] calculated a correction curve to account for this effect. They have also demonstrated the possibility of crystallographically orienting the sample by a magnetic method. An improved magneto-optical method for local measurements of the cubic and uniaxial anisotropy in garnet films is described in[280]. The experiment consisted of measuring the transverse susceptibility $\chi_\perp$ as a function of the field $H_\perp$ applied along the ⟨112⟩ axis. The measurements were made at positive and negative $H_\perp$. To improve the signal/noise ratio, the polarization was modulated. The domain wall walls and the instabilities of the configuration of the homogeneous magnetization[231] were suppressed by a sufficiently strong bias field $H_\parallel$. The $\chi_\perp(H_\perp)$ curve has extrema at both signs of $H_\perp$. The asymmetry of the peaks makes it possible to determine the ratio K_1/K_u, and from their position one can determine the values of these constants. In addition, by recording the function $\chi_\perp(H_\parallel)$ at $H_\perp > H_K$ it is possible to determine K_1 independently.

The quality factor q is defined as

$$q = \frac{H_K}{4\pi M_s}. \tag{21}$$

Bubbles exist in iron-garnet films under the condition $q > 1$, for only in this case is the domain magnetization directed perpendicular to the plane of the sample.

The exchange constant A can be determined from expression (14) for the Bloch-wall energy.[283-285] Relations (9) and (18) can be used to express the constant A as a function of l, $4\pi M_s$, and H_K. The difficulty of calculating A by this method lies in the fact that small errors in the determination of l and $4\pi M_s$ lead to a large error for A.

In a number of papers, the exchange constant of the iron garnets was assumed to be proportional to their Neel temperature.[48,224,286-288] The standard was taken to be the value of A for yttrium iron garnet, taken at $T = 0$ °K ($A_{YIG} = 5.55\times10^{-7}$ erg/cm^2) or at room temperature ($A_{YIG} = 4.15\times10^{-7}$ erg/cm^2). This approach, however, excludes the temperature dependence of the exchange constant.[283] A simple theory explaining the temperature dependence was developed in[284]. The value of A can also be determined from data on spin-wave resonance.[288]

Ferromagnetic resonance (FMR) consists of resonant absorption of energy by a ferromagnet from an external electromagnetic field; it is described in terms of the precession of the total magnetic moment **M** of the sample about the direction of the applied magnetic field **H**, with the aid of the Landau–Lifshitz equation

$$\frac{\partial \mathbf{M}}{\partial t} = -\gamma[\mathbf{M}\times\mathbf{H}] - \frac{\lambda}{M^2}\gamma[\mathbf{M}\times[\mathbf{M}\times\mathbf{H}]] \tag{22}$$

or the Gilbert equation

$$\frac{\partial \mathbf{M}}{\partial t} = -\gamma[\mathbf{M}\times\mathbf{H}] + \frac{\alpha}{M}\left[\mathbf{M}\times\frac{\partial \mathbf{M}}{\partial t}\right]; \tag{23}$$

Here $\alpha = \lambda/\gamma\mathbf{M}$ is the Gilbert dimensionless damping parameter, λ is the Landau–Lifshitz damping parameter, and γ is the gyromagnetic ratio.

The resonance condition is

$$\omega_{res} = \gamma H_{eff}, \tag{24}$$

where the effective field H_{eff} depends in the general case on the symmetry of the crystal, on its internal structure, on the shape of the sample, on the magnitude and the direction of its magnetization, and on the orientation of the external magnetic field relative to the crystallographic axis and the surfaces that bound the sample.[280,290] In the simplest case of perpendicular resonance, when the static magnetic field is applied normal to the plane of the film and the microwave field is applied in the plane of the film, the effective field H_{eff} is a sum of three terms: the external magnetic field H, which is sufficient to saturate the sample, the demagnetizing field $-4\pi M_s$ due to the magnetic poles on the sur-

face of the film, and the anisotropy field H_K.[168,207,291-294]

Ferromagnetic resonance makes it possible to determine the values of $4\pi M_s$, γ, and H_K if several microwave frequencies or several orientations of the external magnetic field are used.[289-291] The value of H_K can also be obtained by measuring the angular dependence of the resonant field of the principal peak.[207,290] By measuring the width ΔH of the resonance curve one can determine the damping parameters α and λ.[59,290]

Magnetostriction in materials with bubbles is one of the causes of the appearance of uniaxial anisotropy.[49,168] The magnetostriction in materials with cubic symmetry is given by[242]

$$\frac{\Delta l}{l}=\frac{3}{2}\lambda_{100}\left(\alpha_1^2\beta_1^2+\alpha_2^2\beta_2^2+\alpha_3^2\beta_3^2-\frac{1}{3}\right)+3\lambda_{111}\left(\alpha_1\alpha_2\beta_1\beta_2+\alpha_2\alpha_3\beta_2\beta_3+\alpha_3\alpha_1\beta_3\beta_1\right), \tag{25}$$

where $\Delta l/l$ is the relative change of the dimensions in a direction specified by the direction cosines β_i; α_i are the direction cosines of the magnetization vector; λ_{111} and λ_{100} are the magnetostriction constants.

The values of λ_{100} and λ_{111} can be determined by the ferromagnetic resonance method by measuring the resonant-field shift due to uniaxial compression.[263,295-297]

The dynamic properties of ferrites are characterized by the mobility μ of the domain walls, defined as

$$\mu=\frac{v}{H-H_{st}}, \tag{26}$$

where v is the wall velocity under the influence of the field H; $H_{st}\approx H_c$ is the starting field. In iron-garnet films, however, proportionality of the wall velocity to the driving field was observed only at small field amplitudes. At large driving-field amplitudes the dependence of v on $H-H_{st}$ deviates as a rule from linear and reveals a saturation effect.[29,298,299]

Attempts to connect the mobility with other parameters of the material were undertaken in[299-301]. One of the relations that is best satisfied is the proportionality of the mobility to the domain-wall width Δ_w[300]:

$$\mu=\frac{\gamma}{\pi\alpha}\Delta_w. \tag{27}$$

Expression (27) illustrates the important role played by measurement of the domain-wall mobility in investigations of the nature of the processes of damping in magnetic materials. The present lack of a fundamental theory for the calculation of the damping parameters does not make it possible to predict the dependence of μ on other parameters of the material.

A convenient object for both a theoretical and experimental investigation of the dynamics of domain walls is a flat domain wall. The displacement x of such a wall under the influence of a field H applied along the easy magnetization axis can be described by the equation

$$m\ddot{x}+\beta\dot{x}+kx=2M_sH, \tag{28}$$

where m is the effective mass of the wall, β is the viscous-friction coefficient, and k is the constant of the quasielastic restoring force. This equation is used in the investigation of the motion of domain walls in alternating or pulsed magnetic fields. The motion of the domain walls with allowance for their mass was investigated in[57,302-308] where, in particular, a dependence of the domain-wall mass on the constant magnetic field applied in the plane of the film was observed. Inertia effects can be neglected in the description of the domain-wall motion in materials with moderate mobility.[309-311]

A number of methods have been developed to measure the mobility μ in garnets.[309-319] The authors of[311,312] determined μ by measuring the real and imaginary parts of the susceptibility in small three-dimensional garnet crystals with the aid of a modified FMR installation.

Seitchik *et al.*[309] registered by a photoelectric method the relaxation time of domain walls of strip domain structure into a new equilibrium position following the action of a steplike bias field. The wall displacement was determined by a stroboscopic method. Kleparskiĭ *et al.*[310] have proposed to determine the numerical values of the domain-wall displacement from the fact that the maximum displacement is equal on the average to half the initial domain width. The method of[309,310] was used in[73,304-308,320-323] to investigate the dynamic properties of domain walls in garnet films.

In a number of studies[313-315,324-326] the mobility μ was determined by investigating the motion of the domain walls in an alternating magnetic field.

Bobeck *et al.*[316] have proposed a bubble-collapse method for the determination of the mobility, in which the measured quantities were the amplitude H_p and the duration τ_p of the field pulse that must be applied to collapse a bubble situated in a bias field H_b. The mobility μ was determined with the aid of a plot of τ_p^{-1} against H_p. The radius of the dynamic collapse of the bubble, the value of which must be known to calculate the displacement of the domain wall, was assumed to be half the radius of the static bubble collapse. A detailed analysis of the method, including certain approximations, was presented in[205,327].

The simplicity of the bubble-collapse method has caused it to be extensively used.[17,84,298,318,320,328-333] Some shortcomings of this method are discussed in[334].

Vella-Coleiro and Tabor[317] have proposed a method of measuring the mobility μ, based on the displacement of an isolated bubble under the influence of a pulsed field gradient produced by a pair of linear conductors. The bubble velocity was assumed equal to the ratio of the distance S traversed by the bubble under the influence of a gradient-field pulse to the duration τ_p of this pulse. The bubble-translation method[317] was used in an investigation of the dynamic behavior of bubbles in[29,50,73,84,90,321,335-348]. Figure 20 shows a plot of the velocity of a bubble of 12 μ diameter against the driving field in a film with composition $Y_{2.6}Sm_{0.4}Ga_{1.2}Fe_{3.8}O_{12}$.

The use of high-speed laser photography[349] for direct observation of the position of a bubble in the course of its motion has shown that the bubble can move "by iner-

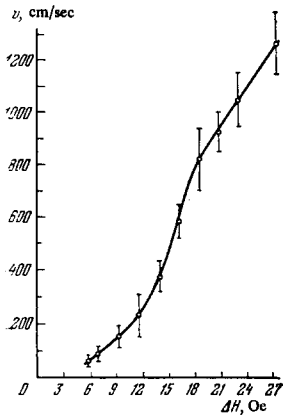

FIG. 20. Dependence of the CMD velocity on the bias-field drop along its diameter in a film of composition $Y_{2.6}Sm_{0.4}Ga_{1.2}Fe_{3.8}O_{12}$. The vertical lines show the scatter of the experimental data obtained in a series of ten repeated measurements.

tia" after the termination of the field gradient pulse.[350-352] In particular, in[350] the bubble was displaced 3.7–4.5 μ in a time $\tau_p = 0.5$ μsec, whereas the total displacement was equal to 6.4–13.2 μ. It was also observed that the shape of the bubble changes during the course of its motion.[350-354]

Zimmer *et al.*[318] used high-speed photography to determine the radial velocity of domain walls that move under the influence of a pulsed homogeneous field.

At the Physics Department of the Moscow State University, a magneto-optical installation was developed for the study of the dynamic behavior of domain structures, making use of an electron-optical converter to enhance the brightness of the image[355,356] and making it possible to register high-speed photographs of the dynamic domains and time sweeps (chronograms) of the bubble image.[319] Registration of the bubble chronograms make it possible, by applying a single field pulse, to determine the time dependence of the bubble diameter and by the same token the radial velocity of its domain walls, whereas the method of high-speed photography yields only the bubble diameter at a certain instant of time. Figure 21 shows photographs of chronograms of the bubble image in a film of composition $(YGdYbBi)_3(FeAlGa)_5O_{12}$ under the influence of magnetic-field pulses of various amplitudes, applied at the instant of time $t = 0$.[319]

An investigation of pulsed magnetization of iron-garnet films has shown that this process begins with motion

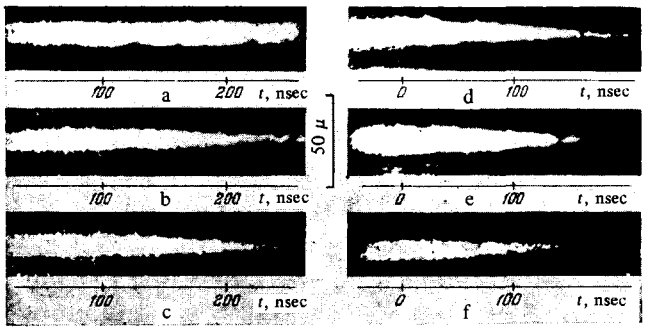

FIG. 21. Time scans of bubble image for field pulses of various amplitudes. H_p (Oe) = 0 (a), 100 (b), 400 (c), 600 (d), 800 (e) and 1,000 Oe (f) in a film of composition $(YGdYbBi)_3(FeAlGa)_5O_{12}$ ($h = 20$ μ, $4\pi M_s = 175$ G, $H_0 = 120$ Oe). The bias field is 100 Oe.[319]

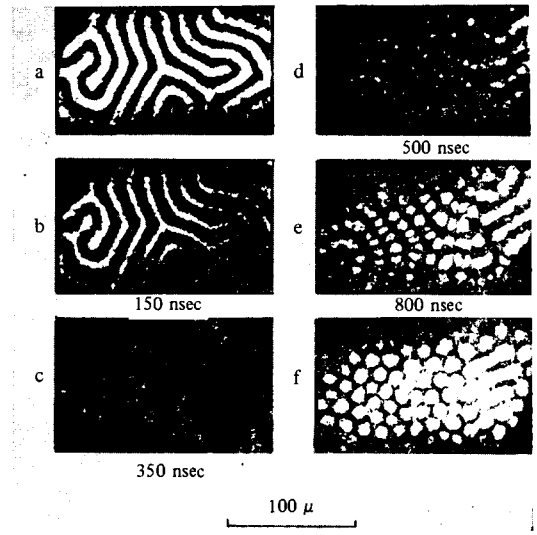

FIG. 22. Initial (a), dynamic (b—e), and resultant (f) domain structures following application of a field pulse of amplitude $H_p \approx 500$ Oe and duration $\tau_p \approx 400$ nsec in a film of composition $(YGdYbBi)_3(FeAl)_5O_{12}$ ($h = 15$ μ, $4\pi M_s = 190$ G, $H_0 = 141$ Oe). The numbers indicate the instants of registration of the dynamic domains relative to the instant of application of the pulse.[319]

of the domain walls, in which alternate sections move with different velocities.[319] The difference between the velocities of the "slow" and "fast" sections leads to formation of discontinuities in the "inconveniently" magnetized domains. If the action of the magnetization-reversing pulse is stopped before the regions produced after the break of the domains are completely remagnetized, then the dimensions of these regions begin to increase, as a result of which a bubble lattice is produced. Figure 22 shows photographs illustrating the formation of a bubble lattice in a film of composition $(YGdYbBi)_3(FeAl)_5O_{12}$.[319]

In the case of sufficiently rapid expansion or contraction of strip and cylindrical magnetic domains in garnet films, unique dynamic configurations are produced,

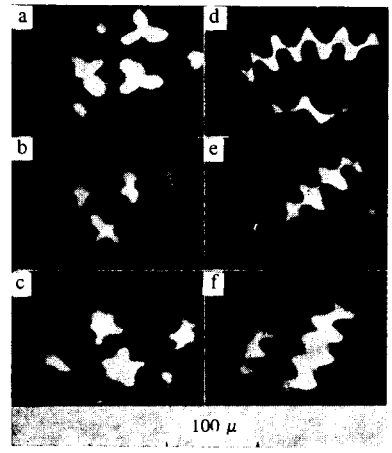

FIG. 23. Dynamic configurations in a film of the system $(YGdYbBi)_3(FeAlGa)_5O_{12}$, produced at the instant of time t after the action on the bubble (a—c), and strip domains (d—f) of a field pulse with amplitude H_p and duration $t_p = 2$ μsec, a) $H_p = 43$ Oe, $t = 1.8$ μsec; b) 63 Oe, 2.0 μsec; c) 75 Oe, 2.2 μsec; d) 65 Oe, 1.6 μsec; e) 122 Oe, 2.2 μsec; f) 132 Oe, 1.6 μsec.

which are not observed under static conditions.[319,358-362] Figure 23 shows by way of example photographs of such configurations, observed in a film of composition $(YGdYbBi)_3(FeAlGa)_5O_{12}$ in the course of radial expansion of strip domains in bubble under the influence of a pulse of a homogeneous magnetic field.

High-speed photography was used in[363,364] to investigate the topological switching of bubble lattices,[315,325] and for the study of the motion of bubbles in an inhomogeneous field.[365,366]

A theoretical description of the motion of domain walls is the subject of[300-302,328,367-392]. The theory of mobility of straight and cylindrical domain walls was initially developed on the basis of a solution of the Landau–Lifshitz–Gilbert (LLG) Eqs. (22) and (23).[300,367] For an isolated domain wall moving in an infinite medium, assuming a constant wall thickness, a linear dependence of the wall velocity on the field amplitude was obtained.[205,334,368]

Walker[369] has shown that for a Bloch wall in bulky materials there exists an exact solution of the LLG equation, if the effective field does not exceed the critical value $H_w = 2\pi\alpha M_s$. In weak fields $H < H_w$ the wall velocity is proportional to the effective field, and the mobility μ is determined by expression (27). With increasing velocity, however, the wall becomes compressed and saturation of the velocity takes place in strong fields. In fields exceeding H_w, the wall motion has an oscillatory character. A numerical solution for a Bloch wall was given in[370-375]. In films of materials with bubbles, however, the interaction of the domain wall with the stray fields, which inevitably arise because of the proximity of domains whose magnetization is directed normal to the plane of the sample, leads to a more complicated structure of the domain wall. Since the stray fields vary with distance from the surface, the wall configuration depends at least on two parameters (Fig. 24).

An exact solution of the LLG equation for such a wall is difficult. A reasonable approximation, which makes it possible to simplify the expressions is given by Slonczewski[376-380] for the case $q \gg 1$ and not too thin a film. These requirements are satisfied more or less for materials with bubbles. In Slonczewski's theory, the problem reduces to an ordinary albeit nonlinear differential equation with boundary conditions and a certain angle χ as the argument. Calculations for the other extremal case of thin films are given in[238,381].

The argument χ describes the local character of the domain structure: $\chi = 0$ denotes a Bloch wall and $\chi = 90°$ a Neel wall. It is assumed that a Bloch wall is observed at least at the center of the film, whereas the stray fields lead to a Neel orientation near the surface of the film. The transition between the two orientations can take place by a simple rotation (case of a "light" wall); the magnetization at the center of the wall can experience one or more additional rotations on going from one surface of the film to the other ("heavy" wall).[237] Such additional transitions are localized in the so-called horizontal Bloch lines (HBL).

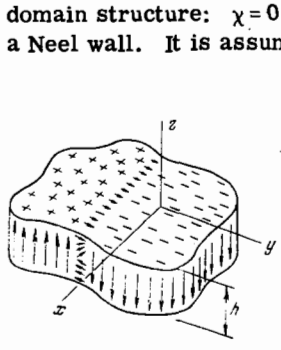

FIG. 24. Model of domain-wall structure in films of materials with bubbles.[382]

It is universally accepted at present that the dynamic conversion of the "light" wall into a "heavy" wall is responsible for the relatively low maximal velocities that can be obtained in iron-garnet films.

Using the obtained approximate differential equation, Slonczewski[377-379] has shown that the stray fields from surface poles destabilize the structure of the wall at critical values of the velocity v_p lower than the Walker limiting velocity v_w and of the driving field H_p. It was next shown in the theory that for a straight wall in fields $H > H_p$, generation, motion, and annihilation of HBL takes place, as a result of which the wall velocity decreases asymptotically to the limit $v_0 \approx 0.3 v_p$.

Further development of the theory is the subject of[380-382], where it is assumed that the "heavy" domain wall contains, besides the moving HBL, stationary vertical Bloch lines parallel to the cylindrical axis of the bubble. The model explains qualitatively the dynamic transformation of the domain walls. An important role is assigned here to the interaction of the moving domain wall with different inhomogeneities in the sample. The results were adapted to a cylindrical wall. It was shown that VBL tend to form a cluster on one side of the bubble, and when the bias field is varied the centers of the bubble and of the cluster move along a spiral trajectory.

The profiles, effective masses, energies, and critical velocities for the "light" and "heavy" (with HBL) domain walls were obtained in[383,384] by numerical solution of the differential Slonczewski equation for static and for stationarily moving domain walls. One of the conclusions resulting from the analysis of the character of the instabilities at critical velocities is that dynamic grouping of HBL is impossible for the film thickness interval that is favorable for bubble devices.

The difficulty of comparing the theoretical results with the experimental data lies in the fact that for materials of practical interest the critical field H_p is comparable with the coercive force. To increase the critical field H_p, Malozemoff[336] introduced into the composition of the garnet film a small amount of terbium, which has the largest damping from among all the rare-earth ions in the garnet, and obtain good agreement between the experimental data and the result of Slonczewski's theory. Other investigations[57,304,308,318,393-399] carried out on materials with moderate and weak damping ($\alpha < 0.05$) have shown a less satisfactory agreement with the theoretical results.

"Hard" bubbles were first investigated by Tabor *et al.*[397] The most distinguishing features of the behavior of the "hard" bubbles are the following: the existence of a wider stability range with respect to variation of

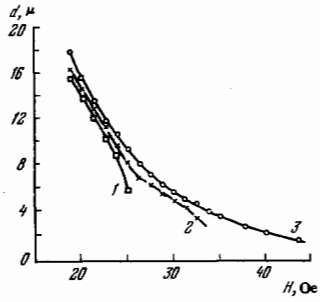

FIG. 25. Dependence of bubble diameter on the bias field for three domains in a film $Y_{2.6}Sm_{0.4}Ga_{1.2}Fe_{3.8}O_{12}$.

the bias field and of the CMD diameter; the direction of motion of these bubbles makes an angle up to 90° with the direction of the gradient of the effective field; their mobility is much lower than that of "normal" bubble. Figure 25 shows the dependence of the bubble diameter on the bias field; curve 1 was obtained for a "normal" bubble and the other for domains with different "hardness." The measurements were performed in the entire range of stability of the bubble. Figure 26 shows the results of an investigation of the dependence of the velocity (total, the components normal and parallel to the direction of the gradient, and their ratio) on the bias-field drop along the diameter of a "hard" bubble in a film with composition $Y_{2.6}Sm_{0.4}Ga_{1.2}Fe_{3.8}O_{12}$.

The magneto-optical characteristics of the "normal" and "hard" bubble are the same, so that it is natural to assume that the difference between them lies in the structure of the domain walls. A model of the domain wall of a "hard" CMD was proposed in[397–399] and is based on the assumption that the wall consists of oppositely magnetized Bloch segments separated by Neel segments (the so-called vertical Bloch lines (VBL)). The repulsion force between the VBL increases the bubble diameter[349,400–403] and stabilizes the dumbbell-like domains.[349,404] The motion of the VBL decreases the mobility of the domain wall.[320,349,403–405] The gyrotropic forces of the VBL deviate from the direction of the gradient of the applied field as they move the bubble.[336,349,391,401–405] The angle at which the bubble is displaced relative to the gradient is given by[349]

$$\sin\rho = \frac{2v}{\gamma r^2 \Delta H} n_r, \tag{29}$$

where n_r is the number of rotations through an angle 2π which the magnetization vector executes on going along the perimeter of the wall in a definite direction, r and v are the radius and velocity of the bubble, and H is the field gradient. The number of the VBL is equal to

$$n = 2(n_r - 1). \tag{30}$$

The need for theoretically explaining the experimentally observed dynamic transformation of the bubble[321,326,339,345–354,366,406–410] has made it necessary to postulate the existence in the domain-wall structure of not only vertical but also horizontal Bloch lines.[328,377–380] The generation, motion, and annihilation of the VBL and HBL are the causes of the change in the character of the dynamic behavior of the bubble.

A study of the structure of domain walls is possible only by Lorentz microscopy which, unfortunately, cannot be applied to garnet films because of the relatively large thickness of the film with the substrate. VBL were actually observed in thin films of cobalt.[408] A weighty argument favoring the existence of VBL in the structure of the bubble walls is provided by the observation, by the powder method, of different types of flat domains connected with bubble in a permalloy layer sputtered over a garnet film.[340–342]

It is practically impossible to use "hard bubble" in domain memory and logic devices. To suppress the "hard bubble," a number of methods have been developed,[409–414] the main idea being to produce a domain-wall structure such that the existence or formation of VBL in it is unfavored. This can be attained with the aid of an additional magnetic layer produced in two-layer garnet films,[409–411] formed as a result of ion implanation[346,412,415–418] or as a result of coating the film with a permalloy layer.[340–342,413,414] The suppression of "hard" bubble took place also in garnet films after they were annealed in an inert atmosphere[416] and in films whose easy axis is not perpendicular to their plane.[419]

6. REPRODUCIBILITY AND TEMPERATURE STABILITY OF THE PRINCIPAL MAGNETIC PARAMETERS OF GARNET FILMS

For information reduction and storage devices it is necessary to have at present single-crystal iron-garnet films with bubbles having the parameters[46,167] listed in Table II.

Satisfaction of the first three requirements is determined mainly by the choice of the film composition, the quality of the substrate finish, and the growth procedure and conditions.

The collapse field H_0 and the saturation magnetization $4\pi M_s$, and also the film lattice parameters can be var-

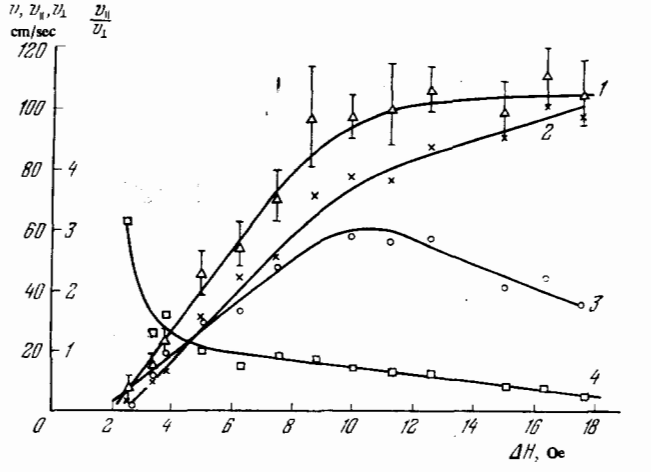

FIG. 26. Dependence of the velocity of a "hard bubble" of diameter $d = 8\ \mu$ on the bias-field drop along its diameter. 1—total velocity (the vertical lines show the scatter of the experimental data obtained in a series of repeated measurements), 2—component $v_\perp$ normal to the direction of the gradient; 3—component $v_\parallel$ parallel to the direction of the gradient, 4—$v_\parallel/v_\perp$.

TABLE II

Bubble diameter, d	6 μ
Thickness h	6 μ, homogeneity ± 1%
Defect density	< 5 cm^{-2}
Collapse field H_0	100 Oe, reproducibility ± 1%
Coercive force H_c	0.3 Oe
Quality factor q	> 1.5
Mobility μ	200 cm · sec^{-1} Oe
Shape and dimension of bubble	Should not depend on the temperature.

ied by introducing into the garnet composition the ions Ga^{3+} and Al^{3+} or a combination of the ions Ca^{2+}, Ge^{4+}, or Si^{4+}. The value of H_0 can be regulated by annealing,[420,421] by chemical polishing,[422,423] or by reheating the melt.[65]

Attempts to satisfy simultaneously the remaining requirements encounter certain difficulties.[46,299,424] As follows from expressions (15) and (27), the mobility μ can be increased by increasing A and γ and by decreasing α and K_u. It is permissible to decrease K_u within certain limits, inasmuch as the quantity q is simultaneously decreased and the bubble becomes less stable. It is possible to increase μ at the expense of A only in a small range, since the exchange constant depends little on the composition of the garnet. The obtained iron-garnet films with small values of α had indeed a high mobility,[46,47] but were subject to the action of another mechanism that limits the velocity of the domain walls, due to the dynamic transformation of their structure. It turned out that the mobility of the domain walls and the maximum possible velocity can be increased in garnet films by using an iron garnet with a large effective g-factor.[338] The value of g in garnets is defined as[425,426]

$$g = (M_R + M_{Fe})\left(\frac{M_R}{g_R} + \frac{M_{Fe}}{g_{Fe}}\right)^{-1}, \qquad (31)$$

where M_R and M_{Fe} are the magnetization of the rare-earth and summary iron sublattices; g_R and g_{Fe} are the g-factors of the rare-earth ion and the iron ion. If we include in the composition of the garnet Eu, which has $J = 0$ in the ground state and consequently $g \gg 2$, and attain $M_{Fe} \to 0$ by replacing Fe^{3+} with diamagnetic ions, then we can obtain a value $q > 30$.[426] The saturation magnetization in the case when $M_{Fe} \to 0$ is different from zero, since Eu has an intrinsic magnetic moment.

A number of garnet films that can be used in bubble

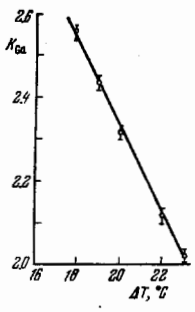

FIG. 27. Dependence of the coefficient of the distribution of gallium on the supercooling ($\omega = 100$ rpm).

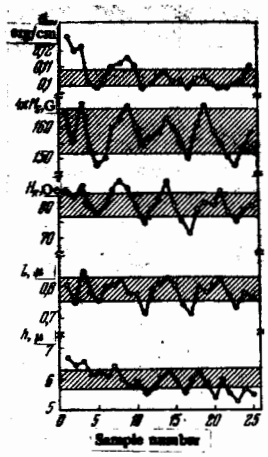

FIG. 28. Reproducibility of the properties of films of composition $Y_{2.6}Sm_{0.4}Ga_{1.2}Fe_{3.8}O_{12}$, grown at $\Delta T = 20$ °C, $\omega = 100$ rpm. $t_{growth} = 10$ min. The shaded region corresponds to a ± 5% deviation of the properties from the nominal values.

memory and logic devices have by now been obtained.[28,29,46–48,50,66,67,83,121,323,335,336] The results of an investigation of these compositions lead to the following conclusions:

When ions having an orbital angular momentum are introduced into an iron garnet, they decrease the mobility of the domain walls.[427] From the point of view of their effectiveness in decreasing the mobility, the sequence of the rare-earth ions is $Tb^{3+} > Ho^{3+} > Dy^{3+} > Sm^{3+} > Er^{3+} > Yb^{3+} \approx Eu^{3+} > Tm^{3+}$, and their influence is proportional in first-order approximation to the concentration of these ions.

Garnet containing spherically symmetrical ions, such as Y and Gd have a large mobility but a low anisotropy. A large magnetostriction and an anisotropy induced in the growth process are observed in garnets containing large rare-earth ions with angular momentum.[428]

If the growth is by the liquid-phase epitaxy, the magnetic characteristics in the compositions of the films depend on the growth conditions, and particularly on the degree of supercooling.[40,45,60,188] By way of example, Fig. 27 shows the dependence of the distribution coefficient K_{Ga} of gallium, which determines its relative content in the crystal, on the supercooling, as obtained when films of the system $Y_3(FeGa)_5O_{12}$ are grown from a $PbO–B_2O_3$ melt. The distribution coefficients are given for Ga in[28,54], for Al in[28], and for Ge and Si in[39]. In the calculation of the charge compositions indicated in Table I, the value of K_{Ga} was assumed to be 2.5. Films grown at identical temperatures and growth times exhibit systematic variation of the physical properties as functions of the serial number of the grown sample,[45] this being due to the change in the composition of the melt, and consequently in the saturation temperature. To obtain films with identical properties it is therefore necessary to lower the melt temperature in accordance with a definite program. The results of an investigation of the reproducibility of the properties of 25 films of composition $Y_{2.6}Sm_{0.4}Ga_{1.2}Fe_{3.8}O_{12}$, grown in succession under identical conditions (supercooling $\Delta T = 20$ °C, rotation speed $\omega = 100$ rpm, growth time $t_{growth} = 10$ min) from a crucible containing 150 g of melt, are shown in Fig. 28.

The temperature stability of the collapse field H_0 and

TABLE III. Temperature characteristics of magnetic properties of films of rare-earth garnets.[240]

	h, μ	T_N, °C	T, °C	l, μ	H_0, Oe	$4\pi M_s$, G	σ_w, erg/cm²	l_T, %/°C	H_{0T}, %/°C	M_T, %/°C	σ_T, %/°C	$\frac{\Delta\sigma_w}{\sigma_w}\Big/\frac{\Delta M_s}{M_s}$
$Y_{2.6}Sm_{0.4}Ga_{1.0}Fe_{4.0}O_{12}$	8.0	139	20	0.21	145	190	0.06	−0.12	−0.36	−0.33	−0.68	2.1
			50	0.22	129	166	0.05	−0.07	−0.42	−0.44	−0.92	2.1
			100	0.22	90	118	0.02	0.00	−1.05	−1.28	−2.50	2.0
$Y_{2.6}Sm_{0.4}Ga_{1.1}Fe_{3.9}O_{12}$	10.0	131	20	0.28	126	175	0.07	−0.04	−0.36	−0.43	−0.84	2.0
			50	0.27	111	152	0.05	−0.06	−0.52	−0.60	−1.20	2.0
			100	0.25	74	101	0.02	−0.28	−1.33	−1.48	−2.80	1.9
$Y_{2.6}Sm_{0.4}Ga_{1.2}Fe_{3.8}O_{12}$	10.0	115	20	0.59	100	160	0.12	−0.16	−0.28	−0.41	−0.80	2.0
			50	0.56	90	140	0.09	−0.19	−0.49	−0.60	−1.11	1.8
			100	0.45	50	77	0.02	−0.84	−2.6	−2.7	−4.5	1.7
$Y_{2.8}Sm_{0.2}Ga_{1.0}Fe_{4.0}O_{12}$	7.0	140	20	0.22	163	228	0.09	0.00	−0.46	−0.43	−0.88	2.0
			50	0.22	140	196	0.07	0.00	−0.52	−0.51	−1.04	2.0
			100	0.21	102	141	0.03	−0.09	−1.05	−1.15	−2.24	1.9
$Y_3Ga_{1.0}Fe_{4.0}O_{12}$	13.0	—	20	0.105	378	450	0.17	−0.15	−0.32	−0.32	−0.69	2.2
			50	0.108	341	400	0.14	−0.07	−0.42	−0.41	−0.83	2.0
			100	0.111	262	312	0.09	0.00	−0.63	−0.65	−1.25	1.9
$Y_3Ga_{1.2}Fe_{3.8}O_{12}$	6.0	148	20	0.12	184	241	0.06	−0.26	−0.28	−0.24	−0.55	2.3
			50	0.13	166	221	0.05	−0.18	−0.35	−0.37	−0.77	2.1
			100	0.14	120	160	0.03	0.00	−1.03	−1.02	−1.96	1.9
$Er_{2.0}Eu_{1.0}Ga_{0.7}Fe_{4.3}O_{12}$	6.0	—	20	0.28	166	248	0.14	−0.20	−0.26	−0.25	−0.47	1.9
			50	0.27	158	236	0.12	−0.21	−0.35	−0.33	−0.63	1.9
			100	0.26	140	213	0.08	−0.23	−0.60	−0.53	−0.95	1.8

of the bubble diameter d are determined, as shown in[429–437], by the temperature dependence of the saturation magnetization $4\pi M_s$ and of the domain-wall energy σ_w.

Investigations of the influence of the temperature on parameters of materials with bubbles were carried out in[29, 46, 50, 66, 67, 86, 240, 276, 263, 288, 312, 322, 432–437]. The magnetic properties of a number of compositions of garnet films investigated in[240] are given in Table III for three values of the temperature. The temperature coefficients of the characteristic length l_T, of the collapse field H_{0T}, and of the saturation magnetization M_{sT}, and the domain wall energy σ_{WT} were calculated from formulas analogous to those given in[395].

The introduction of the ions Ge^{4+} and Si^{4+} into single-crystal iron-garnet films is preferred to the introduction of Ga^{3+} and Al^{3+}, since Ge^{4+} and Si^{4+} occupy exclusively tetrahedral positions in the garnet structure. The ions Ga^{3+} and Al^{3+} replace Fe^{3+} not only in tetrahedral but also in octahedral sites, thus decreasing the Neel temperature by 60–70 °C in comparison with garnets containing Ge and Si and having the same values of $4\pi M_s$.[6, 46, 183, 325, 335, 434–436] To ensure electroneutrality one introduces in the dodecahedral sites, as a rule, Ga^{2+} ions. Figure 29 shows typical temperature dependences of the equilibrium period of strip domains $P_0(T)$, of the collapse field $H_0(T)$, of the saturation magnetization $4\pi M_s(T)$, and of the domain-wall energy $\sigma_w(T)$ for films with comparisons (in the melt) $Y_{1.7}Sm_{0.3}Ga_{1.0}Fe_{4.0}Ge_{0.75}Si_{0.25}O_{12}$ (solid lines) and $Y_{2.0}Sm_{0.4}Ga_{1.1}Fe_{3.9}O_{12}$ (dashed lines).

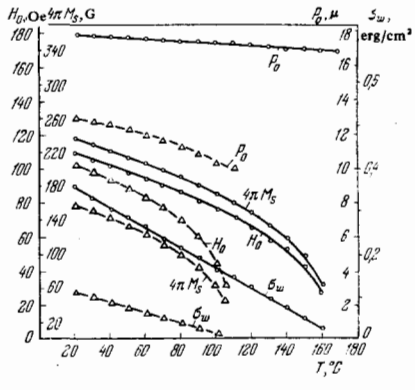

FIG. 29. Temperature dependence of the equilibrium period of strip domains P_0, of the collapse field H_0, of the saturation magnetization $4\pi M_s$, and of the domain-wall energy σ_w for films with compositions (in the melt) $Y_{1.7}Sm_{0.3}Ga_{1.0}Fe_{4.0}Ge_{0.75}Si_{0.25}O_{12}$ (solid lines) and $Y_{2.6}Sm_{0.4}Ga_{1.1}Fe_{3.9}O_{12}$ (dashed lines).[240]

7. CONCLUSION

The best method of obtaining high-grade iron-garnet films with reproducible parameters is liquid-phase epitaxy from the molten solution. The epitaxial growth is most adequately described by a model that takes into account the volume diffusion and the depletion of the growth particles in the single crystal on the film surface. The control of the quality of the epitaxial films and an investigation of their magnetic properties are easiest to carry out by optical and magneto-optical methods. The existing theories describe adequately the static and temperature properties of garnet films, but only qualitatively their dynamic properties. Further progress in the development of bubble devices calls for the synthesis of new garnet compositions with higher domain-wall velocities and wider ranges of temperature stability of the principal magnetic parameters.

[1]A. H. Bobeck, Bell Syst. Tech. J. 46, 1901 (1967).
[2]G. A. Smolenskiĭ, M. A. Boyarchenkov, F. V. Lisovskiĭ, and

V. K. Raev, Mikroélektronika 1, 26 (1972).
[3]Magnitnye domennye logicheskie i zapominayushchie ustroĭstva (Magnetic Domain Logic and Memory Devices), ed. M. A. Boyarchenkov, Moscow, Énergiya, 1974.
[4]G. A. Smolenskiĭ and V. V. Lemanov, Ferrity i ikh tekhnicheskoe primenenie (Ferrites and Their Technical Applications), Leningrad, Nauka, 1975.
[5]M. A. Boyarchenkov and A. G. Cherkashina, Magnitnye élementy avtomatiki i vychislitel'noĭ tekhniki (Magnetic Elements for Automation and Computer Technology), Moscow, Vysshaya shkola, 1976.
[6]Yu. M. Yakovlev and T. S. Gendelev, Monokristally ferritov v radioélektronike (Single-Crystal Ferrites in Radio and Electronics), Sov. Radio, 1975.
[7]K. P. Belov, M. A. Belyanchikova, R. Z. Levitin, and S. A. Nikitin, Redkozemel'nye ferromagnetiki i antiferromagnetiki (Rare Earth Ferromagnets and Antiferromagnets), Nauka, 1965.
[8]K. P. Belov, in: Ferrimagnetizm, Moscow State Univ. 1975, p. 6.
[9]A. R. Gizhinskiĭ and M. E. Fabrikov, Izv. Akad. Nauk SSSR Ser. Neorg. Mater. 10, 784 (1974).
[10]E. A. Giess and R. Ghez, in: Epitaxial Growth, ed. J. W. Matthews, N. Y., Academic Press, 1975.
[11]C. F. Buhrer, J. Appl. Phys. 41, 1393 (1970).
[12]D. E. Lacklison, H. I. Ralph, and G. B. Scott, Sol. State Comm. 10, 269 (1972).
[13]S. Wittekoek, and D. E. Lacklison, Phys. Rev. Lett. 28, 740 (1972).
[14]D. E. Lacklison, G. B. Scott, and H. I. Ralph, IEEE Trans. Magnet. **Mag-9**, 457 (1973).
[15]S. Wittekoek, J. M. Robertson, T. J. A. Popma, and P. E. Bongers, AIP Conf. Proc. 10, 418 (1973).
[16]H. Takeuchi, K. Shinagawa, and S. Taniguchi, Japan J. Appl. Phys. 12, 465 (1973).
[17]S. Ito, I. Mikami, Y. Sugita, and S. Taniguchi, J. Phys. Soc. Japan **34**, 1101 (1973).
[18]A. M. Balbashov, A. Ya. Chervonenkis, A. P. Cherkasov, V. E. Bakhteuzov, A. A. Tsvetkova, and V. P. Cheparin, Pis'ma Zh. Eksp. Teor. Fiz. 18, 572 (1973) [JETP Lett. **18**, 337 (1973)].
[19]A. M. Balbashov, A. Ya. Chervonenkis, A. P. Cherkasov, and V. E. Bakhteuzov, Fiz. Tverd. Tela (Leningrad) 16, 3102 (1974) [Sov. Phys. Solid State 16, 2002 (1975)].
[20]A. M. Balbashov and A. Ya. Chervonenkis, Izv. Akad. Nauk SSSR Ser. Fiz. 38, 2434 (1974).
[21]A. M. Balbashov, A. Ya. Chervonenkis, A. P. Cherkasov, V. E. Bakhteuzov, and S. G. Pavlov, Pis'ma Zh. Tekh. Fiz. 2, 760 (1976) [Sov. Tech. Phys. Lett. 2, 297 (1976)].
[22]G. B. Scott, R. F. Pearson, and T. L. Page, Dig. Intermag Conf., London, 1975, paper 15—6.
[23]A. Ya. Chervonenkis and A. M. Balbashov, Fiz. Tverd. Tela (Leningrad) 18, 1106 (1976) [Sov. Phys. Solid State 18, 631 (1976)].
[24]R. C. Linares, J. Cryst. Growth **3/4**, 443 (1968).
[25]E. A. Giess, B. A. Calhoun, E. Klokholm, T. R. McGuire, and L. L. Rosier, Mat. Res. Bull. 6, 317 (1971).
[26]H. J. Levinstein, S. J. Licht, R. W. Landfort, and S. L. Blank, Appl. Phys. Lett. 19, 486 (1971).
[27]M. Robbins, S. Licht, and H. J. Levinstein, AIP Conf. Proc. 5, 101 (1972).
[28]S. L. Blank and J. W. Nielsen, J. Cryst. Growth 17, 302 (1972).
[29]W. A. Bonner, J. E. Geusic, D. H. Smith, F. C. Rossol, L. G. Van Uitert, and G. P. Vella-Coleiro, J. Appl. Phys. 43, 3226 (1972).
[30]R. Hiskes, Intermag Conf., 1972, paper 8—2.
[31]C. D. Brandle, D. C. Miller, and J. W. Nielsen, J. Cryst. Growth 12, 195 (1972).
[32]R. A. Laudise, Growth of Single Crystals, Prentice-Hall, 1970.
[33]R. Hiskes, J. Cryst. Growth 27, 287 (1974).
[34]S. M. Gendelev and A. G. Titov, Kristallizatsiya ferritov i ortoferritov iz rastvora v rasplave. Obzory po elektronnoĭ tekhnike, Ser. Ferritovaya tekhnika (Crystallization of Ferrites and Orthoferrites from Molten Solution. Reviews of Electronic Technology, Ferrite Techniques Series), No. 15, Moscow, TsNI Elektronika, 1970.
[35]A. G. Titova, Fiz. Tverd. Tela (Leningrad) 1, 1871 (1959) [Sov. Phys. Solid State 1, 1714 (1960)].
[36]E. A. Giess, J. D. Kuptsis, and E. A. D. White, J. Cryst. Growth 16, 36 (1972).
[37]E. A. Giess, C. F. Guerci, J. D. Kuptsis, and H. L. Hu, Mat. Res. Bull. 8, 1061 (1973).
[38]E. A. Giess, J. E. Davies, C. F. Guerci, and H. L. Hu, *ibid.* 10, 355 (1975).
[39]J. E. Davies, E. A. Giess, and J. D. Kuptsis, J. Mat. Sci. 10, 589 (1975).
[40]J. M. Robertson, W. Tolksdorf, H. D. Jonker, J. Crys. Growth 27, 241 (1974).
[41]W. Tolksdorf, G. P. Bartels, G. P. Espinosa, P. Holst, D. Mateika, and F. Welz, *ibid.* 17, 322 (1972).
[42]W. Tolksdorf, G. P. Bartels, P. Holst, and W. T. Stacy, *ibid.* 26, 122 (1974).
[43]J. P. Krumme, G. P. Bartels, and W. Tolksdorf, Phys. Stat. Sol. a17, 75 (1973).
[44]J. Haisma, G. P. Bartels, and W. Tolksdorf, Phil. Res. Rept. 29, 493 (1974).
[45]B. S. Hewitt, R. D. Pierce, S. L. Blank, and S. Knight, IEEE Trans. Magnet. **Mag-9**, 366 (1973).
[46]J. W. Nielsen, S. L. Blank, D. H. Smith, G. P. Vella-Coleiro, F. B. Hagedorn, R. L. Barns, and W. A. Biolsi, J. Electron. Mat. 3, 693 (1974).
[47]R. Ghez and E. A. Giess, J. Cryst. Growth 27, 221 (1974).
[48]L. G. Van Uitert, E. M. Gyorgy, W. A. Bonner, W. H. Grodkiewicz, E. J. Heilner, and G. J. Zydzik, Mat. Res. Bull. 6, 1185 (1971).
[49]E. A. Giess, B. E. Argyle, B. A. Calhoun, D. C. Cronemeyer, E. Klokholm, T. R. McGuire, and T. S. Plaskett, *ibid.*, p. 1141.
[50]W. A. Bonner, J. E. Geusic, D. H. Smith, L. G. Van Uitert, and G. P. Vella-Coleiro, *ibid.* 8, 785 (1975).
[51]J. M. Robertson, S. Wittekoek, T. J. A. Popma, and P. F. Bongers, Appl. Phys. 2, 219 (1973).
[52]J. E. Davies, E. A. D. White, and J. D. C. Wood, J. Cryst. Growth 27, 227 (1974).
[53]E. A. D. White and J. D. C. Wood, *ibid.* 17, 315 (1972).
[54]A. E. Morgan, *ibid.* 27, 226 (1974).
[55]H. L. Glass and M. T. Elliott, *ibid.*, p. 253.
[56]W. Tolksdorf, IEEE Trans. Magnet. **Mag-11**, 1074 (1975).
[57]F. H. De Leeuw and J. M. Robertson, J. Appl. Phys. 46, 3182 (1975).
[58]L. J. Varnerin, IEEE Trans. Magnet. Mag-8, 329 (1972).
[59]H. H. Quon, Y. H. Shing, and D. Walsh, Sol. State Comm. 13, 79 (1973).
[60]J. W. Nielsen, S. J. Licht, and C. D. Brandle, IEEE Trans. Magnet. **Mag-10**, 474 (1974).
[61]A. B. Smith, M. Kestigian, and W. R. Bekebrede, Mat. Res. Bull. 10, 903 (1975).
[62]J. E. Davies, E. A. Giess, and J. D. Kuptsis, *ibid.*, p. 65.
[63]T. Hibiya, Y. Hidaka, S. Fujiwara, and K. Matsumi, J. Phys. Soc. Japan 39, 661 (1975).
[64]R. Krishnan, Phys. Stat. Sol. a30, K177 (1975).
[65]Y. Imamura, Japan J. Appl. Phys. 14, 1393 (1975).
[66]W. A. Bonner, Mat. Res. Bull. 9, 885 (1974).
[67]W. A. Bonner, *ibid.* 10, 15 (1975).
[68]S. Knight, B. S. Hewitt, D. L. Rode, and S. L. Blank, *ibid.* 9, 895 (1974).
[69]R. V. Telesnin and V. N. Dudorov, Izv. Akad. Nauk SSSR Ser. Fiz. 38, 2475 (1974).
[70]V. N. Dudorov, B. V. Mill', and R. V. Telesnin, Prib. Tekh. Eksp. No. 2, 245 (1974).
[71]R. V. Telesnin, V. N. Dudorov, and V. I. Kozlov, Fiz. Tverd. Tela (Leningrad) 17, 2072 (1975) [Sov. Phys. Solid

State 17, 1354 (1975)].
[72]R. V. Telesnin, V. N. Dudorov, and A. T. Morchenko, Kristallografiya 21, 189 (1976) [Sov. Phys. Crystallogr. 21, 99 (1976)].
[73]R. V. Telesnin, V. N. Dudorov, N. P. Dymchenko, V. G. Kleparskiĭ, and V. V. Randoshkin, Fiz. Tverd. Tela (Leningrad) 18, 196 (1976) [Sov. Phys. Solid State 18, 112 (1976)].
[74]V. N. Dudorov, in: Magnetizm i elektronika (Magnetism and Electronics), vol. 154, No. 6, Kuĭbyshev, 1975, p. 81.
[75]R. A. Laudise, R. C. Linares, and E. F. Dearborn, J. Appl. Phys., Suppl. 33, 1362 (1962).
[76]R. C. Linares, R. B. McGraw, and J. B. Schroeder, J. Appl. Phys. 36, 2884 (1965).
[77]R. C. Linares and E. L. Sloan, J. Cryst. Growth 27, 249 (1974).
[78]M. Kestigian, J. Am. Ceram. Soc. 50, 165 (1967).
[79]R. C. Linares, *ibid.* 45, 307 (1962).
[80]H. H. Quon and A. G. Sadler, J. Can. Ceram. Soc. 36, 33 (1967).
[81]A. G. Titova and Yu. L. Sapozhnikov, Izv. Akad. Nauk SSSR Ser. Neorg. Mater. 5, 569 (1969).
[82]L. G. Van Uitert, W. A. Bonner, W. H. Grodkiewicz, G. J. Zydzik, Mat. Res. Bull 5, 455 (1970).
[83]L. G. Van Uitert, W. A. Bonner, W. H. Grodkiewicz, L. Pistroski, and G. J. Zydzik, *ibid.*, p. 325.
[84]W. J. Tabor, G. P. Vella-Coleiro, F. B. Hagedorn, and L. G. Van Uitert, J. Appl. Phys. 45, 3617 (1974).
[85]P. Görnert and P. Hergt, Phys. Stat. Sol. a20, 577 (1973).
[86]P. Görnert and C. G. D'Ambly, *ibid.* a29, 95 (1975).
[87]R. Hiskes and R. A. Burmeister, AIP Conf. Proc. 10, 304 (1973).
[88]R. Hiskes, T. L. Felmlee, and R. A. Burmeister, J. Electron. Mat. 1, 458 (1972).
[89]Y. Suemune and N. Inoue, Japan J. Appl. Phys. 13, 204 (1974).
[90]Y. Suemune and N. Inoue, IEEE Trans. Magnet. Mag-10, 477 (1974).
[91]J. W. Nielsen and E. F. Dearborn, J. Phys. Chem. Sol. 5, 202 (1958).
[92]H. D. Jonker, J. Cryst. Growth 28, 321 (1975).
[93]S. L. Blank, B. S. Hewitt, L. K. Shiek, and J. W. Nielsen, AIP Conf. Proc. 10, 256 (1973).
[94]R. Chez and E. A. Giess, Mat. Res. Bull. 8, 31 (1973).
[95]R. N. Sheftal', in: Rost kristallov (Crystal Growth), vol. 10, Moscow, Nauka, 1974.
[96]L. S. Palatnik and I. I. Papirov, Épitaksial'nye plenki (Epitaxial Films), Nauka, 1971.
[97]A. A. Chernov, Usp. Fiz. Nauk 73, 277 (1961) [Sov. Phys. Usp. 4, 116 (1961)].
[98]W. Baron *et al.*, transl. in: Elementarnye protsessy rosta kristallov (Elementary Crystal Growth Processes), Moscow, IL, 1959.
[99]V. A. Timofeeva, Kristallografiya 5, 476 (1960) [Sov. Phys. Crystallogr. 5, 453 (1960)].
[100]D. Elwell and R. Dawson, J. Cryst. Growth 13/14, 555 (1972).
[101]D. Elwell and R. W. Neate, J. Mat. Sci. 6, 1499 (1971).
[102]G. H. Gelmer, R. Ghez, and N. Cabrera, J. Cryst. Growth 8, 79 (1971).
[103]J. A. Burton, R. C. Prim, and E. P. Slichter, Chem. Phys. Soc. J. 21, 1987 (1953).
[104]P. Chaudhari, IEEE Trans. Magnet. Mag-8, 333 (1972).
[105]A. J. Kurtzig, *ibid.* Mag-6, 497 (1970).
[106]F. B. Hagedorn, J. Appl. Phys. 41, 1161 (1970).
[107]L. M. Buravikhin and V. V. Krasovskiĭ, Pribory i sistemy upravleniya 8, 17 (1971).
[108]P. W. Shumate, Jr., IEEE Trans. Magnet. Mag-7, 586 (1971).
[109]T. Nakagawa and T. Namikata, *ibid.* Mag-10, 488 (1974).
[110]G. S. Kandaurova, V. O. Vas'kovskiĭ, and I. A. Zhuravlev, Mikroelektronika 5, 72 (1976).
[111]R. V. Telesnin, V. N. Dudorov, and S. M. Zimacheva, *ibid.* p. 461.
[112]E. Heinlein and R. D. Pierce, IEEE Trans. Magnet. Mag-6, 493 (1970).
[113]J. E. Geusic, H. J. Levinstein, S. J. Licht, and C. D. Brandle, Appl. Phys. Lett. 19, 93 (1971).
[114]B. E. Argyle and P. Chaudhari, AIP Conf. Proc. 10, 403 (1973).
[115]A. Akselrad, *ibid.*, p. 408.
[116]R. D. Pierce, J. Cryst. Growth 27, 299 (1974).
[117]J. E. Mee, G. R. Pulliam, J. L. Archer, and P. J. Besser, IEEE Trans. Magnet. Mag-5, 717 (1969).
[118]L. S. Birks, Electron Probe Microanalysis, N. Y., Intersci. Publ., 1969.
[119]P. J. Besser, T. N. Hamilton, J. E. Mee, and R. L. Stermer, IEEE Trans. Magnet. Mag-10, 492 (1974).
[120]C. D. Brandle and S. L. Blank, *ibid.* Mag-12, 14 (1976).
[121]E. A. Giess, B. E. Argyle, D. C. Cronemeyer, E. Klokholm, T. R. McGuire, D. F. O'Kone, T. S. Plaskett, and V. Sadagopan, AIP Conf. Proc. 5, 110 (1972).
[122]Trace Analysis, Physical Methods, Ed. G. H. Morrison, N. Y., Intersci. Publ., 1966.
[123]Trace Characterisation, Chemical and Physical Methods, ed. W. W. Meinke and B. F. Schribner, Washington, D. C., 1967.
[124]I. B. Borovskiĭ, Fizicheskie osnovy rentgenospektral'nykh issledovaniĭ (Physical Foundations of X-ray Spectral Investigations), Moscow, 1956.
[125]B. D. Cullity, Elements of X-Ray Diffraction, California, 1967.
[126]S. Geller, H. J. Williams, G. P. Espinosa, and R. C. Sherwood, Bell Syst. Tech. J. 43, 565 (1964).
[127]A. A. Thiele, *ibid.* 48, 3287 (1969).
[128]A. A. Thiele, J. Appl. Phys. 41, 1139 (1970).
[129]S. H. Wemple, S. L. Blank, J. A. Seman, and W. A. Biolsi, Phys. Rev. B9, 2134 (1974).
[130]C. S. Porter, E. G. Spenser, and R. C. leCraw, J. Appl. Phys. 29, 495 (1958).
[131]G. S. Krinchik and M. V. Chetkin, Zh. Eksp. Teor. Fiz. 41, 673 (1961) [Sov. Phys. JETP 14, 485 (1962)].
[132]A. M. Clogston, J. Appl. Phys. Suppl. 31, 1985 (1960).
[133]P. C. Bailey, *ibid.*, p. 39S.
[134]M. V. Chetkin, Fiz. Tverd. Tela (Leningrad) 6, 3753 (1964) [Sov. Phys. Solid State 6, 3013 (1965)].
[135]K. A. Wickershein, J. Appl. Phys., Suppl. 32, 205S (1964).
[136]D. L. Wood and J. P. Remeika, J. Appl. Phys. 38, 1038 (1967).
[137]D. L. Wood and J. P. Remeika, *ibid.* 37, 1232 (1966).
[138]D. L. Wood, J. Chem. Phys. 39, 1671 (1971).
[139]A. P. Malozemoff, J. Phys. and Chem. Sol. 32, 1669 (1971).
[140]H. Takeuchi, S. Ito, I. Mikami, and S. Taniguchi, J. Appl. Phys. 44, 4789 (1973).
[141]G. B. Scott, D. E. Lacklison, and J. P. Page, Phys. Rev. B10, 971 (1974).
[142]G. B. Scott, D. E. Lacklison, and J. L. Page, J. Phys. C8, 519 (1975).
[143]R. V. Pisarev, I. G. Siniĭ, N. N. Kolpakova, and Yu. M. Yakovlev, Zh. Eksp. Teor. Fiz. 60, 2188 (1971) [Sov. Phys. JETP 33, 1175 (1971)].
[144]H. Takeuchi, Japan J. Appl. Phys. 14, 1903 (1975).
[145]E. Sawatzky and D. H. Horne, Rev. Sci. Instrum. 41, 1284 (1970).
[146]A. V. Antonov and V. I. Zhilin, Prib. Tekh. Eksp. No. 5, 212 (1975).
[147]G. S. Krinchik and M. V. Chetkin, Usp. Fiz. Nauk 98, 3 (1969) [Sov. Phys. Usp. 12, 307 (1969)].
[148]J. F. Dillon, Jr., J. Appl. Phys. 29, 539 (1958).
[149]B. Johnson and R. S. Tebble, Proc. Phys. Soc. 87, 935 (1966).
[150]B. Johnson, J. Appl. Phys. 37, 1441 (1966).
[151]R. C. LeCraw, D. L. Wood, J. F. Dillon, Jr., and J. P. Remeika, Appl. Phys. Lett. 7, 27 (1965).
[152]R. F. McDonald, O. Voegeli, and C. D. Mee, J. Appl. Phys.

38, 4104 (1967).
[153]J. F. Dillon, Jr., *ibid.* 39, 922 (1968).
[154]H. Matthews, S. Singh, and R. C. Le Craw, Appl. Phys. Lett. 7, 165 (1965).
[155]E. Sawatzky and E. Kay, J. Appl. Phys. 42, 367 (1971).
[156]W. A. Grassley, R. W. Cooper, J. L. Page, and R. P. Van Stapele, Phys. Rev. 181, 896 (1965).
[157]C. F. Buhrer, J. Appl. Phys. 40, 11 (1969).
[158]S. H. Wemple, J. Electron. Mater. 3, 243 (1974).
[159]G. S. Krinchik and S. A. Gushchina, Zh. Eksp. Teor. Fiz. 56, 1833 (1969) [Sov. Phys. JETP 29, 984 (1969)].
[160]G. S. Krinchik and S. A. Gushcina, Zh. Eksp. Teor. Fiz. 57, 362 (1969) [Sov. Phys. JETP 30, 198 (1970)].
[161]G. Abulaifya and H. le Gall, Sol. State Comm. 11, 629 (1972)
[162]S. Ito, I. Mikami, Y. Sugita, and S. Taniguchi, IEEE Trans. Magnet. Mag-9, 460 (1973).
[163]G. S. Krinchik, V. A. Krylova, E. V. Berdennikova, and R. A. Petrov, Zh. Eksp. Teor. Fiz. 65, 715 (1973) [Sov. Phys. JETP 38, 354 (1974)].
[164]A. V. Antonov and V. I. Zhilin, Fiz. Tverd. Tela (Leningrad) 18, 1269 (1976) [Sov. Phys. Solid State 18, 729 (1976)].
[165]E. V. Berdennikova and R. V. Pisarev, *ibid.*, 81 [45].
[166]B. D. Gorbunova, O. B. Esikova, and A. G. Titova, *ibid.*, 272 [159].
[167]A. H. Bobeck, R. F. Fischer, and J. L. Smith, AIP Conf. Proc. 5, 45 (1972).
[168]D. M. Heinz, P. J. Besser, J. M. Owens, J. E. Mee, and G. R. Pulliam, J. Appl. Phys. 42, 1243 (1971).
[169]S. H. Wemple and W. J. Tabor, *ibid.* 44, 1395 (1973).
[170]R. V. Telesnin, V. N. Dudorov, Yu. A. Durasova, S. M. Zimacheva, V. V. Randoshkin, and I. I. Timokhin, Prib. Tekh. Éksp. No. 6, 179 (1976).
[171]B. C. McCollum, W. R. Bekebrede, M. Kestigian, and A. B. Smith, Appl. Phys. Lett. 23, 702 (1973).
[172]P. B. Hagedorn, W. J. Tabor, J. E. Geusic, H. J. Levinstein, S. J. Licht, and L. K. Shick, *ibid.* 19, 95 (1971).
[173]D. C. Fowlis and J. A. Copeland, AIP Conf. Proc. 5, 240 (1972).
[174]R. W. Shaw, D. E. Hill, R. M. Sandfort, and J. W. Moody, Bull. Am. Phys. Soc., ser. II. 17, 108 (1972).
[175]R. W. Shaw, D. E. Hill, R. M. Sandfort, and J. W. Moody, J. Appl. Phys. 44, 2346 (1973).
[176]Z. Malek and V. Kambersky, Czech. J. Phys. 8, 416 (1958).
[177]C. Kooy and Y. Enz, Phil. Res. Rept. 15, 7 (1960).
[176]V. I. Chechernikov, Magnitnye izmereniya (Magnetic Measurements), Moscow State Univ., 1969.
[179]L. R. Maxwell, in: Ferromagnetism and Ferrimagnetism. Methods of Experimental Physics, v. 6B (Solid State Phys.), N.Y., Academic Press, 1959, p. 193.
[180]T. R. McGuire and P. J. Flanders, in: Direct Current Magnetic Measurements. Magnetism and Metallurgy. v. 1, N.Y., Academic Press, 1969, p. 123.
[181]H. J. Oguey, *ibid.*, p. 189.
[182]S. Geller, H. J. Williams, R. C. Sherwood, J. P. Remeika, and G. P. Espinosa, Phys. Rev. 131, 1080 (1963).
[183]S. Geller, H. J. Williams, R. C. Sherwood, and G. P. Espinosa, J. Appl. Phys. 36, 88 (1965).
[184]S. Foner, Rev. Sci. Instrum. 30, 548 (1959).
[185]P. J. Flanders and W. D. Doyle, *ibid.* 33, 691 (1962).
[186]D. H. Smith, *ibid.* 27, 261 (1956).
[187]K. Dwight, N. Menyuk, and D. Smith, J. Appl. Phys. 39, 491 (1969).
[188]J. P. Krumme, G. Bartels, P. Hansen, and J. M. Robertson, Mat. Res. Bull. 11, 337 (1976).
[189]G. T. Croft, F. J. Donahoe, and W. F. Love, Rev. Sci. Instrum. 26, 360 (1955).
[190]R. F. Penoyer, *ibid.* 30, 711 (1959).
[191]W. S. Byrnes and R. G. Crawford, J. Appl. Phys. 29, 493 (1958).
[192]R. W. Teale, R. F. Pearson, and M. J. Hight, J. Appl. Phys., Suppl. 32, 150S (1961).
[193]R. F. Pearson and P. W. Cooper, *ibid.*, p. 265S.
[194]R. F. Pearson, *ibid.* 33, 123S (1962).
[195]R. F. Pearson and K. Tweedale, J. Appl. Phys. 35, 1061 (1964).
[196]N. I. Sudakov, N. I. Vershinina, A. I. Drokin, and N. D. Ursulyak, Izv. Akad. Nauk SSSR Ser. Fiz. 34, 1077 (1970).
[197]N. I. Vershinina, N. I. Sudakov, A. I. Drokin, N. I. Utkin, and N. D. Ursulyak, Izv. Vyssh. Uchebn. Zaved. Fiz. No. 00, 147 (1969).
[198]J. W. Beck, Rev. Sci. Instrum. 38, 1031 (1967).
[199]C. D. Mee, Contemp. Phys. 8, 385 (1967).
[200]C. D. Mee, IBM J. 11, 468 (1967).
[201]D. J. Craik, P. V. Cooper, and G. Mayers, J. Phys. D6, 872 (1973).
[202]D. J. Craik, Phys. Lett. A39, 45 (1972).
[203]D. J. Craik and P. V. Cooper, J. Phys. D5, 137 (1972).
[204]D. J. Craik and P. V. Cooper, Phys. Lett. A41, 255 (1973).
[205]H. Callen and R. M. Josephs, J. Appl. Phys. 42, 1977 (1971).
[206]R. M. Josephs, AIP Conf. Proc. 10, 286 (1973).
[207]R. V. Telesnin, V. I. Kozlov, and V. N. Dudorov, Fiz. Tverd. Tela (Leningrad) 16, 3532 (1974) [Sov. Phys. Solid State 16, 2300 (1975)].
[208]L. Neel, C. R. Ac. Sci. 239, 8 (1954).
[209]R. Pauthenet, Ann. Phys. (N.Y.), 3, 424 (1958).
[210]S. Geller, Phys. Rev. 181, 980 (1969).
[211]M. A. Gilleo, J. Phys. and Chem. Sol. 13, 33 (1960).
[212]C. Borghese, *ibid.* 28, 2225 (1967).
[213]I. Nowik, Phys. Rev. 171, 580 (1968).
[214]I. Nowik, J. Appl. Phys. 40, 5184 (1969).
[215]A. Grill and M. Schieber, Phys. Rev. B8, 365, 369, 373 (1973).
[216]V. Nekvasil, Czech. J. Phys. B25, 1290 (1975).
[217]G. F. Dionne, J. Appl. Phys. 41, 4874 (1970).
[218]G. F. Dionne, *ibid.* 42, 2142 (1971).
[219]L. Neel, Ann. de Phys. 3, 137 (1948).
[220]A. Herpin and P. Meriel, J. Phys. et Radium 245, 2033 (1957).
[221]F. Bertaut, F. Forrat, A. Herpin, and P. Meriel, C. R. Ac. Sci. 243, 898 (1956).
[222]E. Prince, Acta Cryst. 10, 787 (1957).
[223]R. Bauminger, S. Cohen, A. Marinov, and S. Ofer, Phys. Rev. 122, 743 (1961).
[224]E. E. Anderson, *ibid.* A134, 1581 (1964).
[225]R. J. Aleonard, J. Phys. and Chem. Sol. 15, 167 (1960).
[226]P. Wojtowicz, Phys. Lett. 11, 18 (1964).
[227]A. B. Harris, Phys. Rev. 132, 2398 (1963).
[228]C. D. Brandle and S. L. Blank, IEEE Trans. Magnet. 12, 14 (1976).
[229]P. Hansen, P. Roschmann, and W. Tolksdorf, J. Appl. Phys. 45, 2728 (1974).
[230]A. J. Kurtzig and W. Shockley, *ibid.* 39, 5619 (1968).
[231]J. M. Nemchik, *ibid.* 40, 1086 (1969).
[232]S. H. Charap and J. M. Nemchik, IEEE Trans. Magnet. Mag-5, 566 (1969).
[233]Y. S. Lin and Y. O. Tu, Appl. Phys. Lett. 18, 247 (1971).
[234]W. J. DeBonte, AIP Conf. Proc. 5, 140 (1972).
[235]W. J. DeBonte, IEEE Trans. Magnet. Mag-11, 3 (1975).
[236]E. Schlömann, Appl. Phys. Lett. 21, 227 (1972).
[237]E. Schlömann, AIP Conf. Proc. 10, 478 (1973).
[238]E. Schlomann, J. Appl. Phys. 44, 1837, 1950 (1973).
[239]E. Schlömann, *ibid.* 45, 369 (1974).
[240]R. V. Telesnin, V. N. Dudorov, and V. V. Randoshkin, Fiz. Tverd. Tela (Leningrad) 17, 3015 (1975) [Sov. Phys. Solid State 17, 2000 (1976)].
[241]V. N. Dudorov and V. V. Randoshkin, Izmeritel'naya tekhnika, No. 10, 87 (1976).
[242]E. S. Borovik and A. S. Miller, Lektsii po magnetizmu (Lectures on Magnetism) Khar'kov State Univ, 1966.
[243]A. H. Bobeck, E. G. Spenser, L. G. Van Uitert, S. C. Abrahams, R. L. Barns, W. H. Grodkiewicz, R. C. Sherwood, P. H. Schmidt, D. H. Smith, and E. M. Walters, Appl. Phys. Lett. 17, 131 (1970).

[244]A. Akselrad and H. Callen, *ibid.* 19, 464 (1971).
[245]A. H. Bobeck, D. H. Smith, E. G. Spencer, L. G. Van Uitert, and E. M. Walters, IEEE Trans. Magnet. Mag-7, 461 (1971).
[246]R. C. Le Craw, R. Wolfe, A. H. Bobeck, R. D. Pierce, and L. G. Van Uitert, J. Appl. Phys. 42, 1641 (1971).
[247]A. Rosencwaig, W. J. Tabor, R. D. Pierce, and L. C. Van Uitert, Phys. Rev. Lett. 26, 779 (1971).
[248]H. Callen, Appl. Phys. Lett. 18, 311 (1971).
[249]H. Callen, Mat. Res. Bull. 7, 931 (1971).
[250]A. Rosencwaig and W. J. Tabor, J. Appl. Phys. 42, 1642 (1971).
[251]A. Rosencwaig and W. J. Tabor, AIP Conf. Proc. 5, 57 (1972).
[252]W. T. Stacy and W. Tolksdorf, *ibid.*, p. 185.
[253]J. E. Mee, G. R. Pulliam, J. L. Archer, and P. J. Besser, IEEE Trans. Magnet. Mag-5, 717 (1969).
[254]D. M. Heinz, P. J. Besser, and J. E. Mee, AIP Conf. Proc. 5, 96 (1972).
[255]P. J. Besser, J. E. Mee, P. E. Elkins, and D. M. Heinz, Mat. Res. Bull. 6, 1111 (1971).
[256]F. B. Hagedorn, J. Appl. Phys. 45, 3638 (1974).
[257]V. G. Demidov, A. K. Zvezdin, R. Z. Levitin, A. S. Markosyan, and A. I. Popov, Fiz. Tverd. Tela (Leningrad) 16, 2114 (1974) [Sov. Phys. Solid State 16, 1379 (1975)].
[258]A. K. Zvezdin, R. Z. Levitin, A. S. Markosyan, A. A. Mukhin, and A. I. Popov, Fiz. Tverd. Tela (Leningrad) 18, 387 (1976) [Sov. Phys. Solid State 18, 225 (1976)].
[259]A. K. Papeev, R. Z. Levitin, A. S. Markosyan, B. V. Mill', and T. M. Perekalina, Zh. Eksp. Teor. Fiz. 67, 232 (1974) [Sov. Phys. JETP 40, 117 (1975)].
[260]P. J. Flanders, Rev. Sci. Instrum. 41, 697 (1970).
[261]W. D. Doyle and P. J. Flanders, AIP Conf. Proc. 5, 707 (1972).
[262]E. A. Giess and D. C. Cronemeyer, Appl. Phys. Lett. 22, 601 (1973).
[263]P. Hansen, J. Appl. Phys. 45, 3123 (1974).
[264]C. Vittoria, H. Lesoff, and N. D. Wilsey, IEEE Trans. Magnet. Mag-8, 273 (1972).
[265]B. E. Rubenshteĭn and G. M. Galaktionova, Fiz. Tverd. Tela (Leningrad) 9, 179 (1967) [Sov. Phys. Solid State 9, 134 (1967)].
[266]B. E. Rubenshtein and G. M. Galaktionova, *ibid.*, 2707 [2124].
[267]B. E. Rubenshteĭn, Fiz. Tverd. Tela (Leningrad) 11, 1980 (1969) [Sov. Phys. Solid State 11, 1592 (1970)].
[268]B. E. Rubenshtein, A. G. Titova, and B. A. Lapova, Fiz. Tverd. Tela 6, 3538 (1964) [Sov. Phys. Solid State 6, 2834 (196)].
[269]P. Hansen, J. Schuldt, and W. Tolksdorf, Phys. Rev. B8, 2474 (1973).
[270]A. J. Kurtzig and F. B. Hagedorn, IEEE Trans. Magnet. Mag-7, (1971).
[271]W. F. Druywesteyn, J. W. F. Dorleijn, and P. J. Rijnierse, J. Appl. Phys. 44, 2387 (1973).
[272]J. W. F. Dorleijn, W. F. Druywesteyn, G. Bartels and W. Tolksdorf, Phil. Res. Rept. 28, 133 (1973).
[273]Y. Shimada, H. Kojima, and K. Sakai, J. Appl. Phys. 45, 4596 (1974).
[274]A. Hubert, A. P. Malozemoff, and J. C. DeLuca, *ibid.*, p. 3562.
[275]A. P. Malozemoff and J. C. DeLuca, *ibid.*, p. 4586.
[276]J. P. Krumme, P. Hansen, and J. Haberkamp, Phys. Stat. Sol. a12, 483 (1972).
[277]P. Hansen and J. P. Krumme, J. Appl. Phys. 44, 2847 (1973).
[278]P. W. Shumate, Jr., D. H. Smith, and F. B. Hagedorn, *ibid.*, p. 449.
[279]P. W. Shumate, Jr., *ibid.*, p. 3323.
[280]P. J. Rijnierse, H. Logmans, R. Metselaar, and W. T. Stacy, Appl. Phys. 8, 143 (1975).
[281]R. A. Abram, R. J. Fairholm, M. D. R. Tench, and K. A. Gehring, J. Phys. D8, 94 (1975).
[282]I. G. Avaeva, F. V. Lisovskiĭ, and V. I. Shchetlov, Fiz. Tverd. Tela (Leningrad) 6, 3538 (1964) [Sov. Phys. Solid State 6, 2834 (1965)].
[283]R. D. Enoch, M. E. Jones, and D. G. P. Waters, Appl. Phys. Lett. 26, 127 (1975).
[284]T. C. Slonezewski, A. P. Malozemoff, and E. A. Giess, *ibid* 24, 396 (1974).
[285]J. T. Carlo, D. C. Bullock, and F. C. West, IEEE Trans. Magnet. Mag-10, 325 (1974).
[286]R. C. Le Craw and L. R. Walker, J. Appl. Phys. 32, 167S (1961).
[287]R. Henry, S. D. Brown, P. E. Wigen, and P. J. Besser, Phys. Rev. Lett. 28, 1272 (1972).
[288]R. Henry and D. M. Heinz, AIP Conf. Proc. 18, 194 (1974).
[289]Ferromagnitnyĭ rezonans (Ferromagnetic Resonance), ed. S. V. Vonsovskiĭ, Moscow, Fizmatgiz, 1961.
[290]A. G. Gurevich, Magnitnyĭ rezonans v ferritakh i antiferromagnetinikakh (Magnetic Resonance in Ferrites and Antiferromagnets), Nauka, 1973.
[291]M. Sparks, Phys. Rev. B1, 3831, 3856, 3869 (1970).
[292]R. E. De Wames and T. Wolfram, J. Appl. Phys. 41, 987 (1970).
[293]R. E. De Wames and T. Wolfram, Phys. Rev. Lett. 26, 1445 (1971).
[294]T. Wolfram and R. E. De Wames, Phys. Rev. B4, 3125 (1971).
[295]A. B. Smith, Rev. Sci. Instrum. 39, 378 (1968).
[296]G. A. Petrakovskiĭ and Yu. N. Kotyukov, Fiz. Tverd. Tela (Leningrad) 7, 2339 (1965) [Sov. Phys. Solid State 7, 1892 (1966)].
[297]G. A. Petrakovskii, E. A. Petrakovskaia, and E. M. Smokotin, IEEE Trans. Magnet. Mag-9, 422 (1973).
[298]B. A. Calhoun, E. A. Giess, and L. L. Rosier, Appl. Phys. Lett. 18, 287 (1971).
[299]F. B. Hagedorn, AIP Conf. Proc. 5, 72 (1972).
[300]J. F. Dillon, Jr., in: Magnetism, v. 3, N. Y. Academic Press, 1963, p. 437.
[301]C. Kittel and J. Galt, transl. in: Magnitnaya struktura ferromagnetikov (Magnetic Structure of Ferromagnets), S. V. Vonsovskiĭ, ed. IL, 1959, p. 459.
[302]W. Döring, Zs. Naturforsch. A3, 373 (1948).
[303]G. R. Henry, J. Appl. Phys. 42, 3150 (1971).
[304]F. H. DeLeeuw, IEEE Trans. Magnet. Mag-9, 614 (1973).
[305]F. H. DeLeeuw, J. Appl. Phys. 45, 3106 (1974).
[306]J. W. Moody, R. W. Shaw, R. M. Sandfort, and R. L. Stermer, IEEE Trans. Magnet. Mag-9, 377 (1973).
[307]B. E. Argyle and A. P. Malozemoff, AIP Conf. Proc. 10 273 (1973).
[308]R. W. Shaw, J. W. Moody, and R. M. Stermer, J. Appl. Phys. 45, 2672 (1974).
[309]J. A. Seitchik, W. D. Doyle, and G. K. Goldberg, *ibid.* 42, 1272 (1971).
[310]V. G. Kleparskiĭ, E. I. Il'yashenko, and O. A. Tsyganov, in: Materialy XIV Vsesoyuznogo soveshchaniya po magnitnym élementam avtomatiki i vychislitel'noĭ tekhniki (Proc. 14-th All-Union Conf.) on Magnetic Elements of Automation and Computer Techniques, Moscow, 1972, p. 327.
[311]G. P. Vella-Coleiro, D. H. Smith, and L. G. Van Uitert, IEEE Trans. Magnet. Mag-7, 745 (1971).
[312]G. P. Vella-Coleiro, D. H. Smith, and L. G. Van Uitert, J. Appl. Phys. 43, 2428 (1972).
[313]J. Fairholme, G. P. Gill, and A. Marsh, Mat. Res. Bull. 6, 1131 (1971).
[314]E. V. Karasev, Tr. Inst. Élektron. Upravl. Mashin, No. 21, 126 (1973).
[315]T. H. O'Dell, Phil. Mag. 27, 595 (1973).
[316]A. H. Bobeck, I. Danylchuk, J. P. Remeika, L. G. Van Uitert, and E. M. Walters, in: Proc. of Intern. Conference on Ferrites, Kyoto, 1970, p. 361.
[317]G. P. Vella-Coleiro and W. J. Tabor, Appl. Phys. Lett. 21, 7 (1972).
[318]G. J. Zimmer, L. Gal, K. Vural, and F. B. Humphrey, J.

Appl. Phys. 46, 4976 (1975).
[319]L. P. Ivanov, A. S. Logginov, V. V. Randoshkin, and R. V. Telesnin, Pis'ma Zh. Eksp. Teor. Fiz. 23, 627 (1976) [JETP Lett. 23, 575 (1976)].
[320]A. P. Malozemoff and J. C. Slonczewski, Phys. Rev. Lett. 29, 952 (1972).
[321]E. I. Ilyashenko, V. G. Kelparskii, and S. E. Yurchenko, Phys. Stat. Sol. 28, K153 (1975).
[322]V. G. Kleparskii, N. P. Dymchenko, and S. K. Kukharskaya, *ibid.* a33, K117 (1976).
[323]R. V. Telesnin, V. N. Dudorov, V. G. Kleparskiĭ, and V. V. Randoshkin, Fiz. Tverd. Tela (Leningrad) 18, 1773 (1976) [Sov. Phys. Solid State 18, 1034 (1976)].
[324]B. E. Argyle, and A. Halperin, IEEE Trans. Magnet. Mag-9, 238 (1973).
[325]K. P. Papworth, *ibid.* Mag-10, 638 (1974).
[326]D. J. Craik and D. H. Cottey, J. Phys. D8, 99 (1975).
[327]J. W. F. Dorleijn and W. F. Druyvesteyn, Appl. Phys. 1, 176 (1973).
[328]B. E. Argyle, J. C. Slonczewski, and A. E. Maydas, AIP Conf. Proc. 5, 175 (1972).
[329]A. J. Kurtzig, R. C. Le Craw, A. H. Bobeck, E. M. Walters, R. Wolfe, H. J. Levinstein, and S. J. Light, *ibid.*, p. 180.
[330]S. Ito, I. Mikami, Y. Sugita, and S. Tanigushi, IEEE Trans. Magnet. Mag-9, 460 (1973).
[331]T. Obokata, K. Sokura, and T. Namikata, *ibid.*, p. 373.
[332]Yu. M. Yakovlev, V. S. Filonich, M. M. Klyuchnikov, and Yu. I. Sapozhnikov, Fiz. Tverd. Tela (Leningrad) 15, 1607 (1973) [Sov. Phys. Solid State 15, 1076 (1973)].
[333]M. M. Klyuchnikov, Elektron. Tekh. Ser. 6, No. 8, 99 (1974).
[334]J. A. Cape, J. App. Phys. 43, 3551 (1972).
[335]W. A. Bonner, J. E. Geusic, D. H. Smith, L. G. Van Uitert, and G. P. Vella-Coleiro, Mat. Res. Bull. 8, 1223 (1973).
[336]A. P. Malozemoff, J. Appl. Phys. 44, 5080 (1973).
[337]G. P. Vella-Coleiro, F. B. Hagedorn, Y. S. Chen, B. S. Hewitt, S. L. Blank, and R. Zappula, *ibid.* 45, 939 (1974).
[338]G. P. Vella-Coleiro, S. L. Blank, and R. C. Le Craw, Appl. Phys. Lett. 26, 722 (1975).
[339]H. Nakanishi and C. Uemura, Japan J. Appl. Phys. 13, 1183 (1974).
[340]R. Suzuki and Y. Sugita, J. Phys. Soc. Japan 39, 831 (1975).
[341]R. Suzuki and Y. Sugita, Appl. Phys. Lett. 26, 587 (1975).
[342]R. Suzuki, M. Takahashi, T. Kobayashi, and Y. Sugita, *ibid.*, p. 342.
[343]R. M. Josephs, Appl. Phys. Lett. 25, 244 (1974).
[344]R. W. Patterson, J. Appl. Phys. 45, 5018 (1974).
[345]E. I. Il'yashenko and S. E. Yurchenko, Fiz. Tverd. Tela (Leningrad) 16, 3509 (1974) [Sov. Phys. Solid State 16, 2280 (1975)].
[346]E. I. Il'yashenko and S. E. Yurchenko, Fiz. Tverd. Tela 18, 1112 (1976) [Sov. Phys. Solid State 18, 635 (1976)].
[347]B. G. Kleparskiĭ and S. E. Yurchenko, *ibid.*, 290 [172].
[348]V. A. Bokov, V. V. Volkov, T. K. Trofimova, and E. S. Sher, Fiz. Tverd. Tela 17, 3591 (1975) [Sov. Phys. Solid State 17, 2338 (1976)].
[349]J. C. Slonczewski, A. P. Malozemoff and O. Voegeli, AIP Conf. Proc. 10, 458 (1973).
[350]A. P. Malozemoff and J. C. DeLuca, Appl. Phys. Lett. 26, 719 (1975).
[351]A. M. Malozemoff, J. C. Slonczewski, and G. D. DeLuca, in: 21st Annual Conference on Magnetism and Magnetic Materials, Philadelphia, 1975, paper 5A-1.
[352]G. P. Vella-Coleiro, *ibid.*, paper 5A-2.
[353]A. P. Malozemoff, J. C. Slonczewski, and J. C. DeLuca, Dig. Intermag. Conf., London, 1975, paper 1–10.
[354]R. W. Patterson, A. I. Braginski, and F. B. Humphrey, see[22], paper 1–11.
[355]V. Z. Zubov, Metody izmereniya kharakteristik lazernogo islucheniya (Methods of Measuring Laser Emission Characteristics), Moscow, 1973.
[356]M. M. Butslov, Usp. Fiz. Nauk 6, 76 (1959).
[357]T. M. Morris, G. J. Zimmer, and F. B. Humphrey, J. Appl. Phys. 47, 721 (1976).
[358]T. M. Morris and A. P. Malozemoff, AIP Conf. Proc. 18, 242 (1974).
[359]G. J. Zimmer, T. M. Morris, K. Vural, and F. B. Humphrey, Appl. Phys. Lett. 25, 750 (1974).
[360]G. J. Zimer, T. M. Morris, and F. B. Humphrey, IEEE Trans. Magnet. Mag-10, 651 (1974).
[361]L. Gal, G. J. Zimmer, and F. B. Humphrey, Phys. Stat. Sol. a561 (1975).
[362]F. B. Humphrey, IEEE Trans. Magnet. Mag-11, 1679 (1975).
[363]A. P. Malozemoff and K. R. Papworth, in: 20th Annual Conference on Magnetism and Magnetic Materials, San Francisco, 1974, paper 6D-3.
[364]A. P. Malozemoff and K. R. Papworth, J. Phys. A8, 1149 (1975).
[365]G. P. Vella-Coleiro and T. J. Nelson, Appl. Phys. Lett. 24, 397 (1974).
[366]G. P. Vella-Coleiro, F. B. Hagedorn, and S. L. Blank, *ibid.* 26, 69 (1975).
[367]L. Landau and E. Lifshitz, Phys. Z. Sowjet. 8, 153 (1935).
[368]G. R. Henry, J. Appl. Phys. 42, 3150 (1971).
[369]L. R. Walker, see[300], p. 450.
[370]N. L. Schryer and L. R. Walker, AIP Conf. Proc. 10, 1026 (1973).
[371]N. L. Schryer and L. R. Walker, J. Appl. Phys. 45, 5406 (1974).
[372]H. C. Bourne, Jr. and D. S. Bartran, IEEE Trans. Magnet. Mag-8, 741 (1972).
[373]D. S. Bartran and H. C. Bourne, Jr., *ibid.*, p. 743.
[374]D. S. Bartran and H. C. Bourne, Jr., *ibid.*, p. 609. (1974).
[375]H. C. Bourne, Jr., and D. S. Bartran, *ibid.* Mag-10, 1081 (1974).
[376]J. C. Slonczewski, Intern. J. Magn. 2, 85 (1972).
[377]J. C. Slonczewski; AIP Conf. Proc. 5, 170 (1972).
[378]J. C. Slonczewski, J. Appl. Phys. 44, 1759 (1973).
[379]J. C. Slonczewski, IEEE Trans. Magnet. Mag-8, 668 (1972).
[380]J. C. Slonczewski, J. Appl. Phys. 44, 2705 (1973).
[381]E. Schlomann, IEEE Trans. Magnet. Mag-11, 1051 (1975).
[382]F. B. Hagedorn, J. Appl. Phys. 45, 3126 (1974).
[383]A. Hubert, AIP Conf. Proc. 18, 178 (1974).
[384]A. Hubert, J. Appl. Phys. 45, 2276 (1975).
[385]J. A. Cape, W. F. Hall, and G. W. Lehman, *ibid.*, p. 3572.
[386]Yu. I. Gorobets, Fiz. Tverd. Tela (Leningrad) 16, 3128 (1974) [Sov. Phys. Solid State 16, 2024 (1975)].
[387]Yu. P. Mukhortov, Fiz. Tverd. Tela (Leningrad) 18, 1351 (1976) [Sov. Phys. Solid State 18, 777 (1976)].
[388]V. G. Bar'yakhtar, V. V. Gann, and Yu. I. Gorobets, Preprint 74-67-R, Kiev, 1974.
[389]J. Kaczer and I. Tomas, Phys. Stat. Sol. a10, 619 (1972).
[390]A. K. Zvezdin and V. G. Red'ko, see[310], p. 344.
[391]A. A. Thiele, Phys. Rev. Lett. 30, 230 (1973).
[392]A. A. Thiele, J. Appl. Phys. 45, 377 (1974).
[393]G. P. Vella-Coleiro, AIP Conf. Proc. 10, 424 (1973).
[394]G. P. Vella-Coleiro, *ibid.* 18, 217 (1974).
[395]G. P. Vella-Coleiro, D. H. Smith, and L. G. Van Uitert, Appl. Phys. Lett. 21, 36 (1972).
[396]G. P. Vella-Coleiro, AIP Conf. Proc. 24, 595 (1975).
[397]W. J. Tabor, A. H. Bobeck, G. P. Vella-Coleiro, and A. Rosencwaig, Bell Syst. Tech. J. 51, 1427 (1972).
[398]A. Rosencwaig, W. J. Tabor, and T. J. Nelson, Phys. Rev. Lett. 29, 946 (1972).
[399]A. P. Malozemoff, Appl. Phys. Lett. 21, 149 (1972).
[400]R. F. Lacev, R. B. Clover, L. S. Cutler, and R. F. Waites, AIP Conf. Proc. 10, 488 (1973).
[401]H. Nishida, T. Kobayashi, and Y. Sugita, *ibid.*, p. 493.
[402]W. J. Tabor, A. H. Bobeck, G. P. Vella-Coleiro, and A.

Rosencwaig, *ibid.*, p. 458.
[403]T. Kabayashi, H. Nishida, and Y. Sugita, J. Phys. Soc. Japan 34, 555 (1973).
[404]F. G. West and D. C. Bullock, AIP Conf. Proc. 10, 483 (1973).
[405]J. C. Slonczewski, Phys. Rev. Lett. 29, 1679 (1973).
[406]F. B. Hagedorn, S. L. Blank, and R. J. Pierce, Appl. Phys. Lett. 26, 206 (1975).
[407]J. Haisma, K. L. L. Van Mierloo, W. F. Druyvesteyn, and U. Enz, *ibid.* 27, 459.
[408]P. J. Grundy, D. C. Hothersall, G. A. Jones, B. K. Middleton, and R. S. Tebble, Phys. Stat. Sol. a9, 79 (1972).
[409]A. Rosencwaig, Bell Syst. Tech. J. 51, 1440 (1972).
[410]A. H. Bobeck, S. L. Blank, and H. J. Levinstein, *ibid.*, p. 1431.
[411]R. D. Henry, P. J. Besser, R. G. Warren, and E. C. Whitcomb, IEEE Trans. Magnet. Mag-9, 514 (1973).
[412]R. Wolfe and J. C. North, Bell Syst. Tech. J. 51, 1436 (1972).
[413]Y. C. Lin and G. E. Keefe, Appl. Phys. Lett. 22, 603 (1971).
[414]M. Takahashi, H. Nishida, T. Kobayashi, and Y. Sugita, J. Phys. Soc. Japan 34, 1416 (1973).
[415]R. Wolfe, J. C. North, and Y. P. Lai, Appl. Phys. Lett. 22, 683 (1973).
[416]R. Wolfe, J. C. North, R. L. Barns, M. Robinson, and H. J. Levinstein, *ibid.*, 19 (1971).
[417]D. H. Smith and J. C. North, AIP Conf. Proc. 10, 334 (1973).
[418]R. C. Le Craw, E. M. Gyorgy, and R. Wolfe, Appl. Phys. Lett. 24, 573 (1974).
[419]K. Hoshikawa, T. Hattanda, and H. Nakanishi, Japan J. Appl. Phys. 13, 2071 (1974).
[420]D. H. Smith, F. B. Hagedorn, and B. S. Hewitt, J. Appl. Phys. 44, 4177 (1973).
[421]R. D. Enoch, M. E. Jones, D. L. Murrell, P. J. Fiddyment, and D. G. P. Waters, *ibid.* 47, 2706 (1976).
[422]T. Kasai, Japan J. Appl. Phys. 14, 1421 (1975).
[423]S. J. Licht, J. Electron Mater. 4, 757 (1975).
[424]G. P. Vella-Coleiro, F. B. Hagedorn, Y. S. Chen, and S. L. Blank Appl. Phys. Lett. 22, 324 (1973).
[425]R. C. Le Craw, J. P. Remeika, and H. Matthews, J. Appl. Phys. 36, 90 (1965).
[426]R. C. Le Craw, S. L. Blank, and G. P. Vella-Coleiro, Appl. Phys. Lett. 26, 402 (1975).
[427]H. Harper and R. W. Teale, J. Phys. Chem. 2, 1926 (1969).
[428]E. M. Gyorgy, M. D. Sturge, L. G. Van Uitert, E. J. Heilner, and W. H. Grodkiewicz, J. Appl. Phys. 44, 438 (1973).
[429]M. Y. Dimyan and E. Della Torre, *ibid.* 43, 1285 (1972).
[430]M. Y. Dimyan and E. Della Torre, *ibid.*, p. 5207.
[431]D. H. Smith and A. W. Anderson, AIP Conf. Proc. 5, 120 (1972).
[432]R. C. Le Craw and R. D. Pierce, *ibid.*, p. 200.
[433]G. Winkler, P. Hansen, and P. Holst, Phil. Res. Rept. 27, 151 (1972).
[434]P. F. Tumelty, R. Singh, and M. A. Gilleo, see[351], paper 8A-5.
[435]D. M. Heinz, R. G. Warren, and M. T. Elliott, *ibid.*, paper 8A-6.
[436]T. Obokata, H. Tonigswa, and H. Inoue, *ibid.*, paper 8A-7.
[437]A. B. Smith, M. Kestigian, and W. R. Bekebrede, see[22], paper 1-3.

Translated by J. G. Adashko