Dynamics of domains in iron garnet films in a homogeneous magnetic field

V. V. Randoshkin, L. P. Ivanov, and R. V. Telesnin

M. V. Lomonosov State University, Moscow
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High-speed photography with an exposure time of ~ 10 nsec was used to study the rupture of stripe domains, dynamic distortion of stripe and bubble domains, and influence of a static field in the plane of a sample on the motion of domain walls in single-crystal epitaxial iron garnet films subjected to pulsed bias fields.

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1. INTRODUCTION

Interest is increasing in the nature and properties of domain structures in magnetically ordered materials and, in particular, in materials with magnetic bubble domains. Urgent problems in the physics of bubble domains which have not yet been solved include the dynamics of bubbles at high velocities, distribution of the magnetization in a bubble wall, and influence of the motion on the structure of domain walls.[1,2]

The only method available for recording the position and shape of moving domains is high-speed photography.[1] In the case of nonrepetitive and random processes this method gives information on the initial domain structure, its configuration at some moment in time during or after a magnetic field pulse, and resultant domain structure. The application of high-speed photography to the dynamics of cylindrical magnetic domains in a homogeneous magnetic field has revealed a number of new effects.

The fundamental work of Thiele[3] was concerned with the stability of bubble domains in a homogeneous magnetic field applied along the easy magnetization axis (this is known as the bias field). This work revealed that a circular bubble domain is stable only if its diameter is within the range $d_0 \leqslant d \leqslant d_2$. When the diameter becomes $d < d_0$ a bubble collapses, whereas for $d > d_2$ an elliptic instability sets in and a bubble elongates into a stripe domain. However, investigations of the broadening of bubble domains under the action of a pulsed bias field[1,4,5] have revealed distortion of the bubble shape with a higher rotational periodicity $n > 2$. Distortions of a similar kind occur during broadening of stripe domains.[1,4,6]

Malozemoff and Papworth[7] investigated topological switching of a bubble lattice into a lattice of the opposite polarity by a bias field pulse. Their results indicate that a necessary condition for stable switching of bubble lattices is the existence of an anisotropy of the velocity of domain walls. Other authors[8,9] found that the application of a static magnetic field in the plane of a sample increased the wall velocity and also made it anisotropic. High-speed photography of bubble domain walls revealed the existence of regions moving at different velocities,[10,11] which may, in particular, cause rupture of stripe domains and produce a bubble lattice.[12]

The present paper reports a detailed high-speed photographic investigation of the dynamics of domain structures in iron garnet films under the action of pulsed bias fields of $0-10^3$ Oe intensity.

In the next (second) section we shall describe the method and apparatus used to study the domain dynamics and we shall give the properties of the investigated iron garnet films. In the third section we shall report the results of an experimental investigation of the domain wall velocity, rupture of stripe domains, distortion of the shape of bubble and stripe domains, and influence of a static field applied in the plane of the film on the domain wall dynamics. The fourth section is devoted to a discussion of the experimental results. The main conclusions are formulated in the final section.

2. EXPERIMENTS

We used a high-speed image-converter system described by Ivanov *et al.*[13] The domain structure was investigated by the Faraday effect. The source of illumination was a GaAs–GaAlAs double-heterojunction injection laser emitting at the wavelength of $\sim 0.9\ \mu$. The exposure time was set by the duration of the current pulses used to pump the laser and it amounted to ~ 10 nsec. The pulse laser power did not exceed 10 W, which avoided heating of a sample by laser radiation. The relatively large width of the laser spectrum (~ 40 Å) prevented undesirable interference effects in the observations of domain structures. The domain image brightness was amplified by a UNI-93 image converter with a cesium oxide photocathode whose temporal and spatial resolution was $\sim 10^{-11}$ sec and ~ 15 lines/mm, respectively, and whose current gain was $\sim 10^5$. The noise level was reduced by operating the converter only for a time slightly longer than the duration of the laser light pulses. Images of domain structures were photographed from the converter screen. The beginning of a magnetic field pulse could be delayed relative to the light pulse by $0-10^3\ \mu$sec and their relative positions on the time axis could be set to within 1 nsec for short delay times ($0-2\ \mu$sec).

A homogeneous pulsed magnetic field was applied to an illuminated part of a sample ($200 \times 100\ \mu^2$ in area) by a flat coil 2 mm in diameter located near the surface

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of the sample; current pulses up to 15 A amplitude and edge duration not exceeding 20 nsec were passed through this coil. The fall at the top of the pulse did not exceed 5%. The duration of a magnetic field pulse could be varied within the range 0.1–10 μsec. A bias field up to 200 Oe was produced by the coil inside which the sample was located. A static field in the plane of the sample (up to 500 Oe) was generated by a pair of Helmholtz coils.

The experimental results were obtained in the form of a series of three photographs recording the initial domain structure, its configuration at some moment during the action of a magnetic field pulse or after this pulse, and final domain structure. A comparison of the photographs of moving domains at various moments made it possible to establish the time dependences of the displacement of various parts of domain walls.

Our samples were single-crystal garnet films of the $(YGdYbBi)_3(FeAl)_5O_{12}$ system grown by liquid epitaxy from a molten solution on the (111) planes of gadolinium-garnet ($Gd_3Ga_5O_{12}$) substrates. The properties of these films were as follows: thickness h = 10–20 μ, period of the equilibrium stripe domain structure P_0 = 10–50 μ, bubble domain collapse field H_0 = 50–150 Oe, saturation magnetization $4\pi M_s$ = 70–200 G, anisotropy field H_K = 1.5–4.0 kOe.

3. RESULTS

The dynamic behavior of domains in a pulsed bias field is governed by the amplitude H_p and duration τ_p of the pulses, and is a function of initial domain configuration and of a static magnetic field $H_{\parallel}$ applied in the plane of the sample.

Dynamics of stripe domains. The application of a bias field pulse broadens domains magnetized along the field at the expense of domains which have the unfavorable magnetization. If the amplitude and/or duration of the field pulse are sufficiently small, the initial and final domain configurations are the same (Fig. 1). In the range $|H_p| > H_0$, it is found that some time after the application of the field pulse the unfavorably magnetized domains rupture and the size of the regions formed after such rupture decreases. If the field pulse terminates before complete remagnetization of the unfavorably magnetized domains, their dimensions begin to increase and the dipole interaction between domains produces a magnetic bubble lattice (Fig. 2). Under optimal conditions the distance between neighboring ruptures is close to the period of an equilibrium stripe domain structure. If the amplitude and duration of the field pulse are sufficiently large, a sample is magnetized to saturation (Fig. 3b). After the end of the field pulse, the structure "grows" from the edges of the sample. The velocity of the growth front is close to the velocity of the domain wall moving under the action of a field pulse of amplitude causing magnetization saturation and, in the case of the sample in Fig. 3, this velocity is $v_f \approx$ 13 m/sec. There are different topologies of a growing domain structure with unequal domain widths (Figs. 3c and 3d), which are probably associated with different shapes of the domain structure front at the end of a field pulse. Fronts growing from different sides meet (Fig. 3e) and produce equilibrium domain structures of different topologies but with similar domain widths (Fig. 3f).

Figure 4 shows the dependence $\tau_p^{-1}(H_p)$, where τ_p and

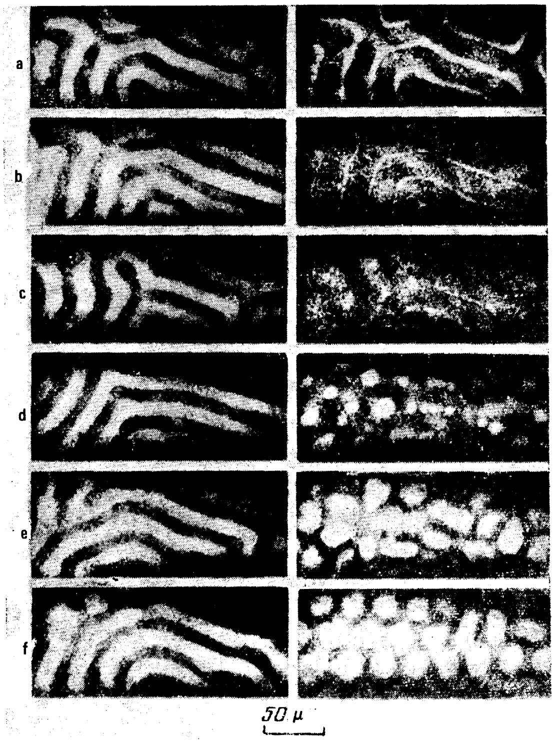

FIG. 2. Initial (on the left) and moving (on the right) domains in H_p = 670 Oe, τ_p = 0.40 μ sec: a) t = 0.18 μ sec; b) 0.38 μ sec; c) 0.48 μsec; d) 1.0 μsec; e) 2.0 μsec; f) ∞.

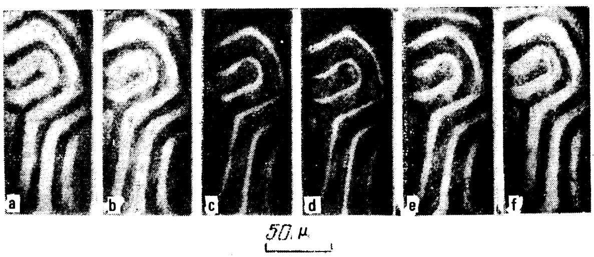

FIG. 1. Initial (a), dynamic (b–e), and final (f) domain structures obtained for H_p = 520 Oe, τ_p = 400 nsec: a) t = 0; b) 50 nsec; c) 100 nsec; d) 200 nsec; e) 350 nsec; f) ∞.

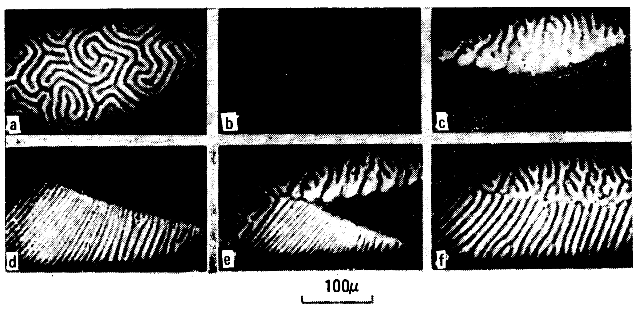

FIG. 3. Initial (a), dynamic (b–e), and final (f) domain structures for H_p = 700 Oe, τ_p = 0.5 μ sec.

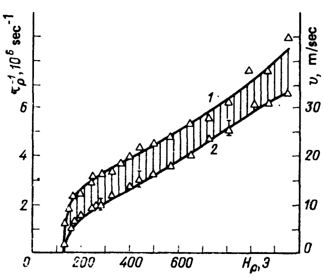

FIG. 4. Range of the amplitudes and durations of field pulses whose repeated application produces a bubble domain lattice.

H_p are the duration and amplitude of a field pulse needed, in zero bias field, to rupture stripe domains (curve 1) and to magnetize a sample to saturation (curve 2). The shaded region in Fig. 4 represents the range of changes in the amplitude and duration of the field pulses which, applied repeatedly, produce a bubble-domain lattice (a single H_p pulse generates a lattice of elliptic and stripe domains of finite length).

Figure 5 shows, for the same sample, the dependence of the initial velocity of the stripe domain walls on the amplitude of a field pulse. In the initial state the sample is subjected to a bias field $H_b = 110$ Oe, which is less than the collapse field $H_0 = 126$ Oe. Therefore, the distance between neighboring unfavorably magnetized domains is several times greater than the period P_0. These domains expand under the action of the field pulse and the domain walls moved a distance of 20–30 μ. The time dependence of the displacement of domain walls is found by plotting the results taken from the high-speed photographs and then the initial velocity is determined.

If the duration of a field pulse broadening stripe domain is sufficiently high but its amplitude is moderate ($|H_p| \lesssim |H_0| + |H_b|$), the shape of the stripe domain becomes distorted to typical configurations shown in Fig. 6. The initial and resultant domain structures are identical only if the field pulses have a moderate amplitude. After the end of a field pulse H_p of sufficiently large amplitude, the relaxation process is accompanied by the rupture of stripe domains and formation of bubbles.

The stripe domain width P^* at which the distortion of the shape takes place increases on increase of H_p. A typical dependence $P^*(H_p)$ is shown in Fig. 7. The time interval t^* after which these distortions appear is governed by the value of P^* and by the time dependence of the domain wall velocity. For moderate pulse durations τ_p there is no distortion in the stripe domain

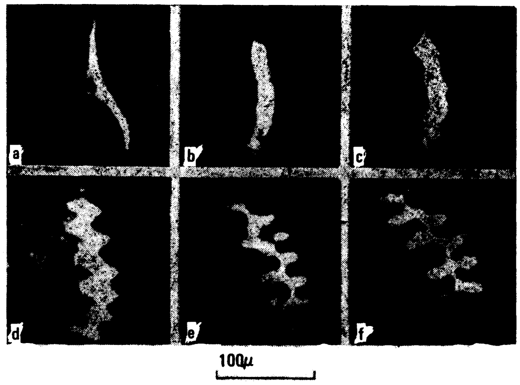

FIG. 6. Dynamic domains in $H_b = -110$ Oe, $H_p = 75$ Oe, $\tau_p = 2.0\ \mu$sec: a) $t = 0$; b) 0.60 μsec; c) 0.80 μsec; d) 1.20 μsec; e) 1.60 μsec; f) 2.00 μsec.

shape.

The period of distortions of stripe domains is close to the value of P_0, but it may vary within a certain range in a random manner from one pulse to the next. There is no dependence of this period on the amplitude H_p.

Dynamics of bubble domains. If a pulsed field is applied along the same direction as the bias field stabilizing bubble domains, the bubble diameter decreases and for sufficiently large amplitudes H_p and durations τ_p a bubble collapses. The dynamics of collapse of bubble domains has been investigated earlier.[11,14]

If the directions of the pulsed and bias fields are opposite, the dimensions of a bubble domain increase. For pulses of sufficiently large duration τ_p the distortion of the circular shape of the bubble domain is observed and the rotation periodicity n depends on the amplitude H_p. Such distortions form as follows: some parts of the domain walls slow down and begin to move in the opposite direction (toward the domain center), whereas others continue their translational motion at a constant velocity. The number of "rays" n in such a star-like structure depends on the amplitude H_p. If the pulse duration is increased, the "rays" begin to branch out. Figure 8 shows typical distortions of the shape of bubble domains (the initial state is shown in Fig. 8a) under the action of field pulses of different amplitudes.

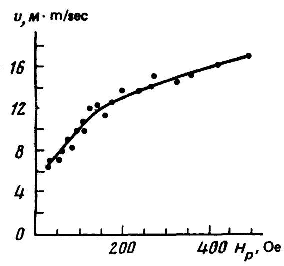

FIG. 5. Dependence of the velocity of stripe domain walls on the amplitude of field pulses.

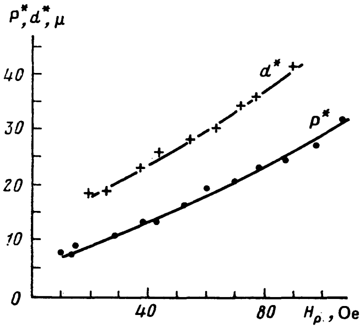

FIG. 7. Dependence of the width of stripe domains P^* and of the diameter of bubble domains d^*, at which the shape distortions appear, on the amplitude of the pulsed field.

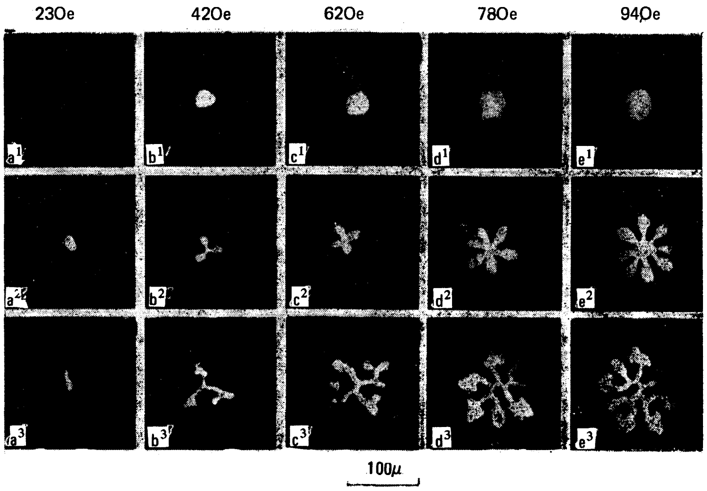

FIG. 8. Dynamic domains at various moments t: a^1) 0; a^2) 0.7 μsec; a^3) 1.3 ρsec; b^1) 1.0 μsec; b^2) 1.7 μsec; b^3) 3.5 μsec; c^1) 1.2 μsec; c^2) 2.0 μsec; c^3) 4.5 μsec; d^1) 2.0 μsec; d^2)3.5 μsec; d^3) 5.0 μsec; e^1) 1.8 μsec; e^2) 4.0 μsec; e^3) 5.5 μsec. The values of the pulsed field H_p are given in the top of the figure. The duration of the field pulses was $\tau_p = 6$ μsec.

Distortions with a rotation periodicity n are observed in a certain range of H_p but the ranges for two consecutive values of n overlap slightly. It is clear from Fig. 8 that an increase of n is accompanied by an increase in the bubble size d^* at which distortions of its circular shape are observed and, the higher the value of n, the later the onset of distortions of this periodicity. A typical dependence $d^*(H_p)$ is shown in Fig. 7.

Figure 9 reproduces photographs illustrating the process of topological switching of bubble domain lattices in one of the samples. In the investigated samples the domain wall velocities did not differ in direction by more than 10%, which made it impossible to switch topologically regular bubble lattices by a bias field pulse. Even when the initial structure was a regular hexagonal lattice of bubbles of the same polarity (dark bubbles against a bright background), no amplitude or duration of the bias field pulse was sufficient to transform it into a regular bubble domain lattice of the opposite polarity (bright bubbles against a dark background). The resultant domain structure was an irregular lattice of bubbles of different diameters.

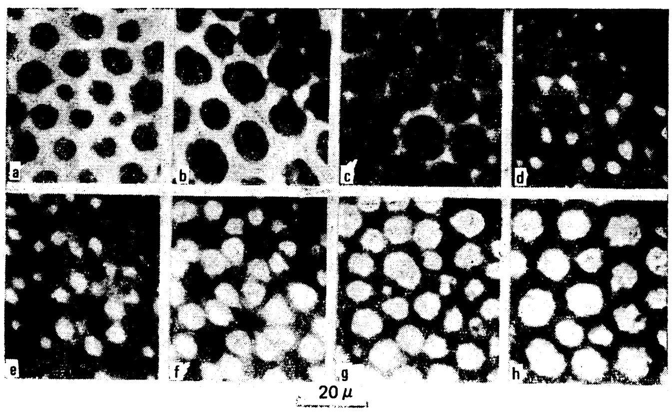

FIG. 9. Dynamic domains observed for $H_p = 173$ Oe, $\tau_p = 0.5$ = 0.5 μsec, $H_b = 0$: a) $t = 0$; b) 0.2 μsec; c) 0.4 μsec; d)0.45 μsec; e) 0.55 μsec; f) 0.8 μsec; g) 2.0 μsec; h)∞.

Influence of a field in the plane of a sample. The influence of a magnetic field applied in the plane of a film on the dynamics of domain walls was studied by recording the radial motion of bubble walls under the action of a bias field pulse H_p and in the presence of a static planar field $H_\parallel$. In the initial state a bubble domain was stabilized by the bias field slightly lower than the collapse field. A comparison of photographs of moving domains at various moments from the application of a field pulse H_p indicated that the velocity of bubble walls depended on the angle of travel of a given part of a domain wall relative to the planar field. Therefore, bubble domains became elliptic. The direction of the major axis of the elliptic domains was usually inclined at an angle $\varphi = 50-90°$ relative to the planar field. By way of example, we reproduced in Fig. 10 some photographs of moving domains obtained in a field $H_p = 65$ Oe ($\tau_p = 0.5$ sec) in the presence of a field $H = 500$ Oe (left-hand column) and in the absence of this field (right-hand column). The average angle φ for this sample was $\bar{\varphi} = 65°$ and the rms deviation was $\delta\varphi = 7°$ deduced for 50 domains. The value of $\bar{\varphi}$ was practically independent of the planar field in the range $H_\parallel = 100-500$ Oe. In a field $H_\parallel = 0$ the ellipticity of bubble domains was weak and in this case we found that $\bar{\varphi} = 35°$ and $\delta\varphi = 15°$.

The initial domain wall velocities in the direction of the major and minor axes of an elliptic domain (v_{max} and v_{min}, respectively) determined in the presence of a planar field $H_\parallel = 500$ Oe differed approximately by a factor of 1.7, whereas in $H_\parallel = 0$ the domain wall velocities v were the same along all directions (within the limits of the experimental error). The application of a field in the plane of a sample increased the domain wall velocity irrespective of the value of H_p.

The dependences of v_{max}, v_{min}, and v on the pulsed field amplitude are plotted in Fig. 11 (curves 1, 2, and 3, respectively) for $H_\parallel = 500$ Oe. We can see that in fields $H_p > 100$ Oe the domain wall velocity increases with the rise of H_p and the rate of rise corresponds to

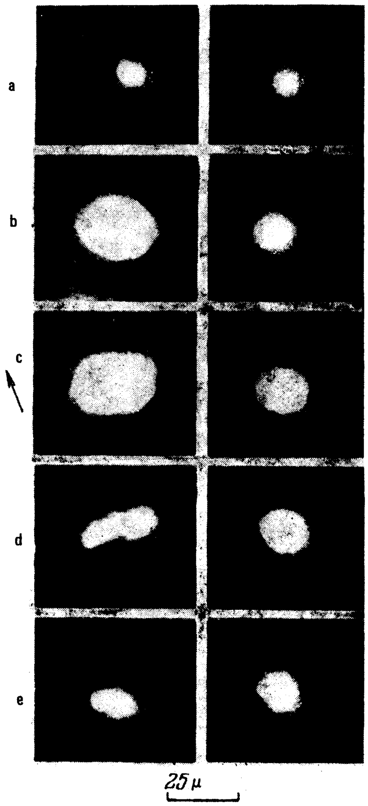

FIG. 10. Dynamic domains observed in $H_p = 65$ Oe and $\tau_p = 0.50$ μsec in the presence of a field $H_{\parallel} = 500$ Oe (left-hand column) and in the absence of this field (right-hand column): a) $t = 0$; b) 0.20 μsec; c) 0.40 μsec; d) 0.55 μsec; e) 0.70 μsec. The arrow gives the direction of the field in the plane of the sample.

a differential mobility $\mu = 2 - 10$ cm · sec^{-1} · Oe^{-1}. Fig. 12 shows the dependences of $v_{\max}$ and $v_{\min}$ on the field $H_{\parallel}$ obtained for $H_p = 470$ Oe. We can see that an increase in H_p enhances the velocities themselves as well as the difference between them. The application of a field 500 Oe in the plane of a sample increases the domain wall velocities severalfold:

$$v_{\max}/v \approx 4.1, \quad v_{\min}/v \approx 2.4.$$

It follows from this investigation of the radial motion of the domain walls that the application of a field in the plane of a film not only increases the velocity of domain walls but makes these velocities anisotropic.

4. DISCUSSION OF RESULTS

A comparison of the experimental results of our investigation of domain wall dynamics with the theory is

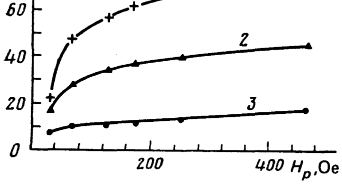

FIG. 11. Dependences of $v_{\max}$, $v_{\min}$, and v (curves 1, 2, and 3, respectively) on the pulsed field in the presence of $H_{\parallel} = 500$ Oe.

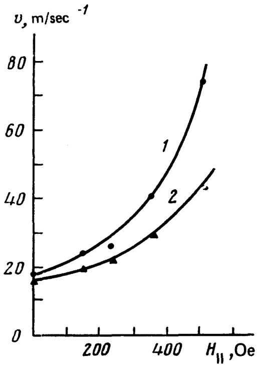

FIG. 12. Dependences of $v_{\max}$ and $v_{\min}$ (curves 1 and 2, respectively) on the field in the plane of the film $H_{\parallel}$ in the presence of $H_p = 470$ Oe.

difficult because the theory of motion of the domain walls[15-25] is developed only for some external field. In the main, the theoretical analyses apply only to the case of steady-state motion which occurs in weak fields. Theoretical investigations are usually based on the Landau–Lifshitz equation for the motion of magnetization.[15] The exact solution of this equation was obtained by Walker[16] only for the case of an isolated Bloch domain wall moving in an infinite medium. The velocity of such a wall in an applied field H is, according to Walker,

$$v=\gamma H\alpha^{-1}(A/K_u)^{1/2}\{1+\pi M_s^2K_u^{-1}[1-[1-(H/2\pi\alpha M_s)^2]^{1/2}]\}^{-1/2}. \quad (1)$$

Here, γ is the gyromagnetic ratio; α is the Gilbert dimensionless damping parameter; A is the exchange interaction constant; K_u is the uniaxial anisotropy constant. The solution (1) is valid if the acting field does not exceed a critical value

$$H_w = 2\pi\alpha M_s. \quad (2)$$

In weak fields $H < H_w$ the wall velocity is proportional to the acting field. However, in high fields the velocity reaches saturation. The maximum velocity is then[16]

$$v_w = 2\pi\gamma M_s(A/K_u)^{1/2}. \quad (3)$$

In thin films the interaction of domain walls with stray fields, which appear necessarily because domains coexist with a magnetization directed along the normal to the plane of the sample, complicates the structure.[17-19] A domain wall becomes twisted. The exact solution of the Landau–Lifshitz equation for such a wall cannot be obtained. A reasonable approximation which simplifies the equation was proposed by Slonczewski for the case $K_u \gg 2\pi M_s^2$ and a moderately thin film, which is true of materials with bubble domains. Slonczewski showed that the stray fields destabilized the structure of a domain wall at the following critical values of the velocity v_s, which is less than the Walker limit, and acting field H_s:

$$H_s = 9.5\gamma h^{-1}(2\pi A)^{1/2}, \quad (4)$$

$$v_s = 24\gamma A/hK_u^{1/2}. \quad (5)$$

According to Slonczewski, in fields $H > H_s$ we may expect generation, motion, and annihilation of horizontal Bloch lines, so that the velocity decreases asymptotically to the limit v_0:

$$v_0 = 7.1\gamma A/hK_u^{1/2}. \tag{6}$$

The motion of the wall then becomes oscillatory.

Hagedorn[21] supplemented Slonczewski's idea on the generation and propagation of horizontal Bloch lines by the concept of gyrotropic Thiele forces[20] and he showed that the action of these forces on a moving horizontal Bloch line in a domain wall produces vertical Bloch lines, which have a greater influence on the domain wall motion.

Estimates indicate that H_s and H_W are usually within the range from 1 to 10 Oe, so that we can expect the motion of a wall to become unsteady in sufficiently high fields $H > 10$ Oe. Using the parameters h, K_u, $4\pi M_s$, and A (the value of A subject to a large error[1]), deduced from the static measurements and gyromagnetic electron ratio $\gamma = 1.76\times 10^7$ rad · sec^{-1} · Oe^{-1} for the sample whose dependence $v(H_p)$ is shown in Fig. 1, we find that Eqs. (2), (3), (5), and (6) give $v_W \approx 40$ m/sec, $v_s \approx 1.1$ m/sec, and $v_0 \approx 0.37$ m/sec. Thus, the experimentally determined range of velocities v of stripe domain walls (Fig. 5) lies in the range $v_s < v < v_W$.

It is clear from Fig. 5 that extension of the curve $v(H_p)$ to $H_p = 0$ intersects the ordinate at a positive value of v. This indicates that there is an additional high-mobility region in weak fields. Such a region has indeed been observed in experimental studies of the translation of bubble domains in an inhomogeneous field.[26]

Rupture of unfavorably magnetized domains can be explained by assuming that a domain wall consists of alternate regions moving at different velocities ("heavy" and "light" regions). For example, a light region may correspond to a Bloch structure at the center of the wall and the heavy one to a Néel structure or to a cluster of vertical Bloch walls. The average velocities of the heavy and light regions v_H and v_L can be estimated as follows:

$$v_H = P_0/4\tau_{p2}, \tag{7}$$

$$v_L = P_0/4\tau_{p1}, \tag{8}$$

where τ_{p1} and τ_{p2} are the minimum durations of the field pulses of given amplitude which have to be applied to cause domain rupture and magnetization of a sample to saturation, respectively. It then follows from Eqs. (7) and (8) that curves 1 and 2 in Fig. 4 describe, respectively, the dependences $v_L(H_p)$ and $v_H(H_p)$.

The difference between the velocities of the heavy and light parts of a domain wall should twist it by an amount which increases with time. Such twisting is not observed experimentally. It is clear from Fig. 2 that the nonuniformity of the width of moving domain does not exceed 1 μ. Consequently, we may conclude that the twisting of a domain wall occurs only during the first moments after the application of a field pulse. Next, the elastic interaction between the heavy and light regions of a wall results in the equalization of their velocities so that the subsequent deviation of the domain wall from the rectilinear shape remains constant and the domain wall moves at an average velocity v_{av}. The deviation of the shape of a domain wall from rectilinear is the cause of rupture of the stripe domains when two neighboring domain walls approach each other. The amplitude of deviation of a domain wall from a linear shape can be estimated from

$$\Delta x = v_{av}(\tau_{p2} - \tau_{p1}). \tag{9}$$

Investigations of the motion of stripe domain walls[27,28] by the photoelectric method,[29] which made it possible to record the integrated velocity averaged over all the walls is an area of 100×100 μ^2, revealed a strong reduction in the wall velocity in 10–12 nsec from the beginning of motion when the threshold value $v_s = 10$–30 m/sec was exceeded. It was concluded that this was due to the creation of Bloch lines. These lines existed also when the wall velocity decreased considerably until the motion stopped and then reversed on condition that the walls did not stop for more than 15–20 nsec; the Bloch lines disappeared when the walls stopped for longer than 20 nsec. This conclusion[29] was not in agreement with other results[10,30] showing that Bloch lines were retained in a domain wall at rest for at least a few seconds and even minutes.

In our opinion, the former results[27,28] do not indicate creation of Bloch lines 10–12 nsec from the beginning of motion of a domain wall but are evidence of the existence, in the initial state of a wall, of regions moving at different velocities, which twist the domain wall by an amount which increases to a maximum in 10–12 nsec. After this time the velocity of the light parts of the wall decreases strongly, so that the integrated velocity also decreases. In weak acting fields the displacement of a wall to a new equilibrium position does not exceed the permissible amplitude Δx of its curvature (according to Refs. 27 and 28, the value of Δx measured by the photoelectric method is 0.2–0.3 μ), so that there is no abrupt reduction in the velocity. The hypothesis of attainment of the limiting curvature of a domain wall, responsible for the abrupt reduction in its velocity, is confirmed also by the observation that after reversal of the direction of a wall there is an initial increase in the velocity during the first few moments after the end of a pulse.[28] The velocity of a straight wall with Bloch lines should not be affected by a change in the direction of motion.

It follows from our results as well as from those reported earlier[10,27,28] that a domain wall consists of alternate regions with different initial velocities. The action of a homogeneous field pulse twists a domain wall so that rupture of stripe domains occurs if the amplitude and duration of this pulse are sufficiently large.

The distortion of the shape of stripe and bubble domains can be explained by analyzing the expression for the total energy of a sample

$$E = E_w + E_H + E_m \tag{10}$$

where E_w is the energy of a domain wall, E_H is the energy of the interaction with an external field, and E_m is the magnetostatic energy of internal demagnetizing field.

We shall consider a sample with a stripe domain structure. In this case the energy of domain walls per square centimeter of the film surface is

$$E_w=2\sigma_w h(d_1+d_2)^{-1}, \tag{11}$$

where σ_w is the surface energy density in a wall; d_1 and d_2 are the widths of favorably and unfavorably magnetized domains.

The energy of the interaction with an external field (per 1 cm^2 of the film area) is

$$E_H=-HM_S h(d_1-d_2)(d_1+d_2)^{-1}=-HM_S h(M/M_S), \tag{12}$$

where M is the total magnetization of a sample.

The greatest difficulty is encountered in the calculation of the last term E_m. For a stripe domain structure the magnetostatic energy (per 1 cm^2) calculated allowing for the μ effect ($\mu=1+2\pi M_s^2 K_u^{-1}$) can be expressed as follows:[31]

$$E_м=2\pi M_S{}^2 h(M/M_S)^2+16\pi^{-2}M_S{}^2 h\alpha^{-1}\mu^{1/2}\cdot \sum_n n^{-3}\sin^2\left[\frac{\pi n}{2}\left(1+\frac{M}{M_S}\right)\right]\frac{\operatorname{sh}\pi n\alpha}{\operatorname{sh}\pi n\alpha+\mu^{1/2}\operatorname{ch}\pi n\alpha}, \tag{13}$$

where

$$\alpha=h\mu^{1/2}(d_1+d_2)^{-1}. \tag{14}$$

The first part of Eq. (13) describes the magnetostatic energy of a homogeneously magnetized plate whose magnetization is M. The second term allows for deviations from homogeneity due to the domain structure. Equation (13) is valid for an arbitrary thickness h.

It follows from Eq. (13) that the magnetostatic energy decreases on reduction of the period d_1+d_2 of a stripe domain structure. The process of splitting of a sample in the domain is complete when the gain in the magnetostatic energy because of the formation of smaller domains becomes less than the energy required to form new domain walls.

During the first few moments after the application of a pulsed field H_p antiparallel to the bias field the total magnetization of a sample begins to decrease. The width of the unfavorably magnetized domains increases because of the motion of domain walls but the magnetostatic energy of the sample also increases. Therefore, when the total magnetic moment reaches approximately its equilibrium value corresponding to the field H_b-H_p, the domain shapes change in such a way as to reduce the magnetostatic energy: the domain structure becomes finer and then some parts of the domain walls begin to move towards the center of the domain while others continue to move away from the center. The domain structure then assumes the form shown in Figs. 6 and 8.

A theoretical analysis of the motion of a domain wall in materials with bubble domains subjected to a magnetic field in the plane of a sample has been carried out only for the case of steady-state motion.[23,24,30] In particular, the Landau–Lifshitz equation[15] has been analyzed[23] by the method of the qualitative theory of differential equations, yielding an expression for the maximum possible velocity of the steady-state motion of a Bloch domain wall:

$$v_{\max}=\gamma(A/K_u)^{1/2}\{[(\sigma+1)^{1/2}-[1-(H_\parallel/H_K)]^{1/2}]^2+\sigma(H_y/H_K)^2\}^{1/2}. \tag{15}$$

Here $\sigma=4\pi M_s/H_K$; $H_K=2K_u/M_s$ is the anisotropy field; $H_\parallel=(H_x^2+H_y^2)^{1/2}$ is the field in the plane of the film; A_y is the component parallel to the domain wall plane.

Although the conditions of validity of Eq. (15) were not realized in our experiments (the motion of a domain wall was not of the steady-state type and we investigated radial expansion of bubble domains and not the motion of a plain domain wall), there is nevertheless a qualitative agreement between Eq. (15) and the experimental results: the velocity of the domain walls increases considerably on increase of $H_\parallel$ and an anisotropy of the wall velocity, predicted by Eq. (15), is observed. Since the direction of the maximum wall velocity found experimentally is not perpendicular to the field $H_\parallel$, contrary to Eq. (15), but makes an angle of $\bar{\varphi}=65°$ with this field, it follows that there is a component of the orthorhombic anisotropy in the plane of the film.[1]

It has been shown[24] that the limiting velocity of steady-state motion of a twisted domain wall is

$$v_{\lim}=v_s(1+|H_\parallel|/H_i), \tag{16}$$

where v_s is the Slonczewski threshold velocity [see Eq. (5)] and H_i is the initial field in which the structure of a domain wall begins to change:[31]

$$H_i\propto 2h^{-1}(A/K_u)^{1/2}(H_K 4\pi M_S)^{1/2}. \tag{17}$$

Since for our samples $H_i\sim 1.5$ Oe, it follows from Eq. (16) that the domain wall velocity should increase by over two orders of magnitude on increase of the field $H_\parallel$ from 0 to 500 Oe, which is contrary to the experimental evidence. Therefore, we may conclude that even if a strong rise of the velocity of the steady-state motion of a twisted domain wall on application of a field $H_\parallel$ in the film plane does take place, the wall velocity drops steeply on attainment of the limiting value $v_{\lim}$.

5. CONCLUSIONS

An investigation of the dynamic behavior of domain structures in iron garnet films subjected to homogeneous magnetic field pulses of $0-10^3$ Oe intensity allowed us to draw the following conclusions.

1. A domain wall has regions with different initial velocities (light and heavy regions), which result in twisting of a domain wall on application of a bias field pulse. When the maximum possible amplitude of twist of a domain wall is attained, the velocities of the light and heavy regions become equalized. The twisting of domain walls results in the rupture of stripe domains.

2. The dynamic distortion of the shape of stripe and bubble domains is of magnetostatic origin. During the first moments after the application of a field pulse antiparallel to the bias field there is a reduction in the total magnetization of a sample because of an increase in the width of unfavorably magnetized domains. Sometime later the structure breaks up into smaller domains and this reduces the magnetostatic energy.

3. The application of a static magnetic field in the plane of a film accelerates, irrespective of the amplitude of the pulsed bias field, the motion of domain walls

and also gives rise to an anisotropy of this motion.

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Infrared divergence in field theory of a Bose system with a condensate

Yu. A. Nepomnyashchiĭ and A. A. Nepomnyashchiĭ

Perm' State University

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Exact equations are obtained (in particular, for the anomalous self-energy part $\Sigma_{12}(0) = 0$ and for the scattering vertex of two phonons $\Gamma_4(p_i \to 0) = 0$), which indicate that in the general case the usual methods of summing the field perturbation-theory diagrams for Bose systems are not valid (the calculation must not be stopped when a converging result is obtained in the lower order in some small parameter). An investigation of the character of the infrared divergence of the field diagrams has yielded the region of applicability of the ordinary summation methods. It is shown that in the case $T > 0$ or of a two-dimensional system at $T = 0$ one must use a special regularization that calls for introducing the phonon vertices counterterms that, in contrast to the relativistic theories, contain no infinities and do not change the initial Hamiltonian at all. Examples of effective summation are presented for cases when the usual approach leads to an erroneous result [$\Sigma_{12}(p \to 0)$, $\Pi(p \to 0)$, and others]. The derivation of the asymptotic Gavoret and Nozieres formulas for the Green's functions and the susceptibilities is re-examined with account taken of the equality $\Sigma_{12}(0) = 0$.

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1. INTRODUCTION

The field theory developed in Refs. 1 and 2 has been successfully used for a qualitative analysis of the properties of superfluid He^4 (primarily the singularities of the spectrum; see, e.g., Refs. 3 and 4), as well as to verify, with the aid of simple models, the correctness of other microscopic approaches[5] and assump-

