Dynamics of a 180-degree Bloch wall in yttrium iron garnet

L. M. Dedukh, V. I. Nikitenko, and A. A. Polyanskiĭ

Institute of Solid State Physics, Academy of Sciences, USSR
(Submitted 15 February 1980)
Zh. Eksp. Teor. Fiz. 79, 605–618 (August 1980)

A new method is developed for measuring the mobility μ of a domain boundary and its mass m, with application to a single crystal of yttrium iron garnet in the form of an elongated rectangular prism, containing an isolated 180-degree Bloch wall parallel to an axis of easy magnetization and to the long edge of the specimen. A dependence of m and μ on the value of the external magnetic field H is observed, beginning with values of H comparable with the coercive force for boundary displacement. It is shown that the measured m exceeds by several orders of magnitude that calculated according to Döring. The possible contribution of various mechanisms to the shaping of the dynamic charactistics of a domain boundary is analyzed. It is shown that the observed features of its motion may have not only a gyroscopic but also a dissipative nature and may indicate a change, with increase of H, of the mechanism of transfer of energy from the moving boundary to the magnon subsystem. The influence of potential barriers, due to dislocations, on the character of the wall motion in an alternating magnetic field is investigated.

PACS numbers: 75.60.Ch, 75.50.Gg

Motion of a domain boundary (DB) is an elementary event determining the magnetization of a ferromagnet. Without an analysis in principle of the basic mechanisms limiting the resistance to this motion, it is impossible to construct a systematic physical theory of the magnetization of magnetically ordered substances. The problem of investigating DB mobility has recently acquired immediate practical significance as well: the DB velocity directly limits the speed of action of new and most promising memory elements for computers, which use microdomains as carriers of information. It is this fact that has stimulated a profound development of the theory, within a very short time, and a broad front of experimental study of the dynamics of DB in uniacial thin-film materials for which $2\pi M^2 \ll K$ (M is the saturation magnetization, K the anisotropy constant); this ensures favorable conditions for formation of cylindrical magnetic domains (bits of information).

The mobility of DB in many-axis dielectric ferrimagnets in which $2\pi M^2 \gg K$, in particular in yttrium iron garnet (YIG), has been less investigated. Yet use of these crystals opens up additional experimental possibilities for solution of several fundamental problems of the physics of DB: investigations of the structure of 180-degree Bloch walls, their interactions with dislocations, etc. Results recently obtained on YIG in a few papers[1-6] have already raised a number of major controversial problems.

The first investigations of YIG showed that the velocity v of a DB increases proportionally with the intensity H of the external magnetic field: $v=\mu(H-H_c)$, where μ is the DB mobility and H_c is the coercive force for motion of it. The value of μ was independent of H and almost two orders of magnitude smaller than that calculated from the damping parameter obtained from measurements of the width ΔH of the ferromagnetic resonance (FMR) line ($\mu=2\omega\delta_0/\Delta H$), where ω is the angular frequency of FMR, $\delta_0=(A/K)^{1/2}$ is the DB width parameter, and A is the exchange-energy constant.[1] Such a striking discrepancy, not observed in other materials, caused surprise[6] and has so far not been explained. The values of μ measured in later papers[5,6] were also small in comparison with the calculated. But in Refs. 5 and 6, there was discovered also a decrease of the mobility with increase of H; a nonlinear $v(H)$ dependence began to show up in the smallest fields.

The causes of this may originate in phenomena of quite different natures. As is well known, the mechanisms that determined resistance to DB motion are customarily divided into two classes. The first of these is produced by potential barriers to the motion of a boundary, due either to the periodicity of the distribution of atoms in the crystal lattice (Peierls barriers[7]) or to defects in it.[8] The energy W of a boundary depends on the coordinate x in the direction of its motion in a potential contour. Motion of a DB over a macroscopic distance, comparable with a dimension of the specimen, can begin only when the force exerted on it by the external magnetic field H exceeds a certain critical value, the coercive force $H_c=[\partial W(x)/\partial x]_{max}/2M$. In fields slightly exceeding H_c, nonlinearity of $v(H)$ may be due[9] to barriers caused by defects of the crystal lattice.

Under conditions of above-barrier motion of a boundary ($H \gg H_c$), the resistance to its motion is determined by the second class of mechanisms, which are of dynamic nature. Its velocity begins to be limited by the diverse methods of transfer of energy from the DB to the various branches of the elementary excitations of the crystal (magnons, phonons, etc.).[10-17] If a DB moves nonuniformly in the field of defects, it may[18] radiate spin waves. These radiation losses may in principle play an important role in the dynamic retardation of such a slowly moving wall. With increase of the value of the external magnetic field, a decisive contribution to the resistance to DB motion is made by processes of scattering of magnons by the wall. The force f of dynamic retardation of a DB may depend on its velocity v not only linearly ($f=\beta v$, where β is an effective viscosity) but also more abruptly; this is de-

 0038-5646/80/080306-08$02.40

termined by the difference of the contributions of many-particle processes[14] to the retardation of the DB with change of v. On approach to v to the value of the minimum phase velocity of spin waves, the efflux of energy from the DB should be determined by radiation losses due to coherent radiation of spin waves.[19]

From this short summary, it becomes obvious that the parameters that characterize the dissipation of energy during reorientation of spins in the process of DB motion must in general depend on its velocity and may, beyond the limits of some v interval, differ from those that are determined by the scattering of energy in a system of precessing spins during measurements of uniform FMR. The $v(H)$ relation may be nonlinear to the extent of the change of the mechanism of dissipative losses described by the damping parameter λ in the Landau-Lifshitz-Gilbert equation. But even for a single relaxation process ($\lambda = \text{const}$) limiting the DB velocity over a wide v interval, nonlinear $v(H)$ dependence may result from a dynamic change of the boundary structure;[20] this has at present been the object of the widest discussion.

In the present paper, an attempt is made to separate the contributions of the indicated, physically different causes that produce the experimentally observed features of DB motion in YIG. In the development of Ref. 5, together with measurements of the mobility of an isolated 180-degree Bloch wall, a determination was made of its mass m. It also must depend on the structure of the wall;[21,22] and this leads us to hope that in comparing the behaviors of $\beta(H)$ and of $m(H)$ we may obtain the additional information that is necessary for solution of the problem posed. In the article we also present the results of a direct experimental study of the motion of DB in the field of microstresses due to individual dislocations.

METHODOLOGICAL PROBLEMS OF THE INVESTIGATION

As is well known,[23] a macroscopic description of the displacement of domain walls is accomplished on the basis of a consideration of the equation of motion of the magnetization $\mathbf{M}$ in a boundary layer:

$$\dot{\mathbf{M}}=\gamma[\mathbf{M}\times \mathbf{H}_{eff}]+\lambda[\mathbf{M}\times \dot{\mathbf{M}}]/M, \tag{1}$$

where γ is the gyromagnetic ratio and H_{eff} is the effective magnetic field acting on $\mathbf{M}$. The dissipative processes that lead to a gradual rotation of M toward H_{eff} are taken into account through the phenomenological parameter λ. For small velocities of displacement of the DB in a bounded crystal, the equation of motion of a 180-degree Bloch wall, under the action of a constant external field H, can be obtained from (1):

$$m\ddot{x}+\beta\dot{x}=F_{eff}=2MH-\alpha x. \tag{2}$$

In the linear approximation, the mass of the boundary[24]

$$m_D=1/4\pi\gamma^2\delta_0 \tag{3}$$

and the effective viscosity

$$\beta=2M/\mu=2\lambda M/\gamma\delta_0 \tag{4}$$

are independent of H. The coefficient

$$\alpha=2MH/x_0 \tag{5}$$

takes account of the change of the force exerted on the wall by the external magnetic field as a result of the appearance on the crystal surface of demagnetizing fields. In a static constant field, F_{eff} becomes zero when the boundary is displaced by a distance $x_0 = 2MH/\alpha$.

A precision determination of the $v(H)$ relation and of the parameters m and β according to (2) can be ensured only in an experimental situation such that during the process of measurement of the velocity there is no change of the area or of α and that no additional sources of change in the effective field acting on the wall come into being. It seems possible to realize such a situation in the experiments described below, on single crystals of pure yttrium iron garnet (YIG) cut from dislocation-free sections of a bulk crystal grown from solution in the melt. A specimen in the form of tetrahedral rectangular prism, whose edges were oriented along [111] (an axis of easy magnetization), $[10\bar{1}]$, and $[1\bar{2}1]$ and had dimensions 5, 0.2, and 0.06 mm respectively, contained an isolated 180-degree Bloch wall, parallel to the $(10\bar{1})$ plane and separating two domains magnetized in directions [111] and $[\bar{1}\bar{1}\bar{1}]$. Near the end {111} surfaces of the prism, there were microdomains in the form described in Ref. 25 (see Fig. 3 of that article). Motion of this DB through the specimen led to practically no change of its area and was accompanied by an increase of the demagnetizing force in strict proportionality to its displacement x. The latter was monitored by measurement of the amplitude x_0 of the wall displacement as a function of the value of the external field (Fig. 1).

Magnetization of the specimen was accomplished under the action of a pulsed magnetic field H, directed along [111] and produced by a Helmholtz coil of radius

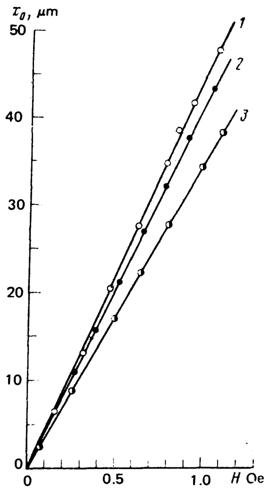

FIG. 1. Variation of the amplitude x_0 of oscillation of a DB with the value of a pulsed magnetic field H, measured for various repetition frequencies of the pulse: 1, quasistatic conditions; 2, $\nu = 2$ kHz; 3, $\nu = 20$ kHz.

5 mm. The field H was measured by compensation of it with a field of opposite polarity from a Helmholtz coil of larger size, calibrated with a Hall probe. The point of compensation of the alternating field was fixed on the basis of the stopping of the DB motion. The measured fields agreed to within 10% with those calculated from the current.

In the experiments described, the DB motion had the character of aperiodic damping ($\beta^2 > 4\alpha m$). For determination of the parameters m and β, the law of DB displacement with time t was measured under the action of a pulsed field repeated with frequency 2 to 20 kHz (the rise time of the H pulse was 40 nsec; the duration of H varied from 4 to 25 μsec). What was directly measured was the relative change of intensity of linearly polarized light passing through a region of the crystal; the region was limited by an aperture and contained rectangular sections of the domains that were separated by the DB, and that did not transmit the light in equal degrees. This last was accomplished by a slight tilt of the $(1\bar{2}1)$ surface of the specimen about $[10\bar{1}]$, which caused the occurrence in the domains of a slight rotation, in opposite directions, of their planes of polarization and a slight uncrossing of the polarizing prisms. The displacement x of the DB and the corresponding change of light intensity ΔI are connected by the relation $x = L\Delta I/\Delta I_0$, where ΔI_0 is the change of light intensity caused by motion of the DB through the whole photometered section, of known width L.

The intensity of the light transmitted through the optical system was measured and recorded by means of a photomultiplier, a stroboscopic oscillograph, and an xy recorder. The small value of the signal obtained under the described conditions, as compared with the signal recorded in investigation of Faraday domains by this method, and the requirement of high accuracy of the measurements entailed a necessity for development of a system of automatic compensation for instability of the amplification factors of all elements of the magnetooptical apparatus. The determination of v and of the parameters m and β from the experimental $x(t)$ curves was accomplished by use of a computer. To introduce the data into the computer, from the output of the stroboscopic oscillograph the signal was fed also to an analog-digital converter; the result was given out in parallel binary code, which was written on to a punched tape. The computer solved a system of three equations of the type

$$x(t_i) = x_0 + C_1 \exp(-r_1 t_i) + C_2 \exp(-r_2 t_i), \quad (6)$$

taken for three prescribed points on the measured $x(t)$ curves; these are the solution of equation (2), where

$$r_{1,2} = [-\beta \pm (\beta^2 - 4\alpha m)^{1/2}]/2m. \quad (7)$$

The coefficients C_1 and C_2 were determined in the process of solution of the system of equations, from the boundary conditions $x(0) = 0$ and $\dot{x}(0) = 0$:

$$C_1 = r_2 x_0/(r_2 - r_1), \quad C_2 = -r_1 x_0/(r_2 - r_1). \quad (8)$$

For the frequencies used, α and x_0 were determined

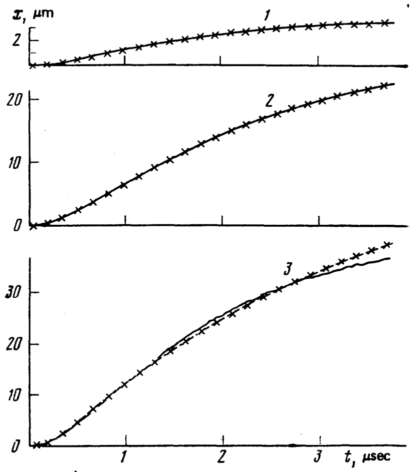

FIG. 2. Experimentally measured (solid lines) and calculated [on the basis of solution of equation (2); dotted with crosses] displacement x of a DB as a function of the time t of action of a magnetic field pulse: 1, $H = 0.1$ Oe; 2, $H = 0.8$ Oe; $H = 1.8$ Oe.

from supplementary measurements of the $x_0(H)$ curve (Fig. 1). This processing made it possible to find, for each value of H, the parameters m and β, the maximum velocity of the boundary, the time to attain it, etc.

RESULTS OF THE EXPERIMENT

1. *Above-barrier* DB *motion*. Figure 2 shows typical examples of the experimentally determined (solid lines) variations of the displacement x of the DB with t, the time of action upon it by a rectangular pulsed magnetic field H, equal to 0.1 Oe in Curve 1, 0.8 Oe in Curve 2, and 1.8 Oe in Curve 3. The motion of the DB occurred under the action of a force that decreased with time. Therefore if there were no inertia (if $m = 0$), the DB velocity should decrease exponentially with passage of time t. The presence of mass in the DB caused a gradual increase of v after H was turned on and a lag in the stopping of the boundary after H was turned off (Fig. 3). The maximum value v_{max} of the velocity of the DB was attained after a certain interval of time of its motion. Values of v_{max}, determined as $(dx/dt)_{max}$ for each pulse of the field H, are shown in Fig. 4a. In

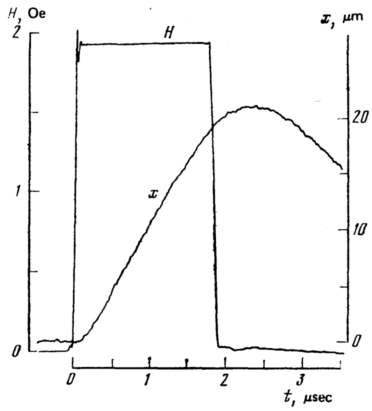

FIG. 3. Pulse of the magnetic field H and DB displacement x caused by it, recorded with an xy recorder.

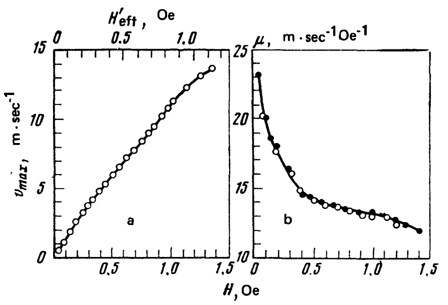

FIG. 4. Dependence of the maximum velocity (a) and of the mobility (b) of a DB on the value of the external magnetic field (H) and of the effective magnetic field (H'_{eff}): ○, $\mu = v_{max}/H'_{eff}$; ●, $\mu = 2M/\beta$.

order to obtain the real dependence of the DB velocity on the value of the field, it is necessary to take into account the change of the effective field (H'_{eff}) acting on the DB after the time of attainment of v_{max}. It is obvious that $H'_{eff} = H - (\alpha/2M)x_m$, where the value of $\alpha/2M$ describes the change of the demagnetizing field during displacement of the DB by unit pathway, and x_m is the pathway of the DB from the origin of its motion to the instant corresponding to v_{max}. A scale of the calculated values of the effective field corresponding to v_{max} is given at the top in Fig. 4a. The corresponding values of the DB mobility for various values of H'_{eff} are shown in Fig. 4b by the white circles. Nonconstancy is clearly evident: a decrease of μ with increase of the field. The values of μ and of v_{max} determined by this method were practically independent of the repetition frequency of the pulses of H.

Figures 2 and 4 show the results of another method of processing the data, based on a computer selection of the values of m and β in equation (2) with which it would be possible to describe the experimental $x(t)$ curves corresponding to various amplitudes of the rectangular-pulsed external magnetic field. In Fig. 2, the crosses show examples of the approximations to these curves drawn by the computer on the basis of values of m and β obtained by processing of the experimental relations.

For each $x(t)$ relation, corresponding to a constant external magnetic field, the mean square error

$$\psi = \left[\sum_i (x_c^i - x_e^i)^2\right]^{1/2} \Big/ N,$$

was determined, where x_c^i is the calculated value of the displacement at the instant t, x_e^i is the experimentally measured value, and N is the number of points at which this difference was measured ($N \approx 200$). No systematic change of ψ with H was detected when H varied over the range 0.05 to ~1 Oe. The value of ψ was fairly small, not exceeding $1 \cdot 10^{-6}$ cm. Each $x(t)$ curve could be described sufficiently well by equation (2) (Fig. 2); the values of m and β changed with increase of H (Fig. 5). The values of β determined by this method were independent of the pulse-repetition frequency ν used. The values of μ calculated from β by use of (4) agreed quite satisfactorily with those obtained from the data on the $v_{max}(H'_{eff})$ relation. They are shown by the dark circles on the $\mu(H)$ graph of Fig. 4b. The values of the DB mass depended on ν. On decrease of ν from 20 to 2 kHz, m decreased by ~20%. This is a natural consequence of the fact that because of dissipative losses, the DB after a time $t_p = 1/2\nu$ has not succeeded in reaching the value $x = x_0$ corresponding to a pulse of amplitude H of infinite duration, or the value $x = 0$ when H is turned off (see Fig. 1). Therefore the more reliable values of m correspond to small ν. Figure 5 shows the data obtained for m when $\nu = 2$ kHz. Further lowering of ν was impossible because of a sharp increase of the noise in the measuring instruments.

When H was varied over the interval 1–2 Oe, a systematic increase of the mean square error was observed. When $H \gtrsim 1.5$ Oe (the values of m and β corresponding to these field values are not shown in Fig. 5), a deviation of the calculated $x(t)$ relation from that measured experimentally was also already easily observed on the graph (Fig. 2, Curve 3). For $H = 1.8$ Oe, the value of ψ, $7.4 \cdot 10^{-6}$ cm, exceeded by more than an order of magnitude the value corresponding to small H. This indicates that at large H, the experimental $x(t)$ curves cannot be described with sufficient accuracy by equation (2) with a constant value of β or of m corresponding to the given field. The increase of ψ was primarily due to deviations of the calculated values of x from the measured in sections of the curve where manifestations of boundary inertia no longer determine the $x(t)$ behavior.

In order to estimate the dissipation of energy in the crystals studied under FMR conditions, spheres of diameter 0.3–0.5 mm were prepared from the YIG bars from which the specimens for study of DB dynamics were cut. FMR measurements at frequency $\omega = 59$ GHz at room temperature showed that the FMR linewidth in all the spheres was less than 1 Oe. This gives a value $\lambda_F < 0.00015$, which, as in the papers published earlier, does not correspond to the λ_μ obtained from measurements of μ. The values of λ_μ calculated from the data of Fig. 5 exceeded 0.06.

The peculiarities of the domain structure of the speci-

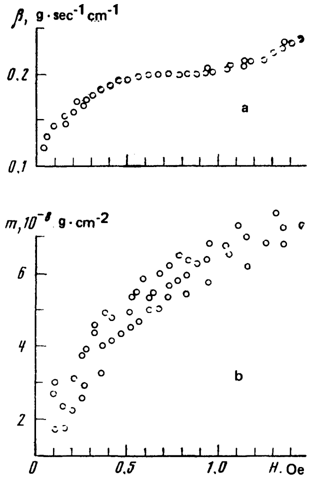

FIG. 5. Dependence of the effective viscosity β (a) and mass m (b) of a DB on the value of the magnetizing field H.

mens prepared provided a possibility of testing the dependence of the results of the measurements on the number of DB moving in them. By magnetic shaking of the domain structure of the specimen, it was possible to produce in it, instead of a single DB, two (the distance between them was equal to the half-width of the prism) and to investigate their dynamics. Both variants of the domain structure are equivalent with respect to the value of the magnetostatic energy on the ends of the prism, but they differ by a factor of about two with respect to the total area of the domain boundaries. Experiment showed that replacement of a single DB in the specimen by two led, naturally, to a decrease of the velocity of motion of the DB, for the same field pulse, by a factor two.

2. *Motion of a* DB *in a potential contour produced by a dislocation microstress field.* The results described above were obtained in a dislocation-free specimen. The coercive force for DB displacement in the field of the other defects was very small (less than 0.01 Oe). Under these conditions, the DB motion was limited by the laws of transfer of energy from the moving DB to the magnon subsystem. The contribution of magnon-phonon processes is apparently unimportant for single crystals of YIG. A decisive effect of it may show up[15-17] at velocities comparable with the velocity of sound; but in YIG, that considerably exceeds not only the measured values of v but also the minimum phase velocity of spin waves. Relaxation due to transfer of electrons between Fe^{3+} and Fe^{2+} ions may be neglected at room temperature: if it were important, then a photomagnetic effect[26] would be observed in the specimens investigated, and none was detected. In specimens containing dislocations, the parameters determined by our method for DB motion limited by viscous friction may differ substantially from those obtained for dislocation-free crystals. This is due primarily to the fact that the effective force acting on a wall in a constant external field depends not only on H and on α, but also on the distance between the DB and the dislocation and on characteristics of the potential contour $W(x)$ produced by it.

Figure 6 illustrates the dependence of the amplitude of oscillation of a 180-degree DB, under the action of an alternating pulsed field, on the distance between its equilibrium position and an edge dislocation. In the photographs, the DB has a double image; each image represents an instant at which the DB stops before a change of direction of the motion. The dislocation is revealed at the center of the photograph as a double-refraction rosette[27] under illumination of it by linearly polarized light along an axis coinciding with the direction of observation. In Fig. 6a, the DB moves at a great distance from the dislocation; its amplitude of oscillation corresponds to the action of the external field alone: the influence of the dislocation is negligibly small. Figures 6a–6e show a sequence of changes of the amplitude of oscillation of the DB on displacement of its equilibrium position from top to bottom under the action of an additional static field. It is evident that, depending on the distance between the dislocation and the DB, there is observed either an increase of the amplitude of oscillation of the DB or a decrease of it, down to a complete stopping of the wall. The rigidity of the DB, caused by the large magnetostatic fields[28] that appear on curving of the wall, prevent it from bending around the dislocation line, and as a result the velocity of the whole DB changes when they interact. The structure of the DB itself also changes, to the greatest degree under conditions of motion of the DB in the immediate vicinity of the dislocation: the amplitude of displacement of Bloch lines increases. In Figs. 6c and d it is also evident that domains of a new type (the white regions at the dislocation), which originate during its interaction with the DB and were studied in detail in Refs. 28 and 29, take a complicated form under dynamic conditions.

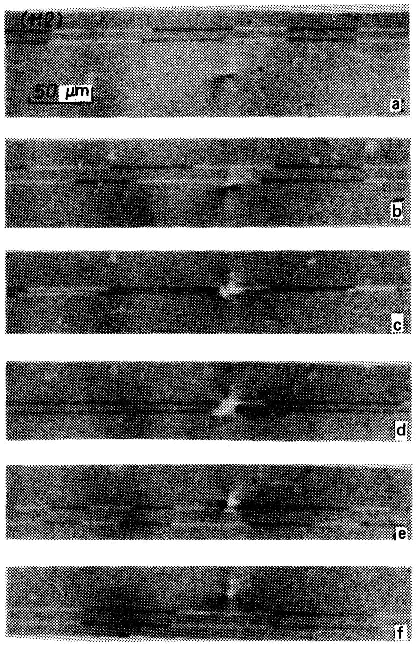

FIG. 6. Form, in linearly polarized light, of a 180-degree DB, oscillating under the action of a pulsed magnetic field of constant amplitude, under conditions such that its equilibrium position is located at various distances from an edge dislocation perpendicular to the plane of the figure, at the center of the double-refraction rosette.

The nature of the potential contour produced by a dislocation for motion of a DB and causing the change of its velocity can be described on the basis of the results of investigation of their interaction under quasistatic conditions. Figure 7 shows the dependence of the displacement of a DB on the value of a static magnetic field propelling the DB, with respect to the dislocation, from bottom to top (Curve 1) or in the opposite direction (Curve 2). The extended linear sections of the $x(H)$ curves characterize the demagnetizing factor of the plate. The influence of the dislocation on the displacement of the DB under the action of an external field leads to disturbance of the linearity of $x(H)$ at considerable distances from the dislocation; during motion of the DB in both directions, after its approach to a certain distance x_c from the dislocation there is observed a gradually increasing attraction of the DB to the dislocation. The presence of this poten-

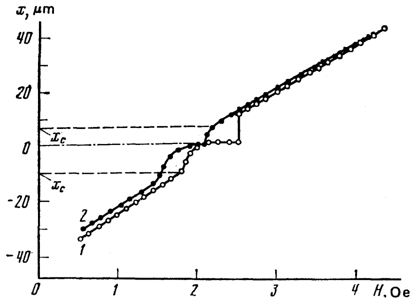

FIG. 7. Dependence of the displacement x of a DB in the elastic field of the dislocation shown in Fig. 6, from bottom to top (Curve 1) and in the opposite direction (Curve 2), on the value of the external static magnetic field. The position of the dislocation corresponds to $x = 0$.

tial well, which is unsymmetric with respect to the direction of motion of the DB, affects the DB motion (Fig. 6) even at considerable distances from the dislocation. The attraction effect causes an increase of the amplitude of oscillation of the DB on approach of it to the dislocation, under conditions of constant amplitude of the alternating field. Subsequently the effect of the barrier in the potential contour begins to manifest itself in a high value of the coercive force for DB motion. Under its influence, the amplitude of the oscillation sharply decreases.

Figure 8 shows the motion of a 180-degree DB under the action of a sinusoidal field, near a dislocation. The amplitude of the field was so prescribed that the DB surmounted the dislocation in both directions over the period of its oscillation. The instant at which the DB stops at the dislocation shows up in the photographs as a white line located in the middle. The intensity of this line decreases with increase of temperature; this indicates a decrease of the time required for surmounting of the dislocation by the boundary, and thermally activated surmounting of this barrier by the boundary. The white region at the center of Fig. 8 is a domain that originates at the dislocation during its interaction with the DB.[28,29]

Disturbance of the nature of the motion of a single DB in the potential field of a local obstacle affects the regularities of the motion of a whole set of domain boundaries in a crystal. Figure 9 shows the behavior of three DB in a crystal under conditions such that one of them interacts with a dislocation (in the center of the photograph, the double-refraction rosette). It is seen that the amplitude of oscillation of the free DB

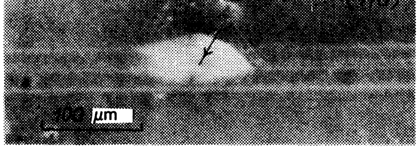

FIG. 8. Image, in linearly polarized light, of a 180-degree DB, oscillating under the action of a sinusoidal field, near a dislocation (shown by the arrow) perpendicular to the plane of the figure (110).

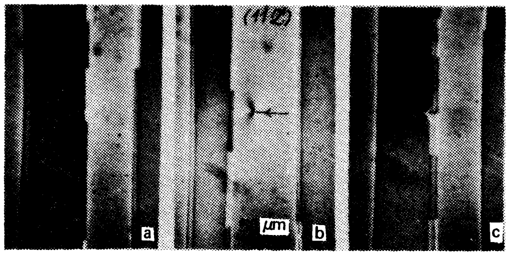

FIG. 9. Effect of the interaction of a single DB with a dislocation upon the behavior of other boundaries in the crystal, oscillating under the action of a pulsed field. The dislocation is marked by an arrow.

increases (Fig. 9a) or decreases (Fig. 9c) if the DB interacting with the dislocation decreases or increases, respectively, its path of motion.

The described effects of the influence of a potential contour produced by long-range defects of the crystal lattice may cause nonlinearity of the v vs H relation and may lead to considerable errors in the determination of m and β, unless the constancy of α is monitored over the whole range of DB displacement amplitudes used.

DISCUSSION OF RESULTS

The method developed in this paper for study of DB motion has a number of advantages as compared with the method used earlier for YIG.[1-3,6] It enables one not only to establish exactly the type of DB, but also to investigate its structure,[5,25] to determine whether there are crystal-lattice defects on its path of motion that produce significant barriers to the DB motion, and to determine the mass of the Bloch wall. The values of μ measured in the experiments described agree in order of magnitude with those obtained in Refs. 2 and 3 but are smaller than those given in Ref. 1. In investigations of v by the induction method within the framework of Refs. 1–3 and 6, difficulties arise in the determination of the number of boundaries that move during the magnetization reversal. Therefore in Ref. 1 (as was mentioned in Refs. 1 and 2), high values of the induced current and therefore of v may be determined by several DB.

The significant decrease of μ with increase of the field, as well as the $m(H)$ dependence, indicates that the DB motion is not described by a solution of the Landau-Lifshitz-Gilbert equation (2) obtained for a one-dimensional infinite well in the linear approximation. From (1) follows formula (3) of Döring, which expresses the DB mass in terms of its thickness parameter. The calculated value m_D ($m_D \approx 3.5 \cdot 10^{-11}$ g cm^{-2}) is several orders of magnitude smaller than the experimentally determined values (Fig. 5b).

Exact solution[20] of equation (1) predicts a nonlinear dependence of v on H for the simplest one-dimensional Bloch wall, even when the mechanism of dissipation of energy remains unchanged ($\lambda = \text{const}$). It is determined by a dynamic change of the wall structure, which causes a nonlinear increase of H'_{eff} with increase of H. For a uniaxial ferromagnet, in this case

$$v=\frac{\gamma H\delta_0}{\lambda}\left\{1+\frac{q}{2}\left[1-\left(1-\left(\frac{H}{H_W}\right)^2\right)^{1/2}\right]\right\}^{-1/2}. \quad (9)$$

Here $q=2\pi M^2/K$ ($q\approx 20$ for YIG), and

$$H_W=2\pi\lambda M \quad (10)$$

is the critical (Walker) field, above which a stationary solution of equation (1) does not exist. The critical velocity $v=v_W$ corresponding to the field $H=H_W$ is

$$v_W=2\pi\gamma M\delta_0(1+q/2)^{-1/2}. \quad (11)$$

If we suppose that the dissipation mechanism of the system of precessing spins is the same under the conditions of DB motion and of uniform FMR, and if we take for λ the value $\lambda_F=0.00015$ obtained on the basis of data on the width of the FMR line, then the value of the limiting field H_W calculated by (10) is found to be very small (~0.15 Oe). It is beyond the minimum value of H used in the experiment. The velocities measured at these fields ($H<H_W$) are more than three orders of magnitude smaller than the Walker velocity calculated from (11). Use of formulas of Ref. 30 for calculation of the limiting velocity of stationary motion in a cubic crystal gives a value not significantly different from that obtained with (11).

If we remain within the framework of the one-dimensional DB model,[20] it is not possible to achieve agreement of its predictions with experiment even if, for estimation of H_W, v_W, and the behavior of $v(H)$ we use the parameter λ corresponding to the minimum β obtained in the experiment (Fig. 5a). It might be supposed that in the case of motion of a Bloch wall, the damping parameter λ_μ significantly exceeds that extracted from experiments on FMR because of the turning on of some additional channel of energy dissipation. In Ref. 14, for example, it was shown that λ_μ may vary substantially with the field because of a difference in the contributions of two- and three-magnon processes to the dynamic braking of the DB. In this case the value of H_W calculated by (10) is found to be rather large (~50 Oe), and the DB velocity, for the whole H range studied, should vary practically linearly with the field. A decrease of μ by a factor two would be reached at fields ~30 Oe, which significantly exceeds those used in the experiment.

Hence the necessity becomes obvious to study more complex processes of dynamic change of structure of a Bloch wall. Even in a state of rest, its structure differs substantially from the one-dimensional.[25] It contains vertical Bloch lines, separating subdomains (Figs. 6 and 9) of right and left-hand rotations within the boundary; these necessarily originate under the influence of the stray fields due to the magnetostatic charges that appear on the free surface of the plate at the place of intersection of the wall. In an external field, they not only move with the DB but also are displaced along it[5] (Figs. 6 and 9). For the same mechanism of dissipation of energy, the motion of existing and of newly nucleating Bloch lines may lead to changes of the form of the $v(H)$ relation[21] and of the value of the limiting velocity of stationary motion of the DB and to an increase of β and of m.[22] Unfortunately, the theory that takes account of these effects was developed for application to films for which $K\gg 2\pi M^2$ and for which the bounding surfaces are perpendicular to the direction of the magnetization in the domains. These conditions are not satisfied by the specimens we investigated. Therefore it is not possible to carry out a rigorous quantitative description of the experimental data with allowance for the contribution of Bloch lines to the peculiarities of the dynamic properties of DB in YIG. A qualitative analysis shows that we cannot explain the whole set of experimental facts on the basis of this mechanism alone for the occurrence of a nonlinear v vs. H relation. The increase of β and m with increase of H may indicate an increase of the density of Bloch lines in the wall. If this process alone determined the $\beta(H)$ and $m(H)$ relations, then they would be similar; this does not agree with the experimental data (Figs. 5a and b). To judge from the $m(H)$ relation, the generation of Bloch lines does not reach a saturation. Then the nonlinear behavior of $\beta(H)$ can be attributed to a change, with increase of field, of the mechanism of dynamic braking of DB with Bloch lines. The velocity v_t of their tangential motion along the DB may in principle[21] considerably exceed the velocity v_n of normal motion with the wall. It is not excluded, for example, that v_t at some H becomes comparable with the minimum phase velocity of spin waves. Then the dissipative processes begin to be determined by Cherenkov radiation of spin waves.

The possibility of a contribution of a change of dissipative mechanism to the formation of a nonlinear $v(H)$ relation may also be indicated by the fact that at large H, the experimentally measured $x(t)$ curves (Fig. 2, Curve 3) cannot be described with acceptable accuracy by equation (2) with a single constant value of the effective viscosity. In the interval in which the relaxation processes are changing, β becomes dependent on v, and (6) is no longer a solution of (2).

CONCLUSION

Thus the analysis made has shown that the nonlinear character of the variation of DB velocity with the value of the external magnetic field may be determined by processes not only of gyroscopic but also of dissipative nature. In this situation, the difference between the damping parameters calculated from experimental data on the mobility of Bloch walls in YIG and from the width of the FMR line is natural. A quantitative separation of the contributions of these mechanisms, different in nature, is impossible because of the absence of a theory describing the dynamic change of structure of a two-dimensional DB (with Bloch lines), moving in a plate of a many-axis ferrimagnet with $K\ll 2\pi M^2$, in which the spontaneous-magnetization vector of the domains separated by the wall is parallel to the surface of the specimen. Change of the mechanisms of transfer of energy from the moving boundary to the various modes of elementary excitations in the crystal (as well as the so high value of the effective mass found in the experiment) may be partly caused by volume and surface defects of the crystal, in addition to the causes already mentioned. Such defects may determine the peculiarities of the dynamic transformation of the wall structure and of the relaxation processes caused by excitation of quasilocal oscillations, nonuniformity of the DB motion, etc. For further experimental study of the phenomena discussed, it is necessary to investigate the variation of v with H over a wider range of variation of H, of the temperature, and of the real structure of the crystal.

The authors express their deep gratitude to Yu. P. Boglaev and T. A. Kostenko for help in setting up the computer program, and also to B. I. Ivanov for discussion of the results.

[1]F. B. Hagedorn and E. M. Gyorgy, J. Appl. Phys. **32**, 282S (1961).
[2]M. A. Wanas, J. Appl. Phys. **38**, 1019 (1967).
[3]H. Harper and R. W. Teale, J. Phys. C **2**, 1926 (1969).
[4]Ya. A. Monosov, P. I. Nabokin, and L. V. Nikolaev, Zh. Eksp. Teor. Fiz. **68**, 1821 (1975) [Sov. Phys. JETP **41**, 913 (1975)].
[5]L. M. Dedukh, V. I. Nikitenko, A. A. Polyanskiĭ, and L. S. Uspenskaya, Pis'ma Zh. Eksp. Teor. Fiz. **26**, 452 (1977) [JETP Lett. **26**, 324 (1977)].
[6]A. Safiullah and R. W. Teale, IEEE Trans. Magn. **14**, 900 (1978).
[7]H. R. Hilzinger and H. Kronmüller, Phys. Status Solidi (b) **59**, 71 (1973).
[8]S. V. Vonsovskiĭ, Magnetizm (Magnetism), M., Nauka, 1971 (translation, Wiley, 1974).
[9]E. Feldtkeller, Phys. Status Solidi **27**, 161 (1968).
[10]J. F. Janak, Phys. Rev. **134**, A411 (1964).
[11]H.-L. Huang, J. Appl. Phys. **40**, 855 (1969).
[12]A. A. Thiele, Phys. Rev. B **14**, 3130 (1976).
[13]V. N. Fedosov and V. I. Minakov, Fiz. Met. Metalloved. **46**, 1166 (1978) [Phys. Met. Metallogr. (USSR) **46**, No. 6, 34 (1978)].
[14]A. S. Abyzov and B. A. Ivanov, Zh. Eksp. Teor. Fiz. **76**, 1700 (1979) [Sov. Phys. JETP **49**, 865 (1979)].
[15]G. M. Nedlin and R. Kh. Shapiro, Fiz. Tverd. Tela **18**, 1696 (1976) [Sov. Phys. Solid State **18**, 985 (1976)].
[16]V. G. Bar'yakhtar, B. A. Ivanov, and A. L. Sukstanskiĭ, Zh. Eksp. Teor. Fiz. **75**, 2183 (1978) [Sov. Phys. JETP **48**, 1100 (1978)].
[17]A. K. Zvezdin and A. F. Popkov, Fiz. Tverd. Tela **21**, 1334 (1979) [Sov. Phys. Solid State **21**, 771 (1979)].
[18]V. I. Minakov and V. N. Fedosov, All-Union Conference on the Physics of Magnetic Phenomena, Summaries of Reports, Kharkov, 1979, p. 368.
[19]V. G. Bar'yakhtar, B. A. Ivanov, and A. L. Sukstanskiĭ, Pis'ma Zh. Eksp. Teor. Fiz. **27**, 226 (1978) [JETP Lett. **27**, 211 (1978)].
[20]N. L. Schryer and L. R. Walker, J. Appl. Phys. **45**, 5406 (1974).
[21]J. C. Slonczewski, J. Appl. Phys. **44**, 1759 (1973); **45**, 2705 (1974).
[22]G. M. Nedlin and R. Kh. Shapiro, Fiz. Tverd. Tela **17**, 2076 (1975) [Sov. Phys. Solid State **17**, 1357 (1975)].
[23]L. D. Landau and E. M. Lifshitz, Phys. Z. Sowjetunion 8, 153 (1935) (reprinted in L. D. Landau, Collected Works, Pergamon, 1965, No. 18 and in D. ter Haar, Men of Physics: L. D. Landau, Vol. 1, Pergamon, 1965, p. 178).
[24]W. Döring, Z. Naturforsch. **3a**, 373 (1948).
[25]V. K. Vlasko-Vlasov, L. M. Dedukh, and V. I. Nikitenko, Zh. Eksp. Teor. Fiz. **71**, 2291 (1976) [Sov. Phys. JETP **44**, 1208 (1976)].
[26]L. M. Dedukh and V. V. Ustinov, Fiz. Tverd, Tela **17**, 2594 (1975) [Sov. Phys. Solid State **17**, 1727 (1975)].
[27]V. I. Nikitenko and L. M. Dedukh, Phys. Status Solidi (a) **3**, 383 (1970).
[28]V. K. Vlasko-Vlasov, L. M. Dedukh, and V. I. Nikitenko, Zh. Eksp. Teor. Fiz. **65**, 376 (1973) [Sov. Phys. JETP **38**, 184 (1974)].
[29]V. K. Vlasko-Vlasov, L. M. Dedukh, and V. I. Nikitenko, Phys. Status Solidi (a) **29**, 367 (1975).
[30]V. A. Gurevich, B. A. Ivanov, and A. L. Sukstanskiĭ, Fiz. Tverd. Tela **20**, 3125 (1978) [Sov. Phys. Solid State **20**, 1803 (1978)].

Translated by W. F. Brown, Jr.