Interaction of a dislocation with a domain wall produced by a gradient field in a magnetically uniaxial film

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An optical polarization method is used to investigate the shape of a Bloch wall produced by a gradient field in a magnetically uniaxial garnet film, in the stress field of a single dislocation. The wall configuration is calculated in two limiting cases. In the first, allowance is made for the magnetoelastic interaction of the stress field of the dislocation with a magnetization localized in domains, when they become nonequivalent, with respect to magnetostriction, under the action of an external field in the plane of the film. In the second, the magnetization is localized directly in the wall, when there is no such stress field and the wall is a 180 degree one. It is shown that for large distances between the wall and the dislocation, the shape of the wall is determined principally by the difference between the magnetostrictive strains in neighboring domains. Disagreements between some experimental data and predictions of the theory are discovered and discussed.

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1. INTRODUCTION

As is well known, the laws of motion of domain walls in ferromagnetic materials are to a considerable degree determined by their real structure. The elementary defects of the crystal lattice that most effectively influence the displacement of domain walls are dislocations. Their long-range nonuniform microstress field produces complicated potential-energy contours for the moving walls, and these must be taken into account in any systematic description of the process of magnetization of magnetically ordered substances. This potential-energy distribution may be dependent principally on the change of exchange and relativistic interactions in the elastic-stress field about a dislocation. Considerable influence may also be exerted by nonlinear effects in the high-strain region near the core of the dislocation, by the nonuniformity produced by the dislocation in the distribution of impurities, etc.

A rigorous theoretical description of the magnetization distribution about a dislocation presents an extremely complicated problem of micromagnetism, in which it is necessary to consider the influence, not easily taken into account, of the magnetostatic charges that appear on the surface and in the volume of the crystal. Partial solutions of this problem have been obtained only for a single dislocation in an infinite specimen containing no domain walls.[1-5] No complete theoretical description of the changes of the magnetization distribution in a crystal during the process of motion of a domain wall in the stress field of a dislocation has been given. The first attempts were made by Pfeffer[6] for slight distortions only of the wall structure. The magnitude and the anisotropy of the interaction of a dislocation and a domain wall have been studied theoretically on the assumption that the wall is plane and that the magnetization distribution in it remains always constant.[2,7,8] But direct experimental study of the interaction of a single dislocation with a 180-degree wall in yttrium-iron garnet, by an optical polarization method,[9] has shown that, in contrast to the predictions of theory,[2,7,8] it is necessary to take into account large deviations of the magnetization during close approach of the dislocation and the wall, which lead to the appearance of a noticeable force of interaction between them at a distance considerably exceeding the wall thickness.

In the experiment,[9] the wall remained practically plane during the interaction process, and it was possible to record only the integral force acting on the wall in the stress field of the dislocation, because the latter was perpendicular to the magnetization of the domains adjacent to the wall, and distortion of the wall was impeded by the magnetostatic charges that appeared on its surface.

A different situation occurs when the dislocation is parallel to the magnetization of the domain and the wall can distort freely in the potential energy distribution produced by the dislocation. Then it is possible to find directly the distribution of the forces exerted by the dislocation on the domain wall, and this makes it possible to establish the nature of the interaction with greatest assurance. This possibility was first successfully realized[10] in uniaxial garnet films, which do not have, near the free surfaces, the closure domains that are always present in multiaxial magnetic materials, such as yttrium iron garnet, and that affect the interaction of a domain wall with a dislocation. In such ferromagnetic films it is possible, by means of a gradient field, to produce in the specimen[11] a single plane wall, at an arbitrary angle to the slip plane of the dislocation; this affords a unique opportunity for detailed study of the anisotropy of the wall-dislocation interaction.

In a previous paper,[10] the first study was made of the form of a domain wall stabilized by a gradient field, in the stress field of single dislocations; and a calculation was made of the distribution of the forces that act on the wall in the potential-energy contours of the dislocations, on the assumption that the magnetostrictive strains in the neighboring domains are identical. On comparison of the experimental data with the theoretical estimates, disagreements were detected, these could be determined, among other things, by the ne-

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glected difference between the magnetostrictive strains in the domains.

The present paper continues the experimental investigation of the shape assumed by such an artifically produced domain wall in the stress field of a dislocation, and of its dependence on the value of the external magnetic field and on the angle between the wall and the slip plane of the dislocation. A calculation of this shape is made on the basis of allowance for the magnetostrictive nonequivalence of the domains adjacent to the wall, a result of the deviation of the magnetization in the film under the influence of the experimentally present component of the magnetic field in the film plane.

2. EXPERIMENT

The investigations were carried out on films of $Y_{2.7}Bi_{0.3}Fe_{3.8}Ga_{1.2}O_{12}$, of thickness ~10 μm, grown by liquid-phase epitaxy on (111) plates of gadolinium-gallium garnet. The dislocatons were detected and analyzed by the method of photoelasticity[12]; the domain structure was investigated in linearly polarized light by use of the Faraday effect. Since the nicols were slightly uncrossed and the birefringence rosettes around the dislocations disappeared, the location of the dislocations in the crystal under such conditions was mentioned on the basis of chemical etching patterns (the dark points: see below, Figs. 2–4). As was verified by supplementary investigations on etched and unetched crystals, the etch pits in the experimental situation used do not introduce any fundamental changes in the character of the dislocation-wall interaction.

A plane domain wall was produced in the crystal by means of a toroidal electromagnet with profiled pole tips. The magnetic field in the magnet gap (Fig. 1) has two components H_z and H_y. The component H_z coincides with the direction of easy magnetization of the film and keeps the wall in the plane $y'=0$, where H_z changes sign. The increase of H_z with distance from this plane is practically linear within the region $|y'| \leq 40$ μm, which exceeds the maximum size of the distortion of the domain wall. The value of the field was controlled by variation of the current in the winding of the magnet. Displacement of the wall along the film was accomplished by motion of the specimen with respect to the magnet gap, controlled with accuracy ±1 μm.

The photographs in Figs. 2 and 3 illustrate the effect of the value of the gradient of the external magnetic field on the variation of the configuration of the domain wall (it separates the dark and light domains) during its motion in the stress field of individual dislocations (dark circles); the motion process was revealed in polarized light by characteristic birefringence rosettes (Fig. 2a). This dislocations and the magnetization M_s in the domains are directed along the normal to the plane (111) of the film (Fig. 2′a).

At large gradients, just as in the previous work,[10] characteristic features of this interaction are long-ranged action (the wall becomes distorted at distances from the dislocations that appreciably exceed the wall thickness) and formation of new microdomains at dislocations upon approach of a Bloch wall to them (Fig. 2b, c, b′, c′). In addition, there is a clearly observable pinning of the wall at dislocations, with formation on the wall of protuberances (Fig. 2*e*, *e*′) whose value at the instant of tearing away characterizes the coercive force.

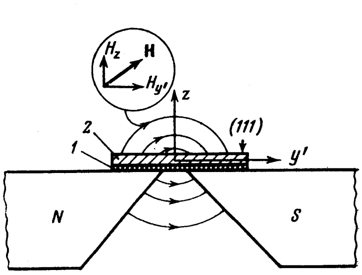

FIG. 1. Position of specimen and field distribution in the magnet that stabilizes the domain wall in a plane. 1) $Y_{2.7}Bi_{0.3}Fe_{3.8}Ga_{1.2}O_{12}$ film; 2), $Gd_3Ga_5O_{12}$ substrate.

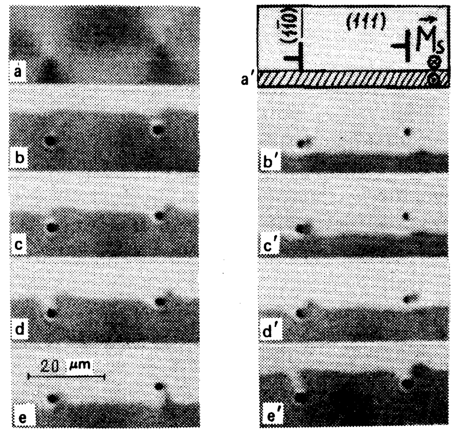

FIG. 2. Change of shape of a Bloch wall, stabilized by a strong gradient field, as it moves from top to bottom (b–e) and from bottom to top (b′–e′) relatively to the dislocations (dark circles), in a direction parallel to their slip plane; a, birefringence rosettes around dislocations in a magnetized crystal; a′, sketch of the arrangement of the wall and of the dislocations in the domains.

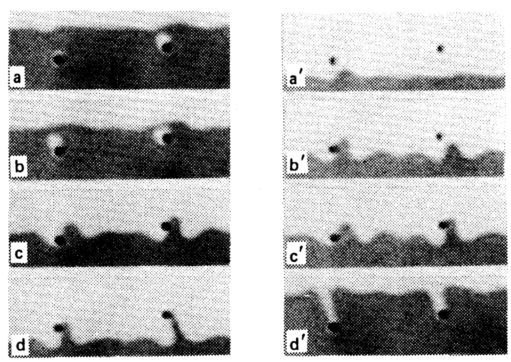

FIG. 3. Change of shape of a domain wall as it moves in a direction parallel to the slip plane of the dislocations, from top to bottom (a–d) and from bottom to top (a′–d′), when the magnetic field gradient is only slightly larger than the critical value.

When the magnetic field gradient $g = \partial H_z / \partial y'$ is decreased to the minimum value that still insures keeping the wall in a plane in the defect-free regions of the crystal, the distortion of the wall increases, and the formation of microdomains at dislocations during its motion from top to bottom is more clearly visible (Fig. 3a, b). When the wall moves from bottom to top, however, no microdomain appears at dislocations (Fig. 3a′, b′), although the general character of the interaction is preserved.

The character of the change of shape of a wall near a dislocation depends on their mutual configuration. Figure 4 illustrates the change of configuration of a wall when its plane, in the initial position, was parallel to the slip plane of the dislocation. In this case there is an especially clearly observable asymmetry of the interaction in relation to the direction of motion of the wall with respect to the dislocation: the light microdomain that originates at the dislocation when the wall moves from the right (Fig. 4b, c) is located completely differently from the dark microdomain that originates in front of the wall when it moves from the left (Fig. 4c′, d′).

It is important to note also the following peculiarity of the interaction, which shows up in both the wall orientations considered: at large distances from the dislocation, the shape of the wall when it moves in one direction can be obtained by symmetric reflection, with respect to the dislocation axis, of the shape assumed by the wall when it moves in the other direction. Near the dislocation, this symmetry is violated.

Change of sign of the gradient of the external field, with preservation of its magnitude, had no effect on the shape of the domain wall in the stress field of the dislocation, for an arbitrary position of the wall with respect to the slip plane.

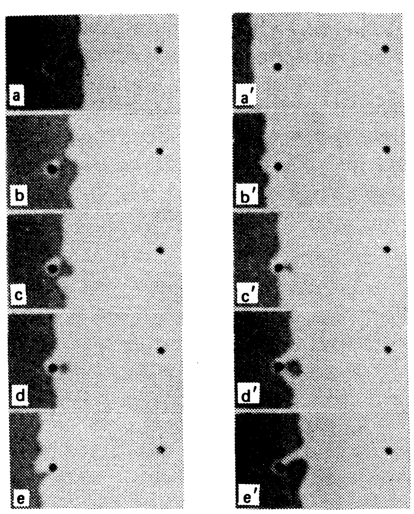

FIG. 4. Change of shape of a Bloch wall as it moves from right to left (a–e) and from left to right (a′–e′) in the elastic field of a single dislocation, whose slip plane is parallel to the domain wall in the initial state.

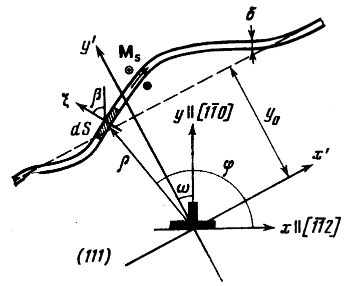

FIG. 5. Calculation of the shape of a Bloch wall in the stress field of a single dislocation.

3. CALCULATION OF THE SHAPE OF THE DOMAIN WALL

A domain wall stabilized by a gradient magnetic field becomes distorted as a result of magnetoelastic interaction of the dislocation microstress field with the magnetization in the specimen. The magnetoelastic energy density of a crystal with internal stresses is described by the expression

$$w_{\mathrm{me}} = -\lambda_{ijkl}\sigma_{ij}\alpha_k\alpha_l, \qquad (1)$$

where λ_{ijkl} and σ_{ij} are the components of the magnetostriction and stress tensors, and where α_k and α_l are the direction cosines of the magnetization M_s. For the case under consideration, in the six-dimensional formalism, the tensor λ_{ijkl}, written with respect to axes $x \parallel [112]$, $y \parallel [1\bar{1}0]$, $z \parallel [111]$ (Fig. 5) of a cubic crystal, has the form[13]

$$\lambda_{ab} = \begin{bmatrix} \lambda_{11} & \lambda_{12} & 2\lambda_{12} & 0 & \lambda_{15} & 0 \\ \lambda_{12} & \lambda_{11} & 2\lambda_{12} & 0 & -\lambda_{15} & 0 \\ 2\lambda_{12} & 2\lambda_{12} & \lambda_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & \lambda_{44} & 0 & -2\lambda_{15} \\ \lambda_{15} & -\lambda_{15} & 0 & 0 & \lambda_{44} & 0 \\ 0 & 0 & 0 & -2\lambda_{15} & 0 & \lambda_{66} \end{bmatrix}, \qquad (2)$$

$$\lambda_{11} = {}^3/_4(\lambda_{100}+\lambda_{111}); \quad \lambda_{12} = {}^1/_4(\lambda_{100}-\lambda_{111}); \quad \lambda_{33} = {}^1/_2\lambda_{100}+\lambda_{111},$$

$$\lambda_{44} = 2\lambda_{100}+\lambda_{111}, \quad \lambda_{66} = \lambda_{100}+2\lambda_{111}, \quad \lambda_{15} = \sqrt{2}(\lambda_{100}-\lambda_{111})/2,$$

where $a, b = 1, 2, \ldots, 6$; λ_{100} and λ_{111} are the magnetostriction coefficients corresponding to magnetization of the crystal along directions $\langle 100 \rangle$ and $\langle 111 \rangle$.

In the elastically isotropic approximation, four independent components of the stress tensor σ_{ij} of the dislocation are determined by the edge component (b_1) of the Burgers vector,

$$\begin{aligned} \sigma_{xx} &= -D_1\frac{y(3x^2+y^2)}{(x^2+y^2)^2} = -D_1\frac{3\sin\varphi+\sin 3\varphi}{2\rho}, \\ \sigma_{yy} &= D_1\frac{y(x^2-y^2)}{(x^2+y^2)^2} = -D_1\frac{\sin\varphi-\sin 3\varphi}{2\rho}, \\ \sigma_{zz} &= -\nu(\sigma_{xx}+\sigma_{yy}) = 2D_1\nu\sin\varphi/\rho, \\ \sigma_{xy} &= D_1\frac{x(x^2-y^2)}{(x^2+y^2)^2} = D_1\frac{\cos\varphi+\cos 3\varphi}{2\rho} \end{aligned} \qquad (3)$$

and two components by the screw component (b_2),

$$\begin{aligned} \sigma_{xz} &= -D_2 y/(x^2+y^2) = -D_2\sin\varphi/\rho, \\ \sigma_{yz} &= D_2 x/(x^2+y^2) = D_2\cos\varphi/\rho. \end{aligned} \qquad (4)$$

Here $D_1 = Gb_1/2\pi(1-\nu)$, $D_2 = Gb_2/2\pi$, G is the shear modulus, ν is Poisson's ratio, and ρ and φ are polar coordinates in the xy plane (see Fig. 5).

The slip planes $(1\bar{1}0)$ of the dislocations used in the experiment, determined from the birefringence rosettes around the dislocations (Fig. 2a), contain two minimal translation vectors of the garnet lattice, of the type $(a/2)\langle 111\rangle$ ($a=12$ Å is the lattice parameter), one of which coincides with the dislocation line, while the other most probably is its Burgers vector b (a 71-degree dislocation). In this case, the screw component of the Burgers vector (the projection of b on the dislocation axis [111]) is $b_2=\sqrt{2/3}a$, while the edge component of the vector b (perpendicular to the dislocation axis) is $b_1=a/2\sqrt{3}$.

Besides the gradient component of the external field, which is parallel to the easy axis of the film and stabilizes the domain wall in the plane $H_z=0$, there is present in the experiment a component H_y, which lies in the plane of the film and turns the magnetization in the domains from the easy axis z through an angle

$$\psi\approx\arcsin\frac{H_{y'}M_s}{2K_u},$$

where K_u is the uniaxial-anistropy constant (Fig. 6). We shall consider a domain wall located at a distance y_0, considerably larger than the wall thickness δ, from the dislocation. Even in this approximation, the rigorous determination of the configuration of the wall from the minimization conditions for the total energy of the system is a complicated and still unsolved problem. Therefore we shall consider two limiting cases: 1) interaction of a dislocation with a wall formed in the presence of a strong field in the plane of the film, when we shall take account of the magnetoelastic interaction of the stress field of the dislocation only with magnetization localized in the domains; 2) interaction with magnetization localized directly in the wall (a 180-degree wall). In both cases we disregard the demagnetizing fields due to emergence of the magnetization at the film surface.

As a result of the turning of the magnetization under the action of the field H_y, in the plane, the domains become magnetostrictively nonequivalent, and the magnetoelastic energy densities at adjacent points lying on opposite sides of the wall that separates these domains are different, since the terms of the form $\alpha_k\alpha_z=\pm\frac{1}{2}n_k\sin 2\psi$ in (1) have different signs in them (n is the unit vector along the field $H_{y'}$; $k=x, y$). This difference determines a pressure

$$p(x, y)=-2\lambda_{ijkz}\sigma_{ij}(x, y)n_k\sin 2\psi, \tag{5}$$

that acts on much a non-180° wall along the normal to its surface (we take as positive the direction from the domain magnetized upward toward the domain magnetized downward). The form of a dimain wall stabilized by a gradient field in the elastic field of a dislocation can be simply described analytically if we neglect also the surface energy of the wall. In this case the condition for minimization of the total energy will be satisfied when the pressure $p(x, y)$ on the domain wall is compensated by the restoring force exerted by the gradient field:

$$p(x, y)-2gM_s(y'-y_0)\cos\psi=0. \tag{6}$$

Since in polar coordinates the expressions for the components of the stress tensor of the dislocation, apart from a numerical factor, have the form $\sigma_{ij}\sim\Phi(\varphi)/\rho$, (6) is easily reduced to a quadratic equation. On solving it, we get an explicit expression for the form of the wall, in polar coordinates attached to the dislocation (Fig. 5):

$$\rho(\varphi)=\{y_0\pm[y_0^2-4\Phi(\varphi)\sin(\varphi-\omega)]^{1/2}\}/2\sin(\varphi-\omega), \tag{7}$$

where ω is the angle between the slip plane of the dislocation and the plane $y'=y_0$ on which $H_z=0$ (the angle between the y' and y axes; see (Fig. 5). The function $\Phi(\varphi)$, in the elastically isotropic approximation, can be separated into two terms $\Phi_1(\varphi)$ and $\Phi_2(\varphi)$, corresponding to the edge and screw components of the Burgers vector of the dislocation:

$$\Phi_1(\varphi)=C_1\cos(2\varphi+\omega)\cos\varphi, \tag{8}$$

$$\Phi_2(\varphi)=C_2\cos(\varphi-\omega), \tag{9}$$

$$C_1=2\lambda_{15}D_1(gM_s)^{-1}\sin\psi,\quad C_2=2\lambda_{44}D_2(gM_s)^{-1}\sin\psi$$

where C_1 and C_2 are characteristic parameters of the equation, with the dimensions of length squared.

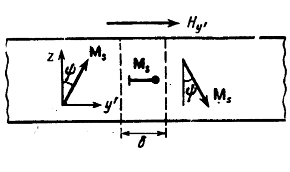

FIG. 6. Deflection of the magnetization in a film under the influence of a field in the film plane.

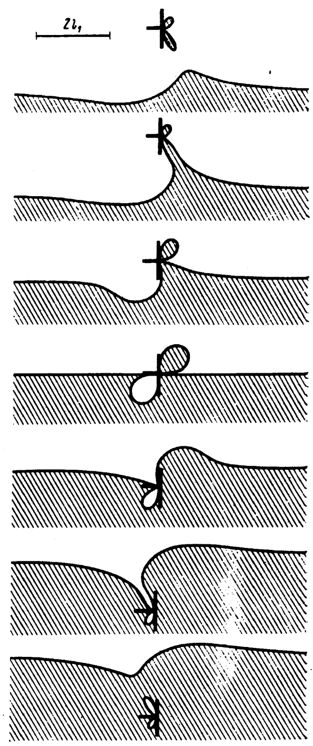

FIG. 7. Variation of the configuration of a domain wall, obtained by allowing for magnetoelastic interaction of an edge dislocation solely with the magnetization in the domains, in the presence of a strong field in the film plane. Slip plane of dislocation perpendicular to plane of film in initial position.

Curves corresponding to equation (7) with $C_2 = 0$, for two prescribed values of the angle ω and for various distances y_0, are shown in Figs. 7 and 8. It is evident that the change of shape of the wall during its motion with respect to the dislocation, as obtained from the calculation, is basically in qualitative agreement with that observed in the experiment.

One can easily estimate the magnitude of the distortion of the wall near the dislocation in the presence of a field in the film plane. If we suppose that $\lambda_{15} \approx 10^{-6}$, $G \approx 10^{12}$ dyn/cm², $b_1 = 0.35 \cdot 10^{-7}$ cm, $M_s = 12$ G, $g \approx 10^4$ Oe/cm, and $\sin\psi \approx 1$, then the only dimensional parameter of the theory, characterizing the magnitude of the maximum distortion of the domain wall and the size of the microdomain that forms at the dislocation, is $l_1 = |C_1|^{\frac{1}{2}} \approx 4$ μm, which agrees well with the experimentally observed values.

If the value of the component of the field in the film plane decreases, then the pressure on the wall caused by deviation of the magnetization in the domains from the easy axis also decreases; and when $H_{y'} = 0$, the determining role will be played by the magnetoelastic interaction of the nonuniform magnetization distribution in the wall with the microstress field of the dislocation.

The nonuniform magnetization distribution in a Bloch wall parallel to the easy axis z of the crystal is conveniently described by means of angles μ and β, respectively the angle of deviation of the magnetization from the xy plane and the angle between a section of the wall and the xz plane (see Fig. 5). The direction cosines of the magnetization in such coordinates have the form

$$\alpha_x = \cos\mu\cos\beta, \quad \alpha_y = \cos\mu\sin\beta, \quad \alpha_z = \sin\mu. \tag{10}$$

Supposing that the wall is of Bloch type and that the magnetization in it is distributed according to the well-known law $\sin\mu = \tanh(\xi/\delta)$, we integrate over the coordinate ξ the increment of the magnetoelastic energy density (1) in the wall with respect to the practically uniform ($y_0 \gg \delta$) density of this energy in the domains, and we get the energy of the section dS of the 180-degree wall in the stress field of the dislocation:

$$\begin{aligned} W_{\rm me}(x, y, \beta)\,dS &= -dS \int \lambda_{ijkl}\sigma_{ij}[\alpha_k\alpha_l - \alpha_k^0\alpha_l^0]\,d\xi \\ &= -2\delta\{(\lambda_{11}\sigma_{xx} + \lambda_{12}\sigma_{yy} + 2\lambda_{12}\sigma_{zz} + \lambda_{15}\sigma_{xz})\cos^2\beta + (\lambda_{12}\sigma_{xx} + \lambda_{11}\sigma_{yy} + 2\lambda_{12}\sigma_{zz} \\ &\quad - \lambda_{15}\sigma_{xz})\sin^2\beta - (2\lambda_{12}\sigma_{xx} + 2\lambda_{12}\sigma_{yy} + \lambda_{33}\sigma_{zz}) + (\lambda_{66}\sigma_{xy} - 2\lambda_{15}\sigma_{yz})\sin\beta\cos\beta\}\,dS, \end{aligned} \tag{11}$$

where α_k^0 and α_l^0 are the direction cosines of the magnetization within the volume of the domains. In the isotropic-magnetostriction approximation ($\lambda_{100} = \lambda_{111} = \lambda$), Eq. (11) simplifies:

$$W_{\rm me}(x, y, \beta)\,dS = -3\lambda\delta\{\sigma_{xx}\cos^2\beta + \sigma_{yy}\sin^2\beta - \sigma_{zz} + \sigma_{xy}\sin 2\beta\}\,dS. \tag{12}$$

The form of the domain wall can be obtained from the condition for minimization of the total energy

$$E = \int dS\{W_0 + W_{\rm me}(x, y, \beta)\} + \int_{-\infty}^{\infty} gM_s(y' - y_0)^2\,dx', \tag{13}$$

where $W_0 \approx 4(AK_u)^{1/2}$ is the surface energy of the wall (A is the constant of nonuniform exhange), and where the last term describes the energy of the wall in the external gradient field. Variation of (13) gives a differential equation for $y'(x)$, which describes the form of the wall. It has the form (we hereafter omit the primes on x' and y')

$$[W_0 + \Delta W(x, y, u)](1 + u^2)^{-3/2} d^2y/dx^2 - 2gM_s(y - y_0) = F(x, y, u), \tag{14}$$

where $u = dy/dx = \tan(\beta - \omega)$. In the general case, the expressions for the functions that describe the generalized magnetoelastic forces $F(x, y, u)$ and the dependence $\Delta W(x, y, z)$ of the reduced surface energy of the wall on its position are unwieldy and therefore are not given here. For small distortions of the wall ($u \ll 1, y \approx y_0$), in the isotropic-magnetostriction approximation,

$$\begin{aligned} F(x, y_0, 0) &= B[(1-2\nu)x^4 + 6x^2y_0^2 - (3-2\nu)y_0^4]/(x^2+y_0^2)^3, \\ \Delta W(x, y_0, 0) &= -By_0[(5+2\nu)x^2 - (1-2\nu)y_0^2]/(x^2+y_0^2)^2, \end{aligned} \tag{15}$$

when the plane of the Bloch wall in the initial position is parallel to the slip plane of the dislocation ($\omega = 0$). When $\omega = 90°$, we have

$$\begin{aligned} F(x, y_0, 0) &= -2Bxy_0[(1-2\nu)x^2 + (5-2\nu)y_0^2]/(x^2+y_0^2)^3, \\ \Delta W(x, y_0, 0) &= Bx[(1-2\nu)x^2 + (7-2\nu)y_0^2]/(x^2+y_0^2)^2, \end{aligned} \tag{16}$$

where $B = 3\lambda\delta D_1$.

The results of a computer solution of the differential equation (14), for $\omega = 0$ and for $\omega = 90°$, for arbitrary amplitude of the distortion of the wall, are shown graphically in Figs. 9 and 10. The following values of the dimensionless parameters were chosen for the calculation:

$$2gM_sB^{-1}d^3 = 8, \quad W_0B^{-1}d = 1$$

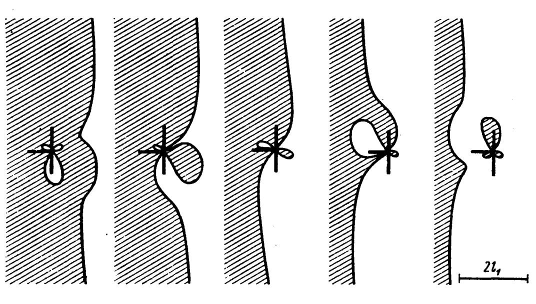

FIG. 8. Variation of the configuration of a domain wall in the case of a strong field in the film plane, when the slip plane of the dislocation is parallel to the film plane in its initial position.

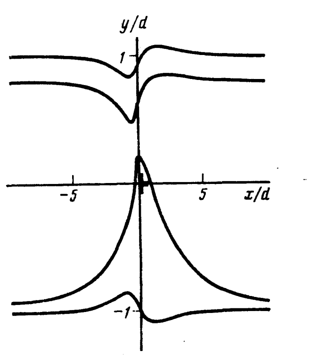

FIG. 9. Result of numerical calculation of the shape of a 180-degree Bloch wall at various distances from a dislocation whose slip plane is perpendicular to the plane of the wall.

(d is the scale of the representation); to these correspond $\lambda\approx 10^{-6}$, $\delta\approx 10^{-5}$ cm, $b\approx 10^{-7}$ cm, $G\approx 10^{12}$ dyn/cm^2, $M_s=12$ G, $g\approx 10^4$ Oe/cm, $W_0\approx 0.1$ erg/cm^2, $d\approx 10^{-4}$ cm. The chosen values of the gradient g of the external field and of the surface energy W_0 of the wall are several times smaller than those achieved in the experiment, in order to take into account qualitatively the destablizing effect of demagnetizing fields.

The character of the distortion of the 180-degree wall at great distances from the dislocation, as the calculation shows, does not correspond to the experiment described. In the case when the slip plane of the dislocation and the wall in its initial position are parallel to each other, the theory predicts a wall shape symmetric with respect to the y' axis and a direction of deviation independent of the sign of y_0 (compare Figs. 10 and 4); when the slip plane is perpendicular to the wall, the wall shape for negative values of y_0 can be obtained from the shape for positive y_0 by symmetric reflection with respect to the x' axis (compare Figs. 9 and 2, 3). The stress field of a screw dislocation in the case of isotropic magnetostriction, as is evident from (12), should have no effect on the shape of a 180-degree Bloch wall. Allowance for anisotropy of the magnetistriction leads to no qualitative change of the wall configuration in the stress field of an edge dislocation but gives a distortion of the wall under the influence of the stress field of a screw dislocation. The form of the wall in this case is also described by an equation of the type (15); when the plane of the wall is perpendicular to the axis [110] (the y axis),

$$F(x, y_0, 0)=6\lambda_{15}\delta D_2(x^2-y_0^2)/(x^2+y_0^2)^2,$$
$$\Delta W(x, y_0, 0)=-6\lambda_{15}\delta D_2 y_0/(x^2+y_0^2). \quad (17)$$

If the wall is perpendicular to the axis [112] (the x axis),

$$F(x, y_0, 0)=-12\lambda_{15}\delta D_2 x y_0/(x^2+y_0^2)^2,$$
$$\Delta W(x, y_0, 0)=-6\lambda_{15}\delta D_2 x/(x^2+y_0^2). \quad (18)$$

Thus the variation of the shape of a domain wall with the orientation of the wall with respect to the crystallographic axes, in the stress field of a screw dislocation, reveals the magnetostrictive anisotropy of the crystal.

The energy (11) of a wall in the stress field of a mixed dislocation is composed of two parts, determined by the edge and screw components of the Burgers vector. Correspondingly, the change of surface energy ΔW and the generalized force F acting on the wall are also determined by the sum of (15) and (17) or of (16) and (18):

$$\Delta W=\Delta W_1+\Delta W_2, \quad F=F_1+F_2.$$

Since the slip plane of the dislocation under investigation is $(1\bar{1}0)$, the shape of a 180-degree wall in the vicinity of a mixed dislocation, under the conditions considered, should not change qualitatively in the two characteristic cases of wall orientation. When the plane of the wall in the initial position is perpendicular to the $[1\bar{1}0]$ axis, the distortion of the wall is symmetric with respect to this axis. When the plane of the wall is perpendicular to the $[\bar{1}\bar{1}2]$ axis, the shape of the wall at a large distance from the dislocation is antisymmetric with respect to this axis, and the sign of the deviation of the wall from a plane charges when it passes through the dislocation. But if the slip plane of the dislocation were to be different from $\{110\}$, then in the case of anisotropic magnetostriction and of a mixed dislocation, the wall would have a complicated, asymmetric shape.

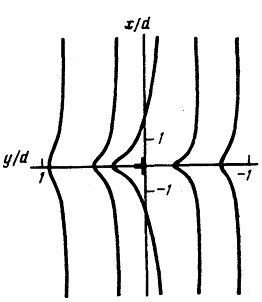

FIG. 10. Numerically calculated shape of a 180-degree wall at various distances from a dislocation whose slip plane is parallel to the plane of the wall.

4. DISCUSSION OF RESULTS

Comparison of the experimental data with the calculation made in two limiting cases shows that in the situation considered (for large distances between the wall and the dislocation), the principal features of the behavior of a domain wall are determined by elastic interaction of the stress field of the dislocation with the magnetostrictive strains in the volume of the domains, in which the magnetization is deflected through a certain angle from the easy axis under the action of the field in the film plane. The contribution of the here disregraded magnetoelastic interaction of the dislocation with the magnetization localized in the wall is much smaller, because when the distances y_0 from the wall to the dislocation are much larger than the wall thickness δ and when $\sin 2\psi\approx 1$, one of the comparable components of the force that is determined by this interaction—the force acting on the wall when it is displaced along y',

$$F_{y'}=-\frac{\partial W_{me}}{\partial y'}=\delta\frac{\partial}{\partial y'}\lambda_{ijkl}\sigma_{ij}\langle\alpha_k\alpha_l-\alpha_k^0\alpha_l^0\rangle \quad (19)$$

(see Ref. 10)—is much smaller than the pressure (5) determined by the magnetostrictive nonequivalence of the domains ($\delta\partial/\partial y\approx\delta/y_0\ll 1$). Here

$$\langle\alpha_k\alpha_l-\alpha_k^0\alpha_l^0\rangle=\frac{1}{\delta}\int(\alpha_k\alpha_l-\alpha_k^0\alpha_l^0)d\xi\approx 1$$

is an average over the wall thickness. But near the dislocation, the experimentally observed wall shape is no longer completely described by taking account only of the pressure (5). Thus when a wall that is parallel to the slip plane of the dislocation moves from right to left, no light microdomain forms at the dislocation on the side of the extra half-plane (Fig. 4c), as would follow from the calculation (Fig. 8). Furthermore, the shape of the microdomains that originate at the dislocations during motion of the wall in a direction parallel to their slip plane (Fig. 2b′, d′) is different from that calculated (Fig. 7), and they do not form at all during motion of the wall in a weak gradient field (Fig. 3a′, b′). These and certain other similar disagreements may be due to the large inhomogeneous deflections of the magnetization near a dislocation, which significantly affect the wallpinning force and the nucleation process.

Also observed in the experiment is an insignificant difference in the curvature of the domain wall on approach to the dislocation from opposite sides, even at considerable distances from its core; this may be attributable to the effect of the inhomogeneous distribution of magnetization in the wall, whose contribution, as was shown above, is small at distances significantly exceeding the wall thickness, and to nonlinear dependence of the magnetoelastic energy on the elastic stresses. The theory without allowance for the magnetoelastic energy of the wall, in the linear-magnetostriction approximation, gives, as is easily seen, a symmetric behavior of the domain wall with respect to the dislocation line, in accordance with the symmetry of the stress field of the dislocation; this agrees satisfactorily with the experimentally observed configuration of the wall at considerable distances from the dislocation. The surface energy of the wall, neglected in the calculation, leads to a difference in the wall configuration depending on the direction of its motion (hysteresis) and somewhat smooths out the abrupt breaks on it.

Noticeable also is an appreciable effect of demagnetizing fields, due to the emergence of the magnetization at the film surface; this shows up especially clearly in a repulsion between the microdomain that originates at the dislocation and the approaching macrodomain (Fig. 3a, b). To decrease the energy of the demagnetization fields, the wall tends to distort; it is restrained from this by the external gradient field, whose value must be larger than a certain threshold value. This tendency is taken into account qualitatively in the calculations by choice of anomalously small values of the surface energy of the wall and of the magnetic field gradient. The good numerical agreement of theory with experiment (microdomain size of order l_1) is explained by the fact that the surface tension of the wall and the demagnetizing field, which were disregarded in the experiment, to a considerable degree compensate each other, since the characteristic dimension of the domain structure achieved in the film used (labyrinth and cylindrical domains) is also of order l_1.

The calculation gives a small distortion amplitude of a 180-degree domain wall formed in a gradient field in the absence of a field in the film plane, even when allowance is made for effective renormalization of the value of the gradient field and for surface energy of the film under the influence of demagnetizing fields. This was partly corroborated in interaction of dislocations with surface maze domains, when the dislocations lead only to effective pinning of the Bloch walls, without noticeable disturbance of their shape.[10] In preliminary experiments done with a magnet that produced no field in the film plane, we also observed only a simple pinning of a 180-degree wall at dislocations, and only when they were in direct contact.

The substantial dependence of the amplitude of distortion of a wall, during interaction with a dislocation, on the value of the field in the plane must be taken into account in detectoscopy of films in the technology of production of magnetic memory elements based on cylindrical magnet domains. Since the amplitudes of distortion of a Bloch wall in the presence of a field in the film plane and without it are, in general, determined by different components of the stress tensor, therefore defects that strongly pin a non-180° domain wall produced by an ordinary two-pole magnet, like that used in our experiment, may be unimportant for the operation of devices based on cylindrical magnetic domains; and, on the other hand, some defects may be missed that strongly impede the motion of a purely 180-degree wall. Therefore the detection of defects should be carried out under conditions as close as possible to the actual ones, by means of a quadrupole magnet that produces a gradient field without an appreciable component in the film plane. Investigations of the interaction of dislocations with a 180-degree wall, obtained with such a magnet, should give the force that pins a wall at a dislocation, in accord with the force determined in Ref. 10 that pins a cylindrical magnetic domain at one; and furthermore, they permit study of the anisotropy of this interaction.

If one solves the problem exactly (numerically) with allowance for the change of all terms of the total energy then on the basis of the wall configuration in the stress field of the dislocation for various values of the field in the plane, one will be able to determine the magnetostriction constants of the film when the value and direction of the Burgers vector of the dislocation are known, and if these constants are known, then one can establish the type of dislocation.

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