Supersonic disturbance of the domain wall dynamics in yttrium orthoferrite

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(Submitted 8 May 1985)
Zh. Eksp. Teor. Fiz. **89**, 1445–1451 (October 1985)

The method of double high-speed photography and two-pulse magnetization reversal was used to study a supersonic disturbance of the motion of domain walls in yttrium orthoferrite. The field dependence of the velocity $V(H)$ of domain walls in $YFeO_3$ did not exhibit hysteresis in the vicinity of the velocity of transverse sound. The time needed to overcome the sound barrier by domain walls was finite and it decreased to several nanoseconds on increase in H. The observed irreversibility of sonic and supersonic domain wall dynamics indicated a resonance interaction of a domain wall with the deformation of a crystal created by the wall itself.

Investigations of the dynamics of domain walls in weak ferromagnets, such as orthoferrites[1] and iron borate,[2] have shown that this dynamics is supersonic and quasirelativistic. As the domain wall velocity V approaches the velocity of transverse sound S_t, the drag associated with the magnetoelastic interaction rises very strongly. The dependence $V(H)$ has a constant-velocity region near $V = S_t$ and this exists in a magnetic field range ΔH_t extending over several tens of oersted. As a result of this anomaly a finite time, depending on the amplitude of the magnetic field pulses is needed to overcome the sound barrier. We investigated the dependence of this time for domain walls in yttrium orthoferrite. A one-dimensional theory of the dynamics of domain walls in weak ferromagnets predicts hysteresis effects for the dependence $V(H)$ in the range $V \geqslant S_t$. When the magnetic field increases in the vicinity of $V = S_t$, where the condition $\mu \Delta H_t / S_t > 1$ is satisfied (μ is the domain wall mobility and ΔH_t is the amplitude of the magnetoelastic anomaly), a plane domain wall in yttrium orthoferrite becomes unstable and its velocity increases abruptly severalfold. The one-dimensional theory predicts that the subsequent reduction in the amplitude of the magnetic field pulses should result in a smooth reduction of the velocity to S_t and then to 0. Experiments indicated the absence of a hysteresis in the dependence $V(H)$ near the velocity of sound.

As the domain wall velocity approaches S_t, the theory predicts an increase in the deformation that accompanies a moving domain wall. When the sound barrier is crossed, the motion of domain walls in yttrium orthoferrite is no longer one-dimensional. The nature of this change depends largely on the time of growth of the deformation that accompanies a domain wall. We shall show that in the case of two-pulse magnetization reversal in yttrium orthoferrite samples a major influence on the non-one-dimensional supersonic motion is the previous history of the samples. If in a pulsed field H a domain wall moves at the velocity of sound S_t for a certain time interval, rapid reversal of the direction of the magnetic field alters greatly the process of crossing the sound barrier. The multidimensional nature of the dynamics weakens greatly and the width of the constant-velocity interval decreases considerably. This is clearly a manifestation of the strong interaction between a moving domain wall and the deformation created by it, which does not have a sufficient time to relax when the direction and magnitude of the domain wall velocity change rapidly.

EXPERIMENTAL METHOD

We investigated transonic and supersonic dynamics of domain walls in yttrium orthoferrite by the method of double high-speed photography[1,3] using plates cut at right-angles to the optic axis. After the first H_1 pulse, which set a domain wall in motion at the sonic or supersonic velocity, we applied a pulse H_2 and the amplitude and direction of the second pulse as well as the time delay between the pulses could be varied. This was done by bonding two pairs of coils, each consisting of 10–15 turns of wire 1.5 and 1 mm in diameter, to the investigated sample. Each coil pair was supplied from a separate pulse generator, the rise times of the pulses were 5 nsec, and the amplitudes of the fields could be varied continuously. The duration of a light pulse was 0.8 nsec. The delay between the light pulses was varied from 3 to 30 nsec. A photographic film was used to record the region traversed by a domain wall during the time between two light pulses. A separate polarizer was placed in each of the two light beams. The angle between the principal planes of the polarizers was equal to twice the angle of rotation of the plane of polarization. One analyzer was used. The principal plane of the analyzer was perpendicular to the bisector of the angle between the principal planes of the polarizers. The region traversed by a domain wall during the delay time was dark on a bright background. When the direction of the domain wall motion was reversed, the region traversed by a wall was bright on a dark background. A microscope was used to focus these regions on a photographic film where they were recorded without the use of an image amplifier. Most of the experiments were carried out at 100 K when the domain wall mobility in $YFeO_3$ samples, grown by the floating zone method with radiation heating,[4] was maximal and amounted to 2×10^4 $cm \cdot sec^{-1} \cdot Oe^{-1}$.

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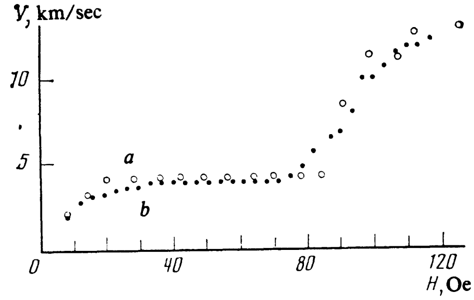

FIG. 1. Dependence of the velocity of a domain wall in $YFeO_3$ on the applied magnetic field when it is increasing $V(H_1)$ (a) and during subsequent reduction of $V(H_1 - H_2)$ (b).

EXPERIMENTAL RESULTS

1. Investigation of the hysteresis of the dependence *V(H)* for domain walls in Yttrium orthoferrite

Figure 1 shows the dependences $V(H)$ for domain walls in $YFeO_3$ subjected to fields H_1 (Fig. 1a) and fields $H_1 - H_2$ (Fig. 1b). An increase in H_1 produced a dependence $V(H)$ of the conventional kind. A linear rise of the domain wall velocity was characterized by a mobility of 2×10^4 cm $\cdot$ sec$^{-1}\cdot$ Oe^{-1} and in an interval $\Delta H_t = 60$ Oe the velocity remained practically constant and equal to the velocity of transverse sound. Next, in a field of 100 Oe there was an abrupt jump in the velocity of some of the domain walls to 14 km/sec. This was followed by the application of the opposite field H_2, the amplitude of which was increased. The dependence $V(H_1 - H_2)$ deduced from the minimum velocity, was practically identical with the dependence $V(H_1)$, although the switching of some of the domain walls from the 14 km/sec velocity to the velocity S_t occurred in a somewhat wider range of magnetic fields. There was no hysteresis in the dependence $V(H)$ although the one-dimensional theory of Ref. 5 predicted its existence. An increase in the field H_2 directed opposite to the field H_1 should give rise to a dependence $V(H)$ described by the expression

$$V=\mu H/[1+(\mu H/c)^2], \tag{1}$$

which was obtained in Refs. 6 and 7. The absence of a hysteresis could be attributed to the multidimensional nature of the supersonic motion of domain walls or the existence of other singularities in the dependence $V(H)$, some of which were clearly visible in, for example, Fig. 3b (see below). A reduction in the resultant magnetic field caused switching of the domain wall velocity from 14 km/sec not to the next lower-velocity singularity in the dependence $V(H)$, but quite rapidly to the velocity S_t. Therefore, the absence of a hysteresis in the dependence $V(H)$ probably indicated the exitence of a series of regions with a constant domain wall velocity.[1]

These regions could be due to the excitation of Winter magnons[8] by moving domain wall because of the presence of growth inhomogeneities with a period of the order of several tens of microns.[9] Such inhomogeneities were revealed by transmission photography of thin plates of the investigated orthoferrite and we were unable to remove them by prolonged annealing in an oxygen atmosphere. Photography of these inhomogeneities was possible because of the periodic variation of the impurity concentration, which affected the transparency of yttrium orthoferrite and of single crystals formed during growth.

2. Investigation of the time needed to cross the sound barrier by domain walls in Yttrium orthoferrite

The existence of a region of constant velocity of domain walls and its equality to the velocity of transverse sound are evidence of a strong resonance interaction of a domain wall with the lattice deformation created by the magnetostatic interaction. A one-dimensional theory considered in the approximation of strong dissipation in the elastic suybsystem of a weak ferromagnetic crystal describes correctly the width of the constant-velocity region ΔH_t and predicts an increase in the drag force acting on domain walls at $V = S_t$ (Refs. 5 and 10). The increase in the drag force is responsible for the finite time needed for the crossing of the sound barrier by domain walls in all fields H exceeding a certain critical value H_{cr} at which steady-state subsonic motion of domain walls in yttrium ferrite became impossible. The existence of a finite time needed by a domain wall to assume a supersonic velocity follows also from the experiments on the motion of "kinks" along a domain wall moving at the velocity of transverse sound. It was shown in Ref. 11 that in a magnetic field of 120–140 Oe a kink moves for a time $\sim$20 nsec. Hence, the whole domain wall begins to move at a supersonic velocity in this field only after 20 nsec. A one-dimensional domain wall (or a wall which retains its initial geometric shape) can travel indefinitely at subsonic or sonic velocities. In magnetic fields above a certain critical value the motion changes to supersonic. The field H_{cr} corresponds to the loss of stability by a one-dimensional domain wall because of the existence of a region with a negative differential mobility in the dependence $V(H)$ (Ref. 10). During the initial stage of the transition to the supersonic range a domain wall moves at a velocity $S_t = 4$ km/sec and still remains plane. If the time from the onset of motion in the field $H > H_{cr}$ is greater than t_{cr1}, the shape of a moving domain wall changes drastically. Hemispherical leading regions form in a domain wall and they move at supersonic veloc-

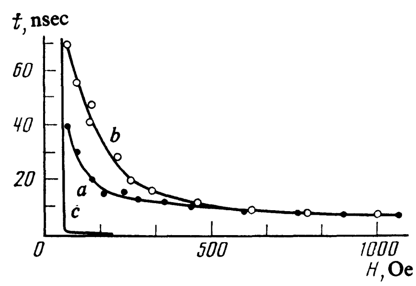

FIG. 2. Magnetic field dependences of the time needed by a domain wall to overcome the sound barrier: a) time t_{cr1} of the onset of the transition of some domain walls to supersonic motion; b) time t_{cr2} of the final transition to the supersonic velocity; c) time for transition of a one-dimensional domain wall to the supersonic velocity (calculated).

ities. The other parts of the wall then move at the velocity S_t.

The dependence of $t_{\rm cr1}$ on the amplitude H is presented in Fig. 2a. As the field H was increased, the duration of motion of a domain wall at the sonic velocity decreased. In the range $t_{\rm cr1} < t < t_{\rm cr2}$ it was possible to observe the motion also of perfectly plane domain walls as well as of walls with leading regions. This time interval was the effective time for the transition of the domain wall dynamics to the supersonic range. The dependence of $t_{\rm cr2}$ on H is plotted in Fig. 2b. A comparison of Figs. 2a and 2b shows that the maximum value of $t_{\rm cr2} - t_{\rm cr1}$ is 30 nsec. It decreases to a few nanoseoconds on increase in H. The dependence of the time of the transition of a domain wall across the longitudinal sound barrier, obtained for an orthoferrite plate perpendicular to the weak ferromagnetic axis, is similar.

The time needed by a domain wall to overcome the sound barrier under the action of a field pulse $H_z(t)$, which is equal to H_z for $t \geqslant 0$ but vanishes for $t < 0$ can be calculated from the equation[10]:

$$\frac{d}{dt}(m\dot{q}) + \frac{m}{\tau}\dot{q} - \operatorname{div}_\perp(mc^2 \operatorname{grad}_\perp q) = 2M_s(H_z + H_z' q) + F_{\rm me}(\dot{q}), \qquad (2)$$

where $m = m_0[1-(\dot{q}/c)^2]^{-1/2}$. The following approximate expression[10] is available for $F_{me}(\dot{q})$:

$$F_{\rm me}(\dot{q}) = -\frac{b\dot{q}}{(\dot{q}^2 - S_t^2)^2 + \Delta^2}$$

where

$$b = \frac{7\delta_t^2 S_t^3}{15 c_t q_t},$$

$$\Delta^2 = \frac{7}{20}\frac{S_t^5}{q_t^2 c[1-(S_t/c)^2]^{1/2}},$$

$$q_t = \frac{\Delta_0 c_t}{2\eta_t c}.$$

We shall consider a singularity of $V(H)$ only in the region of the transverse sound velocity.

In the case of a plane domain wall (if we assume that $H_z' = 0$, since we usually have $H_z' q \ll H_z$), Eq. (2), which is valid on condition that the relaxation time of the magnetic subsystem is much longer than the relaxation time of the phonon subsystem, can be integrated in quadratures:

$$t = \int_0^{V+\varepsilon} \left\{1 + \frac{\xi^2}{c^2[1-(\xi/c)^2]}\right\} \times \left\{\frac{2M_s H_z + F(\xi)}{m_0}\left[1-\left(\frac{\xi}{c}\right)^2\right]^{1/2} - \frac{\xi}{\tau}\right\}^{-1} d\xi, \qquad (3)$$

where t is the acceleration time of a domain wall to a velocity $V+\varepsilon$, where ε is the half-width of the singularity in the dependence $V(H)$.

It is clear from (3) that if $V < V_{st}$ and $H_z > H_z^*$, where

$$H_z^* = \frac{1}{2M_s}\left\{\frac{m_0 S_t}{\tau[1-(S_t/c)^2]^{1/2}} - F_{\rm me}(S_t)\right\}$$

is the field corresponding to the right-hand limit of the range of constant velocity ΔH_t in the dependence $V_{st}(H_z)$, then $t \to \infty$ for $H_z \to H_z^*$ and $t \to 0$ for $H_z \to \infty$. The integral (3) can be calculated exactly by an analytic approach, but because of the cumbersome nature of the resultant expression, we carried out a numerical calculation for different values of H_z and plotted the results in Fig. 2c for $\mu = 2 \times 10^4$ cm $\cdot$ sec^{-1} $\cdot$ Oe^{-1}, $\eta_t = 0.28$ erg $\cdot$ sec $\cdot$ cm^{-3}, and $m_0 = 10^{-12}$ g/cm^3.

The deviation of the experimental values of the time needed to overcome the sound barrier by domain walls from those found by calculation is clearly due to the long relaxation time of the phonon subsystem under our experimental conditions. When the theoretical values are compared with the experimental data, we must also bear in mind that the theoretical value of t does not include the duration of the leading edge of a H_z pulse which in our experiments amounts to about 5 nsec and the higher the theoretical value of t, the closer H_z is to H_z^*. The finite time for the transition to the supersonic dynamics should clearly prevent the overcoming of the sound barrier in the case of periodic high-frequency interaction with domain walls at frequencies of the order of 50–100 MHz. The finite time needed by a domain wall to cross the sound barrier naturally gives rise to a finite time for the transition through successive singularities ΔH_i of the dependence $V(H)$, which appear because of the interaction with Winter magnons, because the important process is the overcoming of a resonance drag when the drag force has sharp maxima at certain specific domain wall ve-

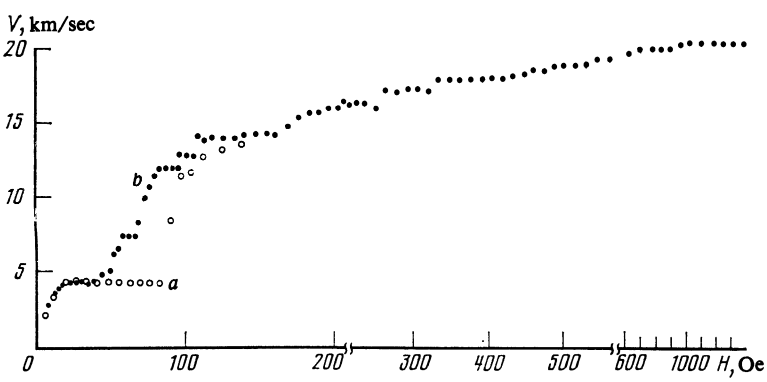

FIG. 3. Dependence of the velocity of a domain wall in $YFeO_3$ on the magnetic field $V(H)$ (a) and the corresponding dependence for the motion in the opposite direction at a velocity $V(H_1 - H_2)$ (b) obtained for a domain wall moving to the right at the velocity of transverse sound for a time longer than $t_{\rm cr}$.

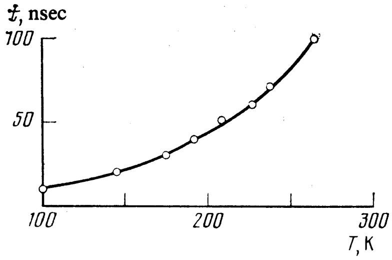

FIG. 4. Temperature dependence of the time t_{cr} during which a domain wall should move at the velocity of sound in the forward direction, followed by an irreversibility of the sonic and supersonic dynamics of domain walls.

locities. However, in this case the crossing of a specific velocity V_i by a domain wall is not accompanied by a visible change in the domain wall shape. Therefore, it is then necessary to improve the method for the determination of the transition time. Having determined the time for the establishment of the limiting velocity of a domain wall, we can judge the time needed for the overcoming of additional singularities in the dependence $V(H)$ and the relaxation times of the processes responsible for such resonance drag.

3. Investigation of the irreversibility of supersonic dynamics of domain walls

A new effect appears when the direction of motion of a domain wall under the action of two successive magnetic field pulses rotates after the wall has traveled in the forward direction only under the action of the force H_1 at the velocity S_t. Figures 3a and 3b show the corresponding dependences $V(H_1)$ and $V(H_1 - H_2)$. A comparison of these figures demonstrates that they differ considerably. For example, the singularity ΔH_t at $V = S_t$ in the dependence $V(H_1 - H_2)$ becomes over four times narrower compared with the corresponding singularity during the forward travel of a domain wall in a field H_1, when $\Delta H_{t1} = 70$ Oe. An important role is played by the time during which a domain wall travels in the forward direction at the velocity of sound. If this time exceeds a certain critical value t_{cr}, then a reduction in ΔH_t in the dependence $V(H_1 - H_2)$ is observed. The temperature dependence of t_{cr} is plotted in Fig. 4. At $T = 100$ K we have $t_{cr} = 10$ nsec, whereas for $T = 265$ K we have $t_{cr} = 100$ nsec. A reduction in the interval ΔH_t during the reverse travel of a domain wall is accompanied by a strong weakening of the multidimensional behavior on transition across $V = S_t$ in a field $(H_1 - H_2)$ (Fig. 5). Figure 5b shows a photograph of a similar double dynamic domain structure observed when a domain wall reached a velocity S_t in a field of H_1. We were unable to observe similar efects for two domain walls moving in the same direction at transonic velocities. This indicated that a domain wall interacted locally with the deformation which accompanied the wall.

A comparison of Figs. 3a and 3b shows that a reduction in ΔH_t reduces the disturbance of the supersonic motion and gives rise to a singularity ΔH_l and several singularities ΔH_i not shown in Fig. 3b. This result provides further support for the inequality $\Delta H\mu/S_t > 1$ regarded as the condition for the existence of a strong disturbance on transition to the supersonic motion of domain walls in a weak ferromagnet. If H_1 and H_2 have the same sign, the duration of motion of a domain wall at the velocity S_t does not affect the nature of the transition to the supersonic motion of the wall after the application of H_2.

We shall now formulate the main results. The dependence $V(H)$ for a domain wall in the investigated weak ferromagnetic shows no hysteresis in the vicinity of the velocity of transverse sound. The time taken by a domain wall to cross the sound barrier is finite and it decreases on increase in H. A domain wall interacts resonantly with the deformation it creates and this gives rise to irreversible process in its dynamics. In general, a domain wall represents a complex nonlinear object and during its motion at the supersonic velocity we can expect a number of new strongly nonlinear effects. Experimental investigations demonstrate the need to allow for the finite duration of the transition process in the elastic subsystem when transient processes in the dynamics of domain walls in weak ferromagnets are considered. In the process of transition to the supersonic velocity a domain wall of yttrium orthoferrite ceases to be a one-dimensional object.[1,11] A theory of the dynamics of domain walls developed

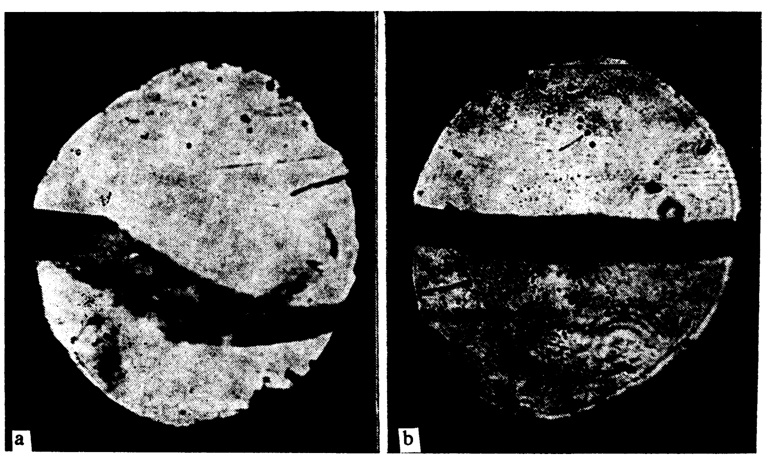

FIG. 5. Photographs of double dynamic domain structures observed on crossing the transverse sound barrier in the forward (a) and reverse (b) directions after moving at a velocity S_t in the forward direction for a time exceeding t_{cr}.

so far is one-dimensional.[6,7] Therefore, it is of interest to seek multidimensional solutions for supersonic and quasirelativistic dynamics of domain walls in weak ferromagnets.

The authors are deeply grateful to E. I. Kondorskiĭ for his encouragement and interest, to A. K. Zvezdin for discussions, and to A. M. Balbashov for supplying the investigated single crystals.

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Translated by A. Tybulewicz