Investigation of supersonic dynamics of domain walls in orthoferrites

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A twofold high-speed photography method was developed for the investigation of the nonlinear non-one-dimensional dynamics of domain walls (DW). Domain-wall dynamics was investigated in yttrium, thulium, and europium orthoferrites at temperatures 290, 110, and 4.2 K. It is shown that DW motion with velocity not higher than that of sound is one-dimensional and steady. On going through the speed of sound, the shape of the DW changes, and its visible width increases. Semicircular formations appear on the moving domain wall and their velocity greatly exceeds that of sound. The curvature radius of these formations depends on the amplitude of the controlling magnetic field and on the DW mobility. Supersonic steady motion of DW takes place only at a discrete set of velocities. Under strongly nonstationary conditions, a bend propagates along a DW moving at transverse-sound velocity. The bend velocity can reach the limiting value.

We investigated the dynamics of domain walls (DW) in orthoferrites of yttrium, thulium, and europium using high-speed twofold photography and a dye laser with pulse duration 1 nsec. We show that one-dimensional motion of the orthoferrite DW takes place only at velocities lower than or equal to the velocities of the transverse or longitudinal sound. On going through the sound velocity, the DW becomes bent and acquires semicircular formations—leading sections. Their curvature radius R depends on the DW mobility and on the amplitude of the pulsed magnetic field. An expression is obtained for the dependence of R on the indicated parameters. This expression agrees qualitatively with experiment. At supersonic velocities the visible width of the DW increases strongly. It appears that the DW sags in the interior of the sample and becomes three-dimensional. Supersonic stationary motion of orthoferrite DW takes place only at a discrete set of velocity values. The possible causes of this phenomenon are discussed. Under strongly nonstationary conditions, a kink-bend propagates along a DW that moves at transverse-sound velocity. The kink velocity can reach the limiting velocity of the DW. This velocity plays an important role in nonlinear dynamics of orthoferrite DW. The results call for the development of a theory of non-one-dimensional and nonstationary dynamics of DW of orthoferrites.

INTRODUCTION

The dynamics of DW in weak ferromagnetic orthoferrites differs substantially from the dynamics of domain walls of all other ferromagnets. This is due to several factors. Principal among them is the strong orthorhombic anisotropy of the orthoferrites, which prevents a substantial change of the structures of the moving domain walls in these crystals. The magnetic-moment reorientation field in orthoferrites is very strong, about 80 kOe (Ref. 1). This increases the range of fields in which the magnetization is due to DW displacement, and permits the domain-wall dynamics in orthoferrites to be investigated in fields substantially stronger than in other ferromagnets. The high mobility of the orthoferrite DW leads to a nonlinear DW dynamics in relatively weak magnetic fields. Unusually high limiting DW velocities were observed experimentally in weak ferromagnetic orthoferrites[2,3] and were explained theoretically in Refs. 3–6.

The experimental investigation of the dynamics of domain walls in orthoferrites has been the subject of a large number of studies. It was first investigated by the Sixtus-Tonks[7,8] and bubble-collapse[9] procedures, and later with the aid of a magnetooptical analog of the Sixtus-Tonks procedure[2,3] and by high-speed photography.[10–12] In the first high-speed photography studies, 10-nsec neodymium-glass laser[10] pulses and 6-nsec dye-laser[11] pulses were used. During times of this order domain walls moving at up to the maximum velocity 2×10^6 cm/sec negotiate a distance on the order of 100–200 μm. Therefore the accuracy of the indicated procedures is not too high and in essence is of the order of the accuracy of the magnetooptic analog of the Sixtus-Tonks procedure, in which one measures the time required for the domain wall to cover a given distance between two light spots. The accuracy of this procedure is determined by the rise time of a photomultiplier signal as the moving domain wall crosses a light spot on the surface of the investigated orthoferrite plate. In Refs. 2 and 13, where this procedure was used, the rise time of the signal of an FÉD-30 photomultiplier was 7 nsec. To increase the accuracy of this procedure this time must be shortened. No procedure other than high-speed photography can identify the shape of the moving DW. The use of high-speed photography has shown that at supersonic velocities the shape of the domain wall in yttrium orthoferrite is greatly altered. To increase the accuracy of investigations of DW dynamics by high-speed photography it is necessary to use the shortest possible light pulses.

In Ref. 12 are briefly described the results of DW-dynamics investigations in yttrium orthoferrite by high-speed photography at light-pulse durations 1 nsec. Here we describe in greater detail the results of investigations of DW dynamics in orthoferrite by the procedure of twofold photography of a moving domain wall in one pass through the sample. This procedure as applied to high-speed domain-

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wall dynamics was first described in Ref. 12. The investigations were made at room temperature as well as 110 and 4.2 K. The theory of nonlinear dynamics of domain walls in orthoferrites, as developed to date, is one-dimensional.[4–6] It describes adequately the maximum velocity of the domain wall. This velocity corresponds to the velocity of spin waves on the linear section of their dispersion law. In the wave-vector range $0<k<k_B/3$ the spin-wave dispersion law is linear and isotropic. Near the center of the Brillouin zone and on its edges, the spin-wave dispersion law is anisotropic.[14] The one-dimensional theory yields an expression for the field dependence of the DW velocity $V(H)$.[5,6] Allowance for the magnetoelastic coupling in the one-dimensional theory leads to the appearance of singularities on this dependence at longitudinal- and transverse-sound velocities.[15,16] A one-dimensional domain wall is unstable near these velocities. This was demonstrated experimentally[3,8] and theoretically.[15,16] Owing to this instability, a bend can propagate along the DW. Earlier experiments have shown that in the DW velocity interval from that of longitudinal sound to that of the spin wave the $V(H)$ plot has a number of regions in which the DW velocity is constant.[12,17] These singularities have so far not been explained theoretically. The experiment described below shows that a continuous $V(H)$ dependence obtains only in the velocity interval from zero to that of the transverse (or longitudinal) sound, with the moving domain wall remaining one-dimensional. In the velocity interval from that of transverse (longitudinal) sound to the maximum the domain wall moves in an orthoferrite plate at a discrete set of velocities, the transitions between which are quite abrupt. Above the transverse (longitudinal) sound velocity the domain wall ceases to be one-dimensional, broadens, and changes shape. These facts require the development of a nonstationary three-dimensional theory of the dynamics of domain walls in orthoferrites.

EXPERIMENTAL PROCEDURE

Domain-wall dynamics in orthoferrites was investigated in the present study by high-speed photography, using 1-nsec pulses from a dye laser. The laser was pumped by a transverse-discharge N_2 laser.[18] Mirrors were used to split the 0.63 μm beam of the dye-laser in two. One of the resultant beams was delayed by from 3 to 15 nsec. Each beam passed through a separate polarizer and was incident on an orthoferrite sample cut perpendicular to the optical axis, and then passed through a microscope and an analyzer and was incident on the camera lens. The polarizers were mounted so as to make the contrasts of the two-domain structure opposite. If, for the first beam, the sample region over which the domain wall already passed was dark (light), while the remaining sample region was light (dark), the polarizer setting for the second beam was such that the sample region traversed by the domain wall was light (dark), and the remaining region was dark (light). One pass of the domain wall along the sample produced thus on one photograph a light (dark) band located between two domain-wall positions corresponding to two instants of time separated by a specified interval. The light-pulse energy was 1 μJ. The master generator was either of G-5-54 or G-5-26 type operating at repetition frequencies 8 Hz and down to 0.1 Hz, respectively. These generators triggered, with adjustable time delays, the transverse-discharge laser, a current generator that produced the pulsed magnetic field, and a high-speed oscilloscope. The camera shutter was opened for a time that was the reciprocal of the field-pulse repetition frequency. Two dynamic domain structures were thus recorded on the photographic film during one pass of the domain wall over the sample. The pulsed magnetic field had a rise time 20 nsec and an amplitude up to 5 kOe. Coils having diameters from 0.5 to 2 mm were glued to two opposite orthoferrite-plate sides that were polished in orthophosphoric acid. The magnetic field used to establish one domain wall in the investigated plate was perpendicular to the sample, and its gradient was along the **a** axis and could be varied from 300 to 2500 Oe/cm. The contrast of the observed dynamic domain structures was very high, and the structures were recorded directly on high-sensitivity films, without the use of brightness enhancers.

EXPERIMENTAL RESULTS

We investigated in the present study the velocities of domain walls of intermediate type in plates of $YFeO_3$, $TmFeO_3$, $EuFeO_3$. The $YFeO_3$ plates, cut perpendicular to the optical axis, were chemically polished, were 100 and 120 μm thick, and were investigated at 290, 110, and 4.2 K.

Figures 1a–1e show several double dynamic domain structures in a $YFeO_3$ plate 120 μm thick at 290 K, in a pulsed magnetic field up to 2 kOe. The time interval between two successive light pulses is 15 nsec. In magnetic fields up to 170 Oe, a domain wall moving along a straight line retains its shape and remains practically straight (Fig. 1a). Starting with a 170-Oe pulsed field, the shape of the moving domain wall changes noticeably. It becomes bent, the velocities of its different parts are no longer equal (Figs. 1b, 1c) and semicircular leading sections are produced on it at random locations. This is the region of unstable motion of the domain wall. Its existence was known from earlier work.[3,8] Nothing was known from these references, however, concerning the shape of the moving domain wall. With further increase of the magnetic field the bent DW, with exception of the initial stages of motion, remains parallel to its preceding position, which was recorded on the same photograph in the course of one pass through the sample (Figs. 1d, 1e). The domain-wall velocity can be determined from the sequence in Figs. 1a, 1d, and 1e.

The transition from one-dimensional subsonic orthoferrite DW motion to non-one-dimensional supersonic motion becomes much more abrupt with increasing mobility. Figures 1f–1k show several twofold dynamic domain structures in a $YFeO_3$ plate 100 μm thick, perpendicular to the optical axis, at 110 K. The DW mobility in this case was close to maximal for the samples at our disposal, and amounted to 2×10^4 cm^{-1} Oe^{-1}. The time interval between the light pulses was 5 nsec. In pulsed magnetic fields of 120 Oe the orthoferrite DW remained linear and its motion was steady. Figure 1f shows the transition to the supersonic motion. The central part of the DW still moves at the trans-

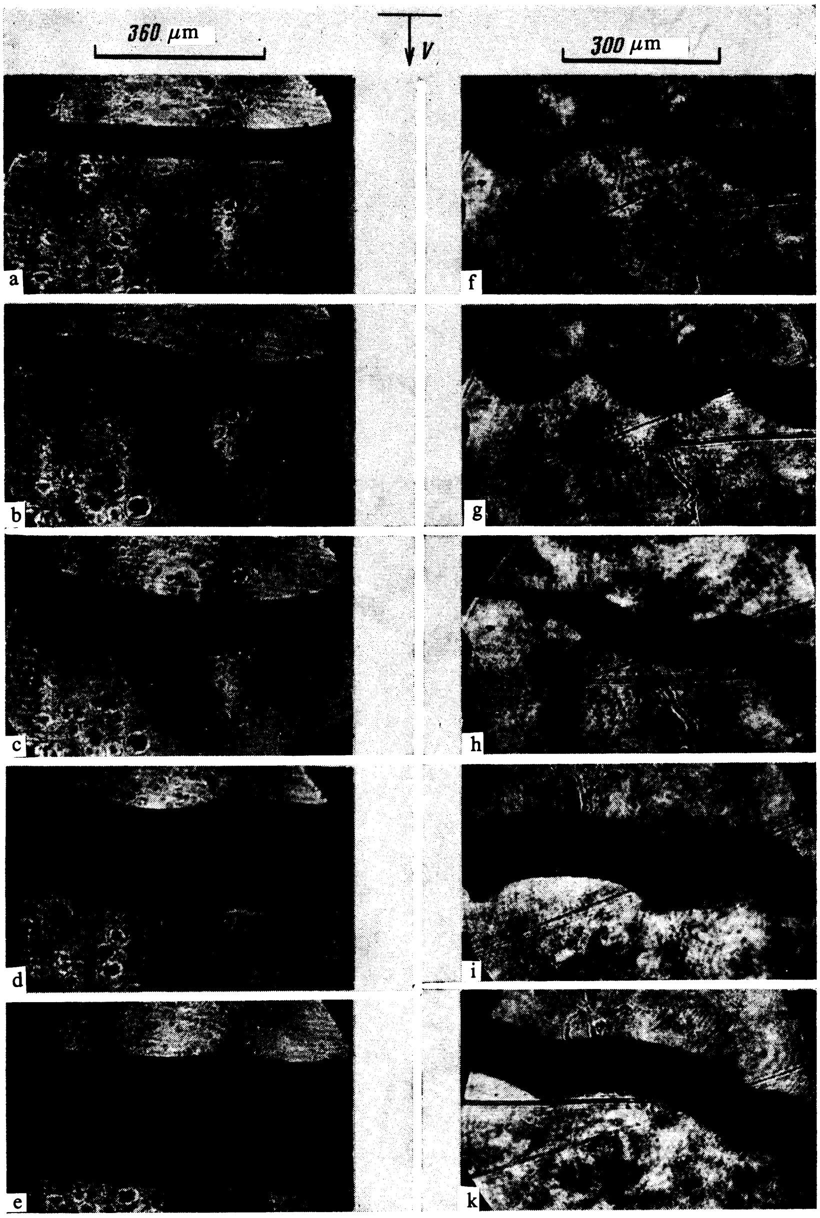

FIG. 1. Sequence of double dynamic domain structures in a $YFeO_3$ plate: a–e) thickness 120 μm, room temperature, time interval 15 nsec in fields: a—127 Oe, b—185 Oe, c—195 Oe, d—1220 Oe; f–k) thickness 100 μm, $T = 110$ K, time interval 5 nsec in fields: e, g, k—380 Oe, $h = 160$ Oe, i—7350 Oe, i, k—DW moves in a direction opposite to that indicated in the figure.

verse-sound velocity, but closer to its edges there appear already leading sections that move much faster. Their positions change from instant to instant (Figs. 1f, g, h) and finally, in the course of the bending, the DW moves as one unit (Figs. 1i, 1k) with velocity V. The points of intersection of the neighboring leading sections have velocities $(\cos\alpha/2)^{-1}$ times larger, where α is the angle at the singular point of the DW. The curvature of the DW also contributes to its equalization. By virtue of all these factures, the DW becomes equalized as it moves through the sample.

The curvature radius R of the DW in supersonic motion depends strongly on H. For the investigated $YFeO_3$ sample at 110 K, R decreases by more than seven times when H changes from 120 to 2650 Oe. The position of the singular points on the DW becomes stabilized with increasing H. The dependence of the curvature radius R on the DW velocity and on the magnetic field H is described by the relation

$$R^{-1}=[2M_sH-F_{ph}(V)-F'(V)-2M_sV/\mu(1-V^2/C^2)^{1/2}]\sigma^{-1}, \quad (1)$$

where μ is the mobility, V the velocity, and C the limiting velocity of the orthoferrite DW. This formula, unlike in Ref. 19, includes the phonon retardation force $-F_{\rm ph}(V)$. It was calculated in the one-dimensional theory for longitudinal and transverse sound.[15,16] Besides these singularities on the $V(H)$ plots, there exist in orthoferrite plates also many other singularities (see below) which have not yet been theoretically explained and lead to additional retardation of the DW. This retardation force $F'(V)$ is also included in Eq. (1). This

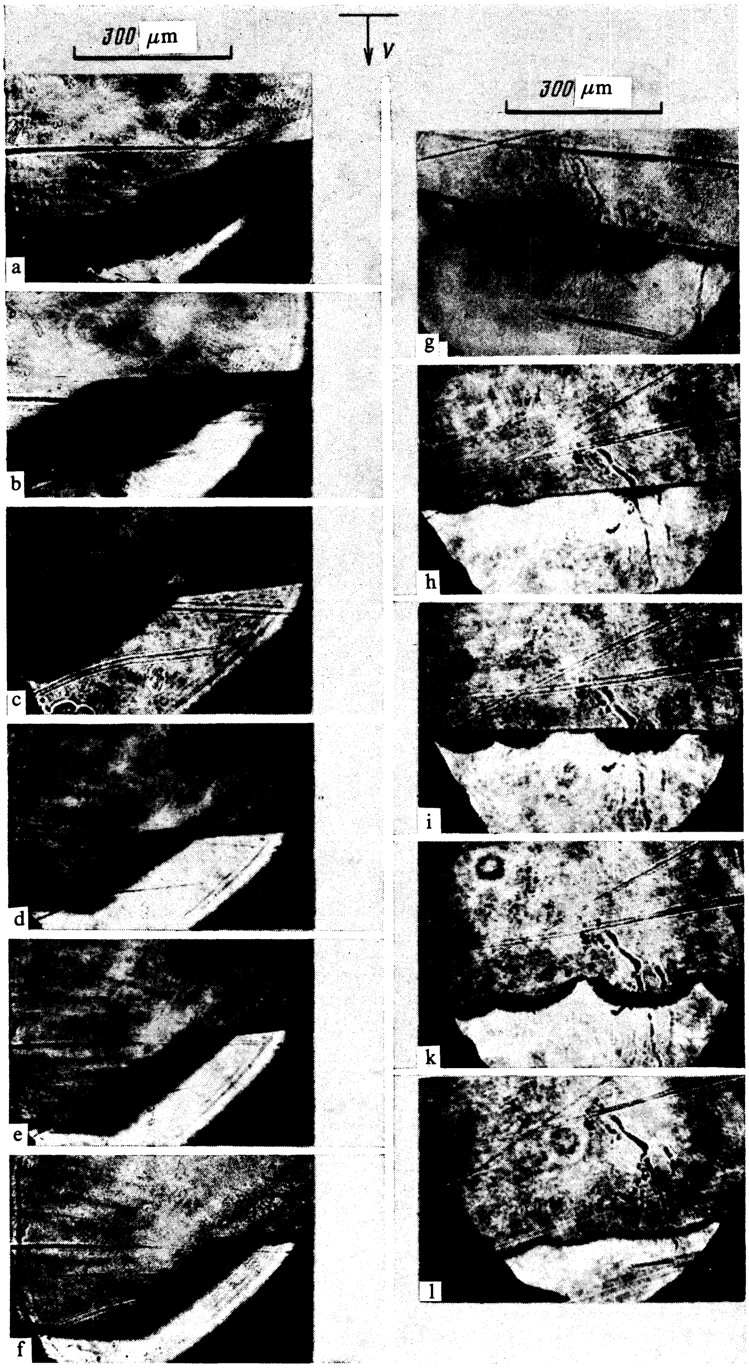

FIG. 2. Sequence of double dynamic domain structures near the transverse-sound velocity (a–f) and of dynamic domain wall ($g - l$) in a $YFeO_3$ plate 100 μm thick at $T = 110$ K: a—at 15 nsec in a field 120 Oe. *n*—at 15 nsec in a field 130 Oe, c–f—at 3 nsec in a field 140 Oe, g—twofold photograph of moving DW at 3 nsec, h–l—photograph of single DW as it surmounts the sound barrier in a field 600 Oe at time intervals 2 nsec.

equation was obtained from a phenomenological equation of DW motion,[5] which includes the surface-tension force σ/R in a non-one-dimensional DW.[19] Equation (1) describes qualitatively the experimental $R(H)$ dependence. From a quantitative comparison of (1) with the experimental $R^{-1}(H)$ one can attempt to determine $F_{\rm ph}(V) + F'(V)$.

Under conditions of high DW mobility, the transition to supersonic motion is very abrupt. At 110 K, a bend whose velocity reaches 20 km/sec can propagate along a $YFeO_3$ DW that moves at transverse-sound velocity. The process of formation and motion of a bend on a DW is illustrated by Figs. 2a–2f. Figure 2a shows a double dynamic domain structure with an interval 15 nsec between light pulses in a magnetic field 120 Oe. The wall has the form usual for the instability region. Further increase of H to 130 Oe leads to an abrupt change of the character of the DW motion (Fig. 2b). The right-hand part of the DW moves at the transverse-sound velocity, while the velocity of the left-hand part of the

DW again drops to the same velocity. A bend with velocity 20 km/sec appears on the domain wall that moves at the transverse-sound velocity. Figures 2c–2f show successive positions of the dynamic domain structures at intervals of 5 nsec. The time interval between two successive photographs is 3 nsec. One can clearly see the motion of the bend from left to right and its peaking in the course of this motion. The bend-formation mechanism is the following. A single DW is produced in the sample by a gradient magnetic field perpendicular to the sample surface. The pulsed field is superimposed on this field. With further motion of the DW, the field acting on the wall decreases gradually, and the wall is in a combined magnetic field corresponding to unsteady motion. Owing to the action of the gradient magnetic field, the motion of the DW again becomes steady, at the velocity of transverse sound. The bend is produced in the interval 120–150 Oe. These numbers agree with the value of grad H. The amplitude of the bend decreases with its growth. On the whole, a bend on a DW that moves at transverse-sound velocity constitutes a complex dynamic formation with variable mass. Its velocity is bounded from above by the velocity of the flexural waves on the DW. An expression for this velocity was obtained in Refs. 15 and 20, and it agrees with the velocity of volume spin waves on the linear section of their dispersion law. This velocity, as is well known, is equal to the limiting DW velocity

$$C=\gamma(2H_E D)^{1/2}, \tag{2}$$

where $D = A/I_0$; $\gamma = eq/2mc$; H_E is the exchange field. The experimentally observed bend velocity is also close to this value. Thus, C plays a decisive role in the dynamics of both the DW and of the bend along it.

From the sequence of the double dynamic domain structures represented in Fig. 2 one can determine the DW velocity. The dependences of the DW velocity on the magnetic field for several $YFeO_3$ samples at 290, 110, and 4.2 K are shown in Fig. 3. The dark points show the $V(H)$ dependence for a DW of intermediate type in a $YFeO_3$ plate 120 μm thick and perpendicular to the optical axis. When the magnetic field is increased to 70 Oe the DW velocity increases to that of the transverse sound. In the interval 70–150 Oe the DW velocity remains constant, and with further increase of H it becomes equal to the longitudinal sound velocity. With increasing H, the DW has a set of discrete velocities, the transitions between which are quite abrupt. The dark circles of Fig. 3 represent about 10 such discrete velocities. An analogous $V(H)$ dependence at 110 K in a $YFeO_3$ sample 100 μm thick is represented by the crosses in Fig. 3. The transition to supersonic velocity is here very abrupt. The reason is the high mobility of the DW, which reaches 2×10^4 cm/sec·Oe. Formation of the bend described above is observed in the region of the transition to the supersonic unstable state. With further increase of H one can see several regions of constant DW velocity, with subsequent transition to the limiting value 2×10^4 m/sec that agrees with the velocity of spin waves in the orthoferrite on the linear section of their dispersion law. The $V(H)$ dependence for $YFeO_3$ at 4.2 K is similar (Fig. 3, light circles). A peculiarity of this dependence is the substantial increase of the magnetic-field intervals ΔH_i in which the DW velocity remains unchanged. The limiting velocity is reached here in a magnetic field 5000 Oe. It should be noted that the employed ultra-high-speed twofold photography procedure did not reveal in any of the cases any DW velocities exceeding the limiting value. Up to 5000 Oe, the investigated orthoferrite plates remained two-domain. The above-limit velocity observed earlier[17–21] by measuring the time required for the DW to transverse the distance between two light spots were probably due to the appearance of new domains ahead of the moving DW. This possibility of explaining the above-limiting velocity was first pointed out in Ref. 22.

It is of interest to investigate thoroughly the DW in the course of passage through the sound barrier. It was reported in Refs. 12 and 23 that in this case the DW broadens greatly. This may be due either to formation of a diffuse DW, or to the existence of above-limit nonstationary velocities. Figure

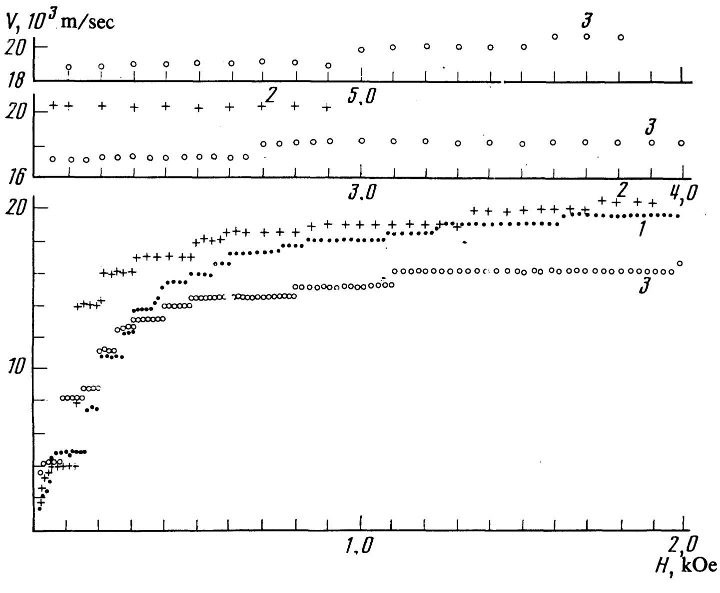

FIG. 3. Dependences of DW velocity in a YFO_3 plate on the amplitude of the pulsed magnetic field: a—thickness 120 μm, $T=290$ K; 2—thickness 100 μm, $T=110$ K; 3—thickness 100 μm, $T=4/2$ K.

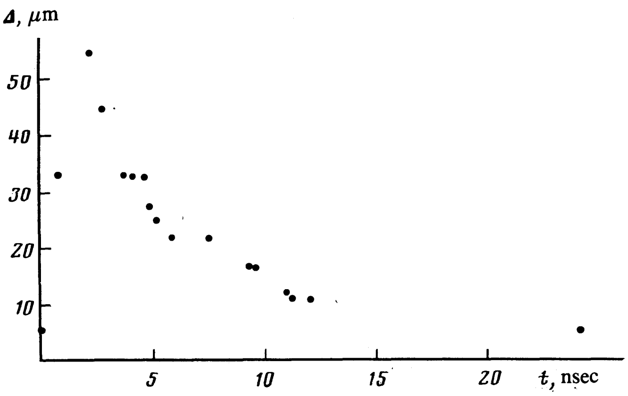

FIG. 4. Time dependence of the visible width of a DW in a $YFeO_3$ sample 100 μm thick at $T = 110$ K in a field 600 Oe.

2g shows a twofold dynamic photograph of a moving DW in $YFeO_3$ at 110 K with interval 3 nsec in the course of one pass of the DW through the sample after overcoming the sound barrier. The DW velocity determined from such photographs did not exceed the limiting value in all magnetic fields up to 5000 Oe, and amounted to 20 km/sec. The observed thickening of the DW sets in gradually (Fig. 2h). The maximum DW width is quite large, 50–60 μm, and is reached 2 nsec after the DW overcomes the sound barrier (Fig. 2i). After another 2 nsec the DW width decreases noticeably (Fig. 2k). At 3–4 nsec later the DW becomes equalized and its width decreases even more noticeably and finally becomes comparable with the width of the static DW (Fig. 2*l*). Figure 4 shows the dependence of the visible width $\Delta_{(t)}$ of the moving DW on the time at 110 K in a magnetic field 600 Oe. Photometry of the photographs of the moving DW has shown at supersonic velocities it flexes while thickening and its central part moves most rapidly. Under the foregoing assumptions, the maximum DW width should be equal to half the thickness of the orthoferrite plate.

The general form of the $V(H)$ plots shown in Fig. 3 for an intermediate DW perpendicular to the sample surface remains the same also for a DW inclined to the sample surface and moving perpendicular to the **a** axis. Here, too, one observes a maximum velocity of 20 km/sec and a number of regions in which the velocity Vi is constant. The $V(H)$ curves for $TmFeO_3$ and $EuFeO_3$ are similar.

DISCUSSION OF RESULTS

On the whole, the supersonic motion of DW in orthoferrites is non-one-dimensional and nonuniform. The non-one-dimensionality sets in whenever the DW surmounts the sound barrier. Lowering the operating frequency of the apparatus from 8 to 0.1 Hz did not change the $V(H)$ dependences. It is possible that a certain number of regions where the DW velocity is constant is due to interaction with optical phonons. No theory of additional singularities on the $V(H)$ plot of an orthoferrite DW exists at present. The experiment described shows that the theory of orthoferrite DW dynamics should be non-one-dimensional. A theory must be developed for nonuniform and non-one-dimensional DW motion. A substantial role in the dynamics of orthoferrite DW is played by the limiting velocity, which corresponds to the velocity of the spin waves in the linear section of their dispersion law. This velocity determines also the maximum possible velocity of the bend that moves along the orthoferrite boundary near the region of the supersonic instability.

The set of DW velocities in the interval between that of transverse sound to that of the spin wave is discrete for various types of DW in all the heretofore investigated orthoferrites. The number of observable constant-velocity intervals depends essentially on the plate thickness. Experiments on $YFeO_3$ plates immersed in H_2O and CCl_4 has shown that the singularities on the $V(H)$ plots remain practically of the same form. If the additional singularities on the $V(H)$ plots were due to interaction with only elastic Lamb waves, for which the displacements are large, each of them would vanish or decrease on account of sound damping in the H_2O or CCl_4. This was not observed in experiment. Therefore the indicated additional singularities cannot be attributed to interaction of the moving DW with elastic Lamb waves. Excitation of bulk acoustic waves at 90 MHz decreased the number of observed ΔH_i intervals and their width. A sound wave upsets the conditions for steady motion of a DW with velocity V_i. These singularities may be due to excitation of flexural waves on the DW, similar to those observed in the present study in the case of bend formation.

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