Investigations of the nonlinear dynamics of domain walls in yttrium orthoferrite by the method of high-speed photography

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The method of high-speed photography is used to investigate the dynamics of a rectilinear domain wall in $YFeO_3$. Light pulses of duration 10 ns, from a neodymium-glass laser with quality-factor modulation, are used. Series of photographs of the "instantaneous" positions of a moving domain wall in a two-domain specimen are obtained for various values of the pulsed fields, and from them the $V(H)$ relation is found. It is shown that up to the limiting velocity of a domain wall, 20 km/s, its form remains rectilinear. Motion of a domain wall existing in the specimen remains the only process for magnetization of the specimen up to fields of 3000 Oe. The experimental results are compared with theory. Along with singularities in the $V(H)$ relation at the speeds of longitudinal and transverse sound, still another singularity is observed in the neighborhood of 15.5 km/cm. Possible mechanisms for explanation of it are proposed.

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Record-high velocities of motion of domain walls are observed in weakly ferromagnetic orthoferrites. The methods originally used for these investigations were the Sixtus-Tonks method[1] and the collapse of bubbles.[2] A considerably more accurate method has been found to be measurement of the time of passage of a moving domain wall over a prescribed distance.[3] It made it possible to observe the limiting velocity of motion of a domain wall in yttrium orthoferrite, which amounts to 20 km/s and corresponds to the velocity of spin waves on the linear section of the dispersion relation $\omega(k)$. The theory of nonlinear dynamics of domain walls in orthoferrites has been developed in papers of Zvezdin[4] and of Bar'yakhtar *et al.*[5] This theory explains the general behavior of the $V(H)$ relation up to the limiting velocity, but there is a discrepancy in the estimation of the value of the field at which this limiting velocity is attained. An exact class of solutions of the Landau-Lifshitz equations for a moving domain wall in an orthoferrite has been found by Eleonskiĭ *et al.*[6]

The method of Ref. 3 for determination of the $V(H)$ relation essentially uses the motion of a domain wall in a pulsed magnetic field, repeated periodically with a frequency of several tens of hertz, and it therefore gives, in general, velocities averaged over a large number of passages of a wall over a prescribed distance. Along with the methods of investigation mentioned above, the method of high-speed photography of moving domain walls in ferromagnets is also being developed. This method has been used for investigation of the dynamics of domain walls in iron-garnet films,[7] where the velocity does not exceed a few hundreds of meters per second, and in permalloy films.[8]

In the present paper, the method of high-speed photography is used for investigation of the dynamics of a solitary domain wall in yttrium orthoferrite, where the velocity of motion is substantially larger than in any other magnetically ordered crystals so far investigated.

EXPERIMENTAL METHOD

The method of obtaining a two-domain structure in a plate of yttrium orthoferrite, cut perpendicular to the optic axis, was described in Ref. 3. In an external magnetic field perpendicular to the surface of the specimen, with a gradient of 300 Oe/cm along the [100] axis, a solitary domain wall exists in the specimen. It is perpendicular both to the specimen surface and to the [100] direction that lies in the plane of the plate. The weakly ferromagnetic moment of the orthoferrite, in not too strong magnetic fields, can rotate only in the (010) plane; therefore the wall is neither purely of Bloch nor purely of Néel type, but is a wall of intermediate type. The pulsed magnetic field that set this wall into motion was produced by two coils with internal diameter 1.6–2.5 mm, each of 13–20 turns. The coils were attached directly on two sides to the orthoferrite plate, of thickness 100 μm, polished chemically. The pulse edge was 30 ns; the maximum amplitude of the magnetic field was 3000 Oe. The increase of the diameter of the coils that produced the pulsed magnetic field was due to the necessity for photographic recording of the instantaneous position of the moving domain structure. This increase of diameter also caused some increase of the duration of the field-pulse edge as compared with that used earlier.[3]

A block diagram of the experimental setup is shown in Fig. 1. High-speed photography of the position of the moving domain wall was accomplished by means of pulses of light from the neodymium-glass laser 1, with quality-factor modulation, operating at wavelength 1.06 μm. The light-pulse duration at the half-power level was 10 ns. Linearly polarized light from this laser, passing through the absorbing filter 2 and the semitransparent plate 3, fell on the $YFeO_3$ sepecimen 4, of thickness 100 μm, cut perpendicular to the optic axis at the operating wavelength. The absorption coefficient of $YFeO_3$ at this wavelength is considerably

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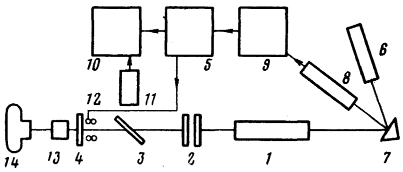

FIG. 1. Block diagram of experimental setup.

lower than at wavelength 0.69 μm, where a ruby laser operates. It is this fact that determined the choice of operating wavelength for investigation of the velocity of motion of a domain wall in the present paper.

The triggering of the current-pulse generator 5 was synchronized with the light pulse from the neodymium-glass laser. The delay between the beginning of the magnetic-field pulse and the light pulse could be smoothly varied. For this purpose, we used an auxiliary helium-neon LG-52 laser, operating at wavelength 0.63 μm, the beam from which was reflected from the same rotating prism 7 that was used for modulation of the Q of the neodymium-glass laser. The light beam from this laser was reflected from the rotating prism 100–500 ns earlier than the occurrence of generation of the neodymium-glass laser in the Q-modulation mode. The light pulse from the LGF-52 fell on the FEU-18 photomultiplier 8, and thence in the form of an electric signal entered the trigger of the G5-48 generator 9, from which it triggered the thyratron current-pulse generator that fed the coils. By changing the delay of this generator, it was possible to control smoothly the interval of time from the beginning of the magnetic-field pulse to the beginning of the light pulse. For recording the light pulse from the neodymium-glass laser, we used a coaxial FK-15 photocell 11, with time constant 10^{-10} s.

The linearly polarized light from the neodymium-glass laser, through the system of neutral filters necessary for protection of the specimens from destruction, fell on the specimen, then on the analyzer, and finally on the image converter 13. From the screen of this converter was photographed the position of the domain wall for a definite delay between the pulses of the controlling magnetic field and of the light.

EXPERIMENTAL RESULTS AND DISCUSSION OF THEM

In the investigation of the dynamics of domain walls in orthoferrites by the method of high-speed photography, we used the method described in the preceding section for obtaining and synchronizing pulses of the magnetic field and light pulses from the Q-switched laser.

On the screen of an S8-12 memory oscillograph, we observed the magnetic-field pulse, with superposition on its plane of part of the light pulse. The time sweep rate was 20 ns/division. The rise time of the magnetic-field pulse was 30 ns. The duration of the light pulse at the half-power level was not greater than 10 ns. The rear edge of the light pulse was very sharp and was fixed with accuracy as much as 2 ns. By

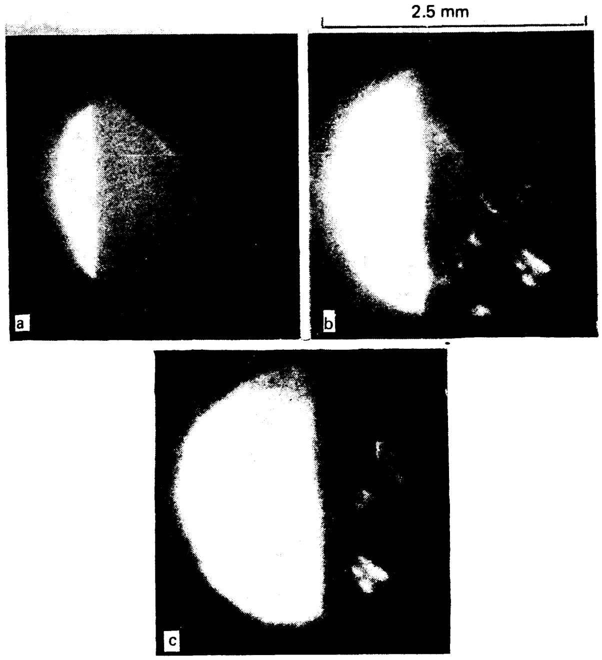

FIG. 2. Sequence of "instantaneous" positions of a domain wall in $YFeO_3$, moving in a pulsed field of amplitude 1100 Oe.

varying the delay between the beginning of the magnetic-field pulse and the light pulse, we could obtain a sequence of photographs of the position of the domain wall at different instants of time. A sequence of photographs obtained in pulsed magnetic field 1100 Oe is shown in Fig. 2. It is seen that the form of the wall remains rectilinear during the process of motion. This is so for all values of the magnetic field up to 3000 Oe. The contrast of the dynamic domain structure is quite high. It is insured by the difference of angles of rotation of the plane of polarization of the light in two adjacent, oppositely magnetized domains, which in a $YFeO_3$ plate of thickness 100 μm, at wavelength 1.06 μm, is 10°.[9]

Thus the only process of magnetization of the specimen is motion of a domain wall that was present initially in the specimen. New domains are not formed during the time of passage of the wall through the whole specimen.

The time dependences $S(t)$ of the distance traversed by the domain wall at several values of the pulsed magnetic field are shown in Fig. 3; they were obtained by pro-

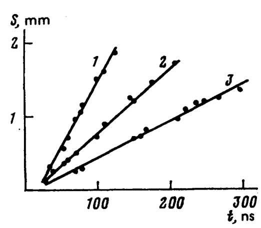

FIG. 3. Variation of the path traversed by a domain wall in $YFeO_3$ with the time interval between the front of the magnetic-field pulse and the light pulse: 1, H=780 Oe, V=18.2 km/s; 2, H=240 Oe, V=9.3 km/s; 3, H=80 Oe, V=3.3 km/s.

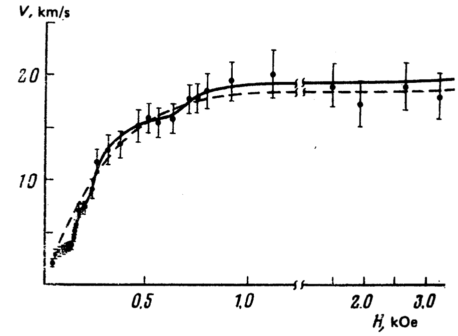

FIG. 4. Variation of the velocity of motion of an isolated domain wall, perpendicular to the surface of a $YFeO_3$ specimen, with the amplitude of the controlling field.

cessing of photographs like those shown in Fig. 2. It is evident from Fig. 3 that the velocity of the domain wall remains constant over a wide time interval, except for an initial interval of 30 ns during which the value of the magnetic field is rising and the wall is acquiring its constant velocity. By drawing the straight line $S(t)$ corresponding to the minimum, mean, and maximum velocities of motion of the domain wall, one can determine the accuracy of measurement of the velocity. From the set of $S(t)$ relations like those shown in Fig. 3, for various values of the pulsed magnetic field, we obtained the $V(H)$ relation shown in Fig. 4. In this figure, singularities are clearly evident at velocities 4 and 7 km/s, corresponding to the velocities of transverse and longitudinal sound. The theory of the interaction of a moving domain wall with sound waves in orthoferrites has been treated in papers of Zvezdin *et al.*[10] and of Bar'yakhtar *et al.*[11]

Estimates of the value of the magnetic-field interval within which the velocity of a domain wall remains unchanged agree with experiment. Besides the singularities mentioned, the $V(H)$ relation shows still another, at $V = 15.5$ km/s, which has not yet found explanation. The experimental accuracy of determination of the domain-wall velocity is here 1.3 km/s.

The change of velocity on passage from magnetic fields 450-620 to fields 680–730 Oe is 1.8 km/s, so that the indicated accuracy is sufficient for observation of the singularity mentioned. Furthermore, this singularity was observed experimentally also in Ref. 12, where a more accurate method was used to measure the time of passage of a wall through a prescribed distance. In this case, as in the present work, chemical polishing of the orthoferrite plates was used. In mechanically polished plates, this singularity is not observed. It is possible that in this case we have interaction of a moving domain wall with a spin wave near the boundary of a Brillouin zone or near the maximum of the density of states.

Experimental $\omega(k)$ relations for orthoferrites are at present lacking. Two-magnon scattering of light, which in principle permits determination of $\omega(k)$ at the edge of a Brillouin zone, has also not been observed in orthoferrites. From theoretical calculations of $\omega(k)$ in orthoferrites, made by White *et al.*,[13] the value of the phase velocoty of a spin wave at the edge of the Brillouin zone is 14.0 km/s, which is close to the experimental value. It is also not excluded that a moving domain wall may interact with surface spin waves, which have not so far been observed in orthoferrites.

The general behavior of the $V(H)$ relation obtained by the method of high-speed photography substantiates the results of Ref. 3, which were obtained by averaging of the times of passage of the wall through a given distance. The dotted curve in Fig. 4 shows the results of a calculation of the domain-wall velocity variation

$$V(H) = \mu_0 H[1 + (\mu_0 H/V_{sw})^2]^{-1/2}, \quad (1)$$

obtained by Zvezdin[4] and by Bar'yakhtar *et al.*[5] Here μ_0 is the mobility, $V_{sw} = \omega/k = d\omega/dk = \gamma(2H_E D)^{1/2}$ is the velocity of spin waves on a linear section of their dispersion curve, H_E is the exchange field, $D = 2A/I_0$, A is the exchange stiffness, and I_0 is the magnetization of a sublattice. The agreement of theory with experiment is very satisfactory. The accuracy of the experimental determination of $V(H)$ depends on the value of the velocity and is determined by the duration of the light pulse. Densitograms of the photographs of "instantaneous" domain-wall positions were obtained. From these data were found the distances traversed by the wall during the time of the light pulse. At the maximum velocities, these distances amounted to 0.2 mm, and the accuracy of the wall position was better than 0.1 mm.

In order to obtain new data on the nonlinear dynamics of domain walls in orthoferrites, further development is necessary both of the method of high-speed photography and of the method of determination of the time of passage of a wall through a prescribed distance.

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