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Dynamics of domain walls in weakly ferromagnetic orthoferrites

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The velocity of domain walls in mechanically and chemically polished plates of $YFeO_3$ is investigated in large pulsed fields at 293 and 100 K. The velocity was determined from the time of passage of the wall over a given distance between two light spots. It is shown that after attainment of a limiting velocity equal to $2\cdot10^6$ cm/sec and corresponding to the minimum velocity of spin waves, there occurs a rapid increase of velocity to $2\cdot10^7$ cm/sec. The increase of velocity begins sooner, the more strongly the moving wall interacts with the unavoidable defects at the surface of the plate. In a mechanically polished specimen, the increase of velocity begins in fields of 0.7 kOe; in chemically polished, at fields larger than 3 kOe. In a mechanically polished $YFeO_3$ plate, at the back edge of the light pulse obtained on reverse motion of the wall through the light spots there occurs an instability that indicates a transition from stationary motion to turbulent. The instability appears after the wall attains the limiting velocity.

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1. INTRODUCTION

The limiting velocity of a domain wall in weakly ferromagnetic orthoferrites was first measured experimentally in work of one of the authors.[1] In yttrium orthoferrite, this velocity is $2\cdot10^6$ cm/sec and corresponds to the minimum phase velocity of spin waves with limiting wave vectors.[2] A solution of the Walker type for a weak ferromagnet was obtained by Zvezdin.[3] Limiting velocities of domain walls have been attained experimentally in pulsed magnetic fields H_p of order of magnitude 1000 Oe. This is much lower than theory predicts.[3] On further increase of H_p, the domain-wall velocity again increases and exceeds the limiting velocity by an order of magnitude. It was first pointed out in a paper of one of the authors[4] that the region of constancy of the limiting wall velocity with respect to magnetic field must be finite, as occurs in interaction of a moving domain wall with sound. Above-limit velocities of a domain wall were first observed in $YFeO_3$ at room temperature in Ref. 5.

The present paper presents results of investigations of motion of domain walls in weakly ferromagnetic orthoferrites with above-limit velocities. The investigations were made at 293 and 100 K for two types of walls in $YFeO_3$ specimens, whose surfaces were polished mechanically and chemically.

2. METHOD OF INVESTIGATION

The velocity of the domain wall was determined, by means of the dynamic Faraday effect, from the measured time of passage over a given distance between two light spots. The method of investigation that we used has been described in Ref. 4.

For production of the pulsed magnetic field, two coils were used, of diameter 1–1.5 mm corresponding to 7–14 turns, fastened from the two sides on to the surfaces of the plates of the orthoferrites under study. At the input of an electron multiplier FÉU-30, in order to diminish the noise, a diaphragm was placed, which transmitted only the two light beams obtained from the two light spots focused on to the plate. The minimum time of passage of a domain wall over a distance of 540 μm,

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as obtained by us experimentally in $YFeO_3$, was about 3 nsec, which is the limit of temporal resolution of the recording part of the apparatus used. This time corresponds to a domain-wall velocity $\sim 2 \cdot 10^7$ cm/sec. In order to investigate the motion of a wall with still higher velocities, it would be necessary to develop new methods, such as photographing the moving wall in pulsed laser light of nanosecond and picosecond durations.

The specimens used for investigation were plates of $YFeO_3$ cut perpendicular to the optic axis at wavelength 0.63 μm, and having a thickness of about 100 μm. These plates were polished first optically and then chemically, in orthophosphoric acid heated to temperature 360 °C. The investigations of the domain-wall velocity were made at 293 and 100 K. In the latter case, the $YFeO_3$ specimens were placed in a special optical cryostat. The magnetic field was produced by coils supplied by a generator that gave up to two kilovolts of pulsed voltage. The maximum current in the coils was 16 A, the forward edge of the pulse from 5 to 10 nsec, the duration from 30 nsec to 1.5 msec. The maximum magnetic field produced by the coils of diameter 1 mm was 3.2 kOe. The repetition frequency of the pulses was 40 Hz. This made it possible to record the time of passage of a wall over a given distance by use of a stroboscopic oscillograph S-7-8. In order to produce a single straight wall, the specimen were placed in a constant gradient field, directed perpendicular to the surface of the plate, with the gradient along or perpendicular to the *a* axis of the crystal. The gradient could be varied from 250 to 2500 Oe/cm. The distribution of the magnetic field inside the coil is shown schematically in Fig. 1.

3. EXPERIMENTAL RESULTS

Figure 2 shows the variation with magnetic field, at 293 and 100 K, of the velocity of a domain wall of the intermediate type, perpendicular to the specimen surface, which was polished mechanically. The domain-wall mobility, determined from the initial section of the curve, was considerably larger at 100 K than at 293 K. The limiting velocities at these temperatures are $2 \cdot 10^6$ and $2.3 \cdot 10^6$ cm/sec.

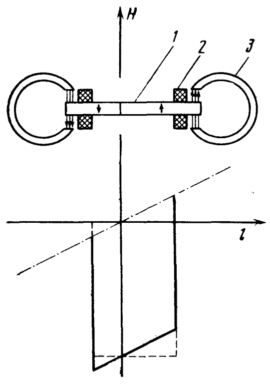

FIG. 1. Magnetic-field distribution in the specimen during domain-wall motion. 1) $YFeO_3$ plate; 2) coils producing a pulsed magnetic field (dotted); 3) magnets producing a gradient field (dash-dotted); field acting on the specimen (solid curve).

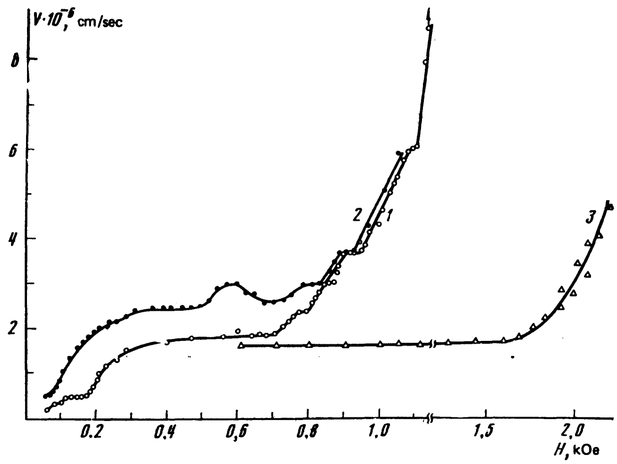

FIG. 2. Velocity of motion of single domain walls in an optically polished $YFeO_3$ plate in a pulsed magnetic field. 1) 293 K; 2) 100 K; wall of intermediate type, perpendicular to the specimen surface; at temperature 293 K, the maximum velocity was $2 \cdot 10^7$ cm/sec. Curve 3, 293 K; wall of Bloch type, oblique to the specimen surface.

The limiting velocity of a domain wall is determined by the minimum phase velocity of spin waves.[2] A formula for the limiting domain-wall velocity of orthoferrites was first obtained in Ref. 2 and had the following form:

$$V=\gamma\sqrt{2H_E D}, \tag{1}$$

where H_E is the exchange field, $D=2A/I_0$, A is the exchange constant, I_0 is the magnetization of a sublattice of the anitferromagnet. Formula (1) was later improved by Bar'yakhtar and coworkers[6] and by Zvezdin,[3] who showed that in a weak ferromagnet (1) must be multiplied by $1+H_D/H_E$, where H_D is the Dzyaloshinskiĭ field. From (1) it follows that for $YFeO_3$, $V=2 \cdot 10^6$ cm/sec.

The values of the limiting velocity obtained experimentally agree with their theoretical values. The difference between the limiting velocities at 293 and 100 K is partly due to the compressibility of the crystal and, perhaps, to partial deformation of the density-of-states curve of spin waves on lowering of temperature, since the limiting domain-wall velocity should be determined by the velocity of spin waves with wave vectors corresponding to the maximum on the density-of-states curve, which lies near the edge of the Brillouin zone. At 293 K, no maximum of $V(H)$ is observed. Saturation of the velocity is practically attained in fields of 400 Oe, which is orders of magnitude smaller than is estimated in Ref. 3. In the flat part of the $V(H)$ curve at 100 K, a small maximum is observed.

In fields larger than 700 Oe, there begins a further increase of the velocity, to a value of order of magnitude $2 \cdot 10^7$ cm/sec. On the back edge of the light pulse obtained on reverse motion of the wall through the light spots, there appears a periodic instability of the velocity, suggesting a transition from stationary single-domain motion of the wall to periodic laminar or turbulent motion.[5]

Figure 3 (curves 1 and 2) shows the results of investigations on a chemically polished specimen of $YFeO_3$. At 293 K, no increase of the velocity after the limiting value is observed in fields up to 3200 Oe. At 100 K, a substantial increase of velocity is observed, beginning with field 2800 Oe. At 300 Oe the wall velocity reaches $6\cdot10^6$ cm/sec. All the experimental results described above relate to a wall of the intermediate type, strictly perpendicular to the specimen surface and to the *a* axis of the crystal.

Figure 2 (curve 3) shows the $V(H)$ relation in a mechanically polished $YFeO_3$ specimen for a wall of the Bloch type, oblique to the specimen surface, at 293 K. Here the limiting velocity is smaller than for a wall perpendicular to the specimen surface,[2] and at $H=1700$ Oe there begins a further increase of the velocity above the limiting value.

4. DISCUSSION OF RESULTS

A general property of most of the $V(H)$ relations shown in Figs. 2 and 3 is an increase of the velocity above the limiting values in large fields. This increase begins sooner, the more strongly the moving wall interacts with the unavoidable defects on the surface of the plate. It is possible that in the case of the plate polished chemically at 100 K, we have to do with intrinsic turbulence. It is possible that here a role is still played by some defects on the surface of the plate. The role of the lateral plane surfaces is not important here. The results do not change if, by means of permanent magnets, we "detach" the wall from the lateral faces of the plate.

Theoretically, the possibility of existence of periodic laminar and turbulent motions of a domain wall must be connected with the retention of higher derivatives in the Landau-Lifshitz-Slonczewski equations of motion of the magnetic moment. It is not excluded that a general theory requires allowance for damping of spin waves with different wave vectors, and this is difficult to carry out within the framework of an equation of motion with a single damping constant.

In all the experiments described in this paper, a single straight wall was obtained in orthoferrite specimens by means of a gradient magnetic field. To confirm the translational character of the motion of this domain wall, within the framwork of our method two light spots were used that were located at equal distances from an immobile straight wall. The times of passage of the wall to these two spots always agreed. With straight behavior of the magnetic-field pulse, we never observed nonmonotnic signals from the photoelectric multiplier. Thus the specimens studied always remained two-domain during the measurement of the time of passage. The succession of signals from the photoelectric multiplier always corresponded to successive crossing by the wall first of the nearer and then of the farther light spot. The chief process of magnetization of the $YFeO_3$ plate was motion of a domain wall that already existed at the moment of application of the field pulse.

In principle, in large pulsed magnetic fields the formation and growth of new nuclei is possible. These processes are of threshold type and begin at fields of order of magnitude 500–700 Oe. At these fields, a domain wall already existing in the specimen moves with large velocities, and this process is the fastest. There is no coherent or incoherent rotation of the magnetic moment in orthoferrites in the fields used by us. These processes occur in fields $\sqrt{H_E H_D}\sim 80$ kOe. It would be interesting to track the motion of domain walls in $YFeO_3$ by photographing their instantaneous positions in pulsed laser light of nanosecond and picosecond durations.

Thus the results of the experiments show that in yttrium orthoferrite, after the attainment by a moving domain wall of the limiting velocity corresponding to the minimum velocity of spin waves, there occurs a further substantial increase of its velocity. Here the character of the domain-wall motion ceases to be stationary and becomes periodically laminar or turbulent. The wall ceases to be a one-dimensional object, and consequently there arises a possibility of Cerenkov radiation of spin waves.

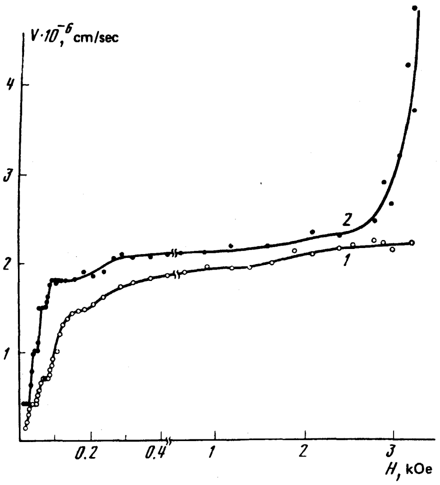

FIG. 3. Velocity of motion of single domain walls perpendicular to the specimen surface, in a chemically polished $YFeO_3$ plate. 1) 293 K; 2) 100 K.

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