Investigation of domain-wall motion in thulium and yttrium orthoferrrites

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The velocity of motion of a plane domain wall of intermediate type is investigated in a chemically polished specimen of $TmFeO_3$, cut perpendicular to the optic axis, at 293, 227, and 178 K. At temperatures 178 and 227 K, the limiting velocity of motion, $20\cdot10^3$ m/s, is attained. On the $V(H)$ relation, regions of constant velocity are observed at $9.6\cdot10^3$ and $13.7\cdot10^3$ m/s. The width of the magnetic-field interval within which the velocity remains constant is independent of the mobility. Possible causes of these anomalies are discussed. It is shown that the domain-wall mobility in $TmFeO_3$ has a maximum at 180 K. The velocities of motion of Bloch and Néel walls are investigated in a chemically polished specimen of $YFeO_3$ cut perpendicular to the [001] axis. The limiting velocities of these domain walls are the same and are equal to $19\cdot10^3$ m/s.

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1. INTRODUCTION

Record-high velocities of motion of domain walls (DW) have been observed in yttrium orthoferrite,[1] where the limiting velocity, $20\cdot10^3$ m/s, was first attained.[2] An interpretation of the limiting velocity of a domain wall in a weak ferromagnet was first given in Ref. 2, where it was shown that it corresponds to the velocity of spin waves on the linear section of their dispersion law. A theory of the nonlinear dynamics of DW in orthoferrites has been constructed.[3–5]

In rare-earth orthoferrites in which the DW mobility is substantially smaller, the limiting velocities have not been observed experimentally. Thus in plates of thulium orthoferrite cut perpendicular to the optic axis, the velocity of motion of a plane DW and the velocity of the vertex of a wedge-shaped domain at room temperature were measured only up to $5\cdot10^3$ and $6.5\cdot10^3$ m/s respectively.[2,6] It was therefore of interest to carry out these investigations at higher DW mobilities. On the other hand, the not too high DW mobility in $TmFeO_3$ made it possible to observe clearly a number of new features during the rise of the velocity to the limiting value.

In orthoferrite plates perpendicular to the optic axis, there is a stripe domain structure. The domains are separated by strictly plane domain walls of the intermediate type, perpendicular to the surface of the specimen. It seemed of interest to investigate the velocity of motion of plane Bloch and Néel DW. These walls can be obtained in orthoferrite plates perpendicular to the axis of weak ferromagnetism, in a magnetic field perpendicular to the surface, with a gradient of 1300 Oe/cm along the [010] and [100] axes, respectively.

2. DOMAIN-WALL DYNAMICS OF THULIUM ORTHOFERRITE

In this research, the velocity of motion of a plane DW of intermediate type was investigated in a specimen of $TmFeO_3$ in magnetic fields up to 3.4 kOe, at 293, 227, and 178 K. The specimen was cut perpendicular to the optic axis from a single crystal of $TmFeO_3$, grown by the method of crucibleless zone melting with optical heating. After this, it was polished mechanically and then chemically to thickness 75 μm, in orthophosphoric acid heated to 360°C. The velocity of motion was determined from the time required for the wall to traverse a prescribed distance, between two light spots.[2]

The variation of the velocity of motion of a DW in $TmFeO_3$ with the pulsed magnetic field, at the temperature indicated above, is shown in Fig. 1. At temperature 293 K, because of the small DW mobility, the limiting velocity is still not attained in pulsed magnetic fields up to 3.4 kOe. At temperature 178 K, the limiting velocity is attained at magnetic field 2.1 kOe. It remains unchanged up to the maximum field. At temperature 227 K, the limiting velocity is just reached. Thus the limiting velocity of DW motion in $TmFeO_3$ at temperatures 178 and 227 K is $20\cdot10^3$ m/s and coincides with the limiting velocity in $YFeO_3$. This velocity corresponds to the velocity of spin waves on the linear section of their dispersion law and is expressed as follows[2]:

$$V_{sw}=\gamma(2H_E D)^{1/2}, \qquad (1)$$

where H_E is the exchange field, $D=2A/I_0$, $\gamma=eg/2mc$, A is the exchange stiffness, and I_0 is the magnetization

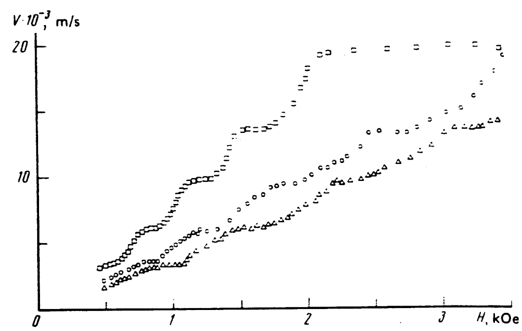

FIG. 1. Variation of the velocity of motion of a DW of the intermediate type, in a chemically polished specimen of $TmFeO_3$, with the amplitude of a pulsed magnetic field, at various temperatures: △, 293 K; ○, 227 K; □, 178 K.

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TABLE I. Velocities of DW motion at which anomalies are observed in the $V(H)$ relation (km/s).

$YFeO_3$, chemical polishing			$TmFeO_3$ chemical polishing	$Bi_{0.042}Y_{0.958}FeO_3$, mechanical polishing
Wall of intermediate type, from Ref. 1	Bloch wall	Néel wall	Wall of intermediate type	Wall of intermediate type
4.3	–	4.2	3.3	3.9
7.0	–	–	6.2	–
10.2	–	9.0	9.6	10.7
14.7	13.5	13.5	13.7	–
18	17.5	17.5	–	–

of a sublattice of the orthoferrite. The Curie temperatures for $YFeO_3$ and $TmFeO_3$ are very close together; therefore it follows from the equality of the limiting velocities for these orthoferrites that the constants D for them are also equal.

The linear variation of the velocity of DW motion with the amplitude of the pulsed magnetic field is disturbed several times. The first time is when it is equal to the velocity of transverse sound waves in thulium orthoferrite, $V_{\mathrm{I}} = (3.3 \pm 0.1) \cdot 10^3$ m/s; the second time is when it is equal to the velocity of longitudinal sound waves, $V_{\mathrm{II}} = (6.2 \pm 0.1) \cdot 10^3$ m/s. Besides this, two other intervals of constant velocity are observed: $V_{\mathrm{III}} = (9.6 \pm 0.2) \cdot 10^3$ m/s and $V_{\mathrm{IV}} = (13.7 \pm 0.2) \cdot 10^3$ m/s. It may be assumed that the last two values of V are caused by interaction of the moving DW with spin waves at the boundary of the Brillouin zone. It must be specially emphasized that the anomaly at $V = 13.7 \cdot 10^3$ m/s is observed only in chemically polished specimens. In mechanically polished plates, it has not been observed. The velocity values at which anomalies are observed in the $V(H)$ relation, for a number of orthoferrites that have so far been investigated, are shown in Table I. The difference between corresponding values of the velocity for different orthoferrites exceeds the experimental accuracy.

The energy spectrum of spin waves in $YFeO_3$ has been calculated.[7] The phase velocities of spin waves at the boundary of the Brillouin zone, for two different directions, are $13.1 \cdot 10^3$ m/s and $13.9 \cdot 10^3$ m/s. It is possible that the discrepancy between the theoretical and experimental values of these quantities is due to approximations made in the calculation of the spin-wave energy. It is not excluded that in order to explain the anomalies in the $V(H)$ relation, it is necessary to pay attention to surface spin waves, which so far have not been observed experimentally in orthoferrites.

The interval of pulsed magnetic fields in which constancy of the velocity is observed in $TmFeO_3$ is independent of the mobility, as long as it is not too large. A wide interval of constancy of the velocity, at $V = 10.7 \times 10^3$ m/s (Fig. 2), is observed also in a mechanically polished specimen of $Bi_{0.042}Y_{0.958}FeO_3$, cut perpendicular to the optic axis from a single crystal that was grown by the method of spontaneous crystallization from solution in the melt. The question of anomalies in the $V(H)$ relation for orthoferrites requires special theoretical consideration.

By use of the method of determination of DW mobility proposed by Rossol,[8] we investigated the dependence

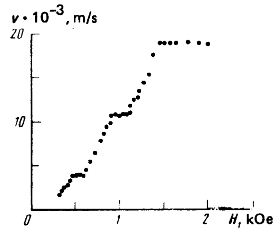

FIG. 2. Variation of the velocity of motion of a DW of intermediate type, in a mechanically polished specimen of $Bi_{0.042}Y_{0.958}FeO_3$, with the amplitude of a pulsed magnetic field.

of the DW displacement on the frequency of a sinusoidal magnetic field in the temperature interval 293–141 K. From the results of the measurements we determined the mobility μ, shown in Fig. 3. Also shown here are the values of μ determined from the slope of the $V(H)$ curves at 293, 227, and 178 K, and equal to 435, 610, and 890 cm/s · Oe, respectively. Good agreement is observed between the mobilities obtained by these two methods.

3. DYNAMICS OF BLOCH AND NÉEL DOMAIN WALLS IN YTTRIUM ORTHOFERRITE

The investigations made above pertain to a plane DW of the intermediate type, perpendicular to the surface of the plate. In this research, investigations were also made of the velocities of motion of Bloch and Néel DW in a chemically polished specimen of $YFeO_3$, but perpendicular to the axis of weak ferromagnetism, [001], from a single crystal grown by the method of crucibleless zone melting with optical heating. In orthoferrite plates cut perpendicular to the [001] axis there is a maze domain structure; the domain walls parallel to the [100] axis are of Bloch type, whereas those parallel to the [010] axis are of Néel type.

Measurement of the velocity of DW motion by the method described earlier[2] is considerably more complicated in such a plate than in plates cut perpendicular to the optic axis. The difficulty consists in the fact that in observation in the direction [001], the contrast of the domain pattern deteriorates substantially because of the presence in the orthoferrites of large double refraction.[9] In orthoferrite plates perpendicular to the optic axis, the Faraday effect is proportional to the thickness d, and in the plates of thickness 100 μm

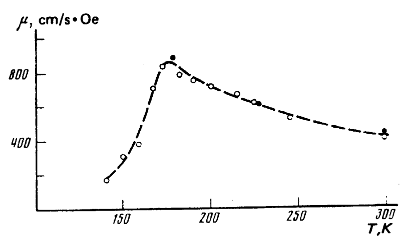

FIG. 3. Variation of the mobility of a DW of intermediate type, in a chemically polished specimen of $TmFeO_3$, with temperature. The dark points denote the mobility determined from the slope of the $V(H)$ curves; the light points, by the method of Rossol.

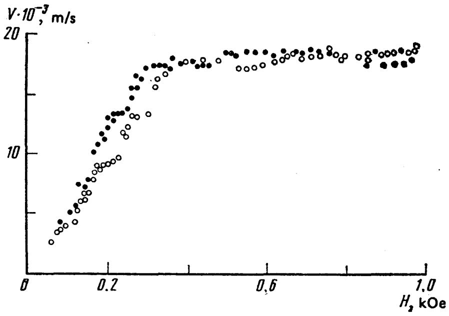

FIG. 4. Variation of the velocity of motion of Bloch and Néel walls, in a chemically polished specimen of $YFeO_3$, with the amplitude of a pulsed magnetic field. The light points denote the velocity of a Néel wall, the dark points that of a Bloch wall.

usually used it amounts to several tens of degrees.[10] In plates perpendicular to the [001] axis, the axis rotation of the resultant polarization ellipse on exit from the plate is described as follows:

$$\theta=\frac{\varepsilon'}{n\Delta n}\sin\frac{2\pi d\Delta n}{\lambda}, \qquad (2)$$

where ε' is the nondiagonal component of the dielectric-constant tensor, Δn is the double refraction, d is the thickness, λ is the wavelength of the light, and n is the refractive index. In orthoferrites, θ does not exceed a few degrees.[9] The best contrast of the domain pattern, according to (2), is achieved at plate thickness

$$d=(2k+1)\frac{\lambda}{4\Delta n}, \qquad (3)$$

where k is an integer.

In our method, two light spots are necessary, polarized mutually perpendicular planes. The directions of the polarization vectors of the light incident on the specimen were chosen to coincide with axes of the indicatrix of the crystal. This can be easily achieved by placing in front of the specimen, in the path of the laser beam, two quarter-wave plates. Thus in orthoferrite plates cut perpendicular to the [001] axis it is possible to achieve the maximum possible contrast of the domain pattern; but the accuracy of measurement of the velocity of motion of Bloch and Néel DW will be lower than in the case of measurement of the velocity of motion of DW of the intermediate type in plates cut perpendicular to the optic axis. The thus obtained variations of the velocity of motion of Bloch and Néel DW with the pulsed magnetic field are give in Fig. 4. On the $V(H)$ relations for Bloch Néel DW there are also small intervals of constancy of the velocity, when it is equal to $4.2\cdot10^3$, $9\cdot10^3$, and $13.5\cdot10^3$ m/s. The limiting velocities of motion of Bloch and Néel DW are the same within the limits of accuracy of the experiment, and are equal to $19\cdot10^3$ m/s. From the relations obtained, it follows that the mobility of Bloch walls ($\mu=6.5\cdot10^3$ cm/s·Oe) is larger than that of Néel walls ($\mu=5.6\cdot10^3$ cm/s·Oe), as was also remarked in Ref. 11.

Thus the limiting velocities of motion of DW of the intermediate type in yttrium and thulium orthoferrites are the same. They are also the same for Bloch and Néel walls in a $YFeO_3$ plate cut perpendicular to the [001] axis. Therefore the limiting velocities of motion of domain walls in orthoferrites, described by the expression (1), are isotropic. This result is in accord with the theoretical analysis of the dispersion law of spin waves in orthoferrites.[7] Still unclear is the question of the difference of limiting velocities for walls perpendicular and at an angle to the surface of a plate cut perpendicular to the optic axis and polished mechanically.[1] The anomalies in the $V(H)$ relations at the velocities of longitudinal and transverse sound should have anisotropy, since those velocities are significantly anisotropic. Investigation of this question requires a considerable increase of the accuracy of determination of $V(H)$ in plates perpendicular to the [001] axis.

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