Velocity of domain walls in weak ferromagnets

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A magneto-optic method was used to carry out an investigation of the velocity of motion of isolated plane domain walls in yttrium orthoferrite, cut perpendicular to the optic axis. The limiting velocity of the walls along the [100] and [010] crystal directions was determined to be $v_a = 2 \cdot 10^4$ m/sec and $v_b = 10^4$ m/sec. The velocity of the tip of a wedge-shaped domain was measured in $TmFeO_3$. It is shown that the limiting velocity of domain walls is dependent upon excitation of an optical spin-wave mode, and the measured values of v_a and v_b are close to the calculated value of the limiting velocity. It is noted that there is a possibility of generation of sound waves propagating as a cone from the vertex of the front of a bent wall. It is suggested that measurement of the anisotropy of the velocity of domain walls can be used to determine the anisotropy of the velocity of spin waves in weak ferromagnets.

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In recent years there has been a considerable increase of interest in the investigation of the dynamics of domain walls in ferromagnets. This problem was first considered theoretically by Landau and Lifshitz.[1] Later Walker[2] derived an expression for the critical velocity of domain walls in ferromagnets. In iron garnet films, the limiting velocity of domain walls amounts to several tens of meters per second, which is considerably less than the Walker limit. Somewhat larger velocities have been obtained in films of iron garnets with orthorhombic anisotropy.[3] Considerably larger velocities, of the order of 10^4 m/sec, have been obtained in orthoferrites.

Usually measurements of the velocity of motion of a wall in orthoferrites are made by the method of collapse of a cylindrical magnetic domain,[4] proposed by Bobeck *et al.*,[5] or by the Sixtus-Tonks method.[6] Both methods make it possible to carry out measurements of the velocity with a sufficient degree of accuracy up to values not exceeding 10^4 m/sec.

At high velocities of motion of the domain wall, as was mentioned by the authors of Refs. 4 and 6, substantial uncertainties arise in the measurement of the parameters that determine the value of the velocity. A critical velocity of domain walls in orthoferrites, equal to $2 \cdot 10^4$ m/sec and considerably exceeding the Walker limit, was observed by us earlier.[7] We also proposed an interpretation of the critical velocity in orthoferrites based on the dispersion law of spin waves.[8] The present paper considers in detail the results of investigations of the velocity of strictly plane domain walls in orthoferrites; the results were obtained by a magneto-optic method, by use of the dynamic Faraday effect.

1. EXPERIMENTAL SETUP

Measurements of the velocity of motion of domain walls were made on platelets of yttrium and thulium orthoferrites, cut perpendicular to the optic axis. The spectrum thicknesses, 90 and 80 μm respectively, for $YFeO_3$ and $TmFeO_3$, insured large contrast of oppositely magnetized domains when they were observed in transmitted light of an LG-52 He–Ne laser operating at wavelength 0.63 μm. The intensities of light that had passed through oppositely magnetized domains differed by a factor of several hundred. An isolated domain wall was obtained by means of a magnetic field perpendicular to the specimen surface, with a gradient directed in the specimen surface either along the [100] axis or perpendicular to it. In the first case (Fig. 1a), a strictly plane and rectangular domain wall was produced[7]; in the second, an isolated domain wall inclined to the specimen surface (Fig. 1b).

The gradient magnetic field was produced by a system of two ring electromagnets. The value of the gradient could be changed by changing the current in the electromagnet windings. The wall motion was controlled by a pulsed magnetic field H_{con}, perpendicular to the specimen surface, produced by a coil of diameter 1.5 to 2 mm, consisting of 15 to 20 turns of PÉV-0.06 wire, and placed immediately upon the specimen under observation, so that the section of the wall whose velocity was to be measured was located at a distance from the center of the coil approximately equal to 1/3 the coil radius. At small amplitudes of the control field, the coil was fed

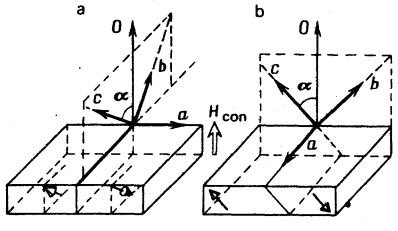

FIG. 1. Scheme for obtaining domain walls in an orthoferrite platelet cut perpendicular to the optic axis; *a*, *b*, and *c* are, respectively, the crystal axes [100], [010], and [001]. a, isolated plane domain wall perpendicular to the specimen surface; the field gradient is directed along the [100] axis. b, isolated domain wall inclined to the specimen surface; the field gradient is directed in the specimen plane perpendicular to the [100] axis.

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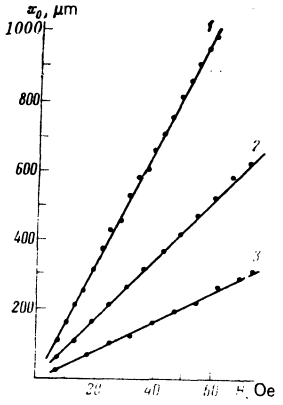

FIG. 2. Maximum departure of a strictly plane domain wall, perpendicular to the specimen surface, from its equilibrium value, as a function of the amplitude of the pulsed magnetic field, for various values of the field gradient: 1, 530 Oe/cm; 2, 1050 Oe/cm; 3, 2400 Oe/cm.

directly from a G5-15 generator. A magnetic field up to 1200 Oe, with duration of the forward front no worse than 15 nsec, was produced by a pulse generator constructed on the basis of a TGI 1-10/1 thyratron, which insured stability of the instant of triggering of the order of 0.1 nsec, with maximum pulsed current 10 A. The thyratron generator was triggered from the G5-15 generator. The pulse duration of the control field was 1.5 μsec; the repetition frequency was 40 GHz.

Measurement of the gradient and control fields was accomplished by measurement of the Faraday effect in the paramagnetic garnet $Dy_3Al_5O_{12}$, with Verdet constant 0.4 min/cm·Oe at wavelength 0.63 μm. A platelet of the garnet, of thickness 200 μm, was substituted for the orthoferrite platelet under investigation. A single-mode beam of light from the LG-52 laser was focused on the garnet platelet in a spot of diameter 15 to 20 μm. The Faraday rotation, and with it the values of the field gradient, were measured along a straight line between the toroidal electromagnets, passing through the centers of their gaps. Figure 2 shows values of the maximum departure of a plant domain wall from the equilibrium position, as functions of the amplitude of the pulsed magnetic control field, as obtained at various values of grad H. This departure X_0 is satisfactorily described by the relation $X_0=H_{con}/(\alpha+\text{grad}\,H)$; hence one can determine the value of α in the phenomenological equation of motion of a domain wall[9] and can estimate the value of the resonance frequency of a domain wall.

The velocity of motion of a domain wall was measured as follows. A single-mode beam from the LG-52 laser was split by a platelet of hexagonal $CaCO_3$, and both beams, polarized in mutually perpendicular planes, were focused on the specimen under investigation in spots of diameter 15 μm, separated from each other by a distance of 150 to 500 μm. The distance between the spots could be measured by measuring the thickness of the $CaCO_3$ platelet. The domain wall, moving under the influence of the magnetic field, successively crossed both light spots, producing two light pulses, which were recorded with a photomultiplier FÉU-30. The signal from the FÉU-30 was fed to a stroboscopic oscillograph S7-8, and from it to an xy recorder PDS-021M. The horizontal sweep of the oscillograph was produced by a linearly increasing voltage, obtained from a battery by means of a ten-revolution potentiometer driven in the rotation of an RD-09 motor through a reducing gear. The maximum time of horizontal scanning was 3 min. The output of the oscillograph was connected to the input of the recorder through an integrating circuit with time constant 2 sec. The smallest pulse front registered by the system was 5 nsec. The shift in time between pulses determined the time of passage of the wall between the light spots. The apparatus made possible the measurement of the value of the velocity of a moving wall up to $2\cdot10^5$ m/sec.

2. RESULTS OF THE MEASUREMENTS AND DISCUSSION

This method was used to measure the velocities of plane domain walls in platelets of yttrium and thulium orthoferrites perpendicular to the optic axis. A plane wall of Bloch type inclined to the specimen surface was produced from a system of tapered domains (see Fig. 1b) in a field with a gradient exceeding 2500 Oe/cm. The variation of the velocity of such a wall with the amplitude of the pulsed magnetic field is shown in Fig. 3. In fields up to 300 Oe the departure of the wall from the equilibrium position is small; therefore in order to a avoid inaccuracies resulting from irregular motion of the wall at the end of its motion, the measurements were made in fields greater than 300 Oe.

In the field range 300 to 500 Oe, instability of the velocity was observed. After the instability range, the velocity gradually increased, reaching a limiting value $v_\perp=1.5\cdot10^4$ m/sec. For a plane wall with a rectangular edge, moving along the [100] axis (Fig. 4), constancy of the velocity was observed in the field range 105 to 135 Oe, at a value $4\cdot10^3$ m/sec, caused by interaction of the wall with transverse sound excited by it. Then the wall velocity increased again, reaching the value $1.6\cdot10^4$ m/sec at $H_{con}=400$ Oe. In fields 400 to 900 Oe, saturation of the velocity was observed; a slow rise of it to the limiting value $v_a=2\cdot10^4$ m/sec.

From our measured velocity $v_\perp$ of the inclined wall, it is possible to determine the velocity v_b of motion of it along the [010] axis, since $v_b=v_\perp\cos\alpha$, where α is the angle between the optic axis and the [001] axis of the crystal (see Fig. 1b). Setting $\alpha=52°$,[10] we get $v_b=10^4$ m/sec. Thus limitation of the velocity is observed for both types of domain walls, and the limiting velocity is found to be substantially different for different directions.

Limitation of the velocity in the high-field range is caused by excitation of an optical spin-wave mode. The value of the limiting velocity of the wall and, with it, of

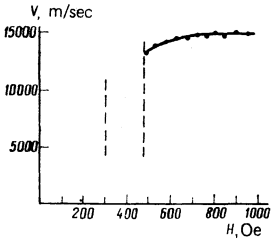

FIG. 3. Velocity of motion of a plane isolated domain wall, inclined to the surface of a $YFeO_3$ specimen of thickness 90 μm, as a function of the control field.

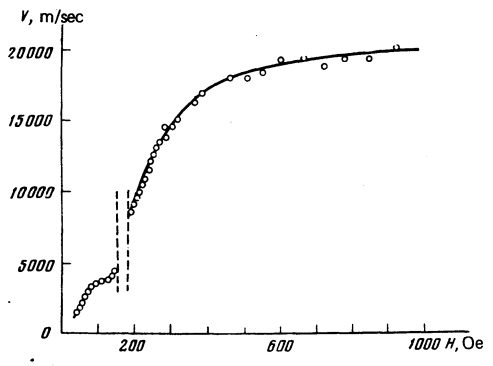

FIG. 4. Velocity of motion of a plane isolated domain wall, perpendicular to the surface of a $YFeO_3$ specimen of thickness 90 μm, as a function of the control field.

the phase velocity of the spin wave excited by it can be determined from the dispersion law of spin waves in an antiferromagnet,

$$\omega^2=\gamma^2[2H_E(H_A+k^2D)], \quad (1)$$

from which we have for $k\to\infty$

$$v_{\text{phase}}=\omega/k=\gamma(2H_ED)^{1/2}=\gamma(2H_EH_A)^{1/2}(A/K)^{1/2}, \quad (2)$$

where H_E and H_A are the effective exchange and anisotropy fields, k is the quasimomentum of the spin wave, $D=2A/I_0$, A and K are the exchange and anisotropy constants, and I_0 is the magnetic moment of a sublattice.

In the case of an orthoferrite, the width of a domain wall is ~ 100 Å, which corresponds to spin waves with $k\sim10^6$ cm^{-1}, and the second term in (1) is considerably larger than the first. The quantities that occur in (2) can be determined from data on antiferromagnetic resonance[11] and spin flop.[12] For $YFeO_3$ we have $(H_E\cdot H_A)^{1/2}\approx 8\cdot10^4$ Oe, $K=4.8\cdot10^5$ erg/cm^3, and $A=4\cdot10^{-7}$ erg/cm,[11-13] whence the critical value of the velocity of a wall is $1.7\cdot10^4$ m/sec. The values that we found for the critical velocities v_a and v_b are close to the calculated value of critical velocity.

Formula (2) was first derived by us,[8] and independently by Bar'yakhtar *et al.*[14] from the consideration that the thickness of the wall tends to zero on attainment of its critical velocity. The difference between the values v_a and $v_\perp$ of critical velocity is possibly due to anisotropy of the velocity of spin waves in orthoferrites. Different interactions of the two types of walls with surface spin waves and with specimen defects may also contribute to the anisotropy of the critical velocity.

The velocities v_a and $v_\perp$ that we found in a platelet of yttrium orthoferrite perpendicular to the optic axis are not, in our opinion, an absolute limit to the velocity: with increase of the control field, we may expect a further increase of the velocity above critical values found; the function $v(H)$ should have a smoothly increasing character with a subsequent sharp increase of velocity. With increase of the control field, waves with smaller k and larger phase velocity should be excited, and this will lead also to widening of the wall. The width of the range of interaction of a moving wall with magnons should in our opinion be finite, as is the case for interaction of it with phonons.

The considerations presented above regarding estimation of the value of v_b are correct in the absence of deformation of the moving inclined wall. It follows from Fig. 3 that the instability range of the inclined wall is considerably larger than for the wall with a rectangular edge. This is perhaps due to distortion of the plane front of the inclined Bloch wall: curving of it along the [010] axis, which may lead to excitation not only of plane acoustic waves but of boundary waves, propagating as a cone from the vertex of the front of the bent wall; that is, the excitation of sound by the moving wall ceases to be one-dimensional.

The field dependence of a plane wall with a rectangular edge has the same character in $TmFeO_3$ as in $YFeO_3$.[7] We did not detect in $TmFeO_3$ the limitation of velocity that we found in $YFeO_3$. Measurements of the velocity of the vertex of the wedge-shaped domain in a $TmFeO_3$ platelet also did not reveal any noticeable saturation of the velocity. The maximum velocity of the vertex of the wedge-shaped domain, which we succeeded in measuring at field 1200 Oe, was $6.5\cdot10^3$ m/sec. Thus the character of the $v(H)$ relation in thulium orthoferrite allows us to expect such a limitation of velocity in this orthoferrite at considerably larger control fields.

Investigation of the anisotropy of the limiting velocity can be used to determine the anisotropy of spin waves in weak ferromagnets. The value of $(H_EH_A)^{1/2}$ in (2) can be determined from data on antiferromagnetic resonance[11] and light scattering.[15] In orthoferrites, the optical mode of antiferromagnetic resonance has been observed only in $TmFeO_3$ in the reorientation range[16] and in domain walls.[17] In the latter case, a resonance wavelength 0.77 mm was obtained. Resonance in a magnetized $TmFeO_3$ platelet has not been detected. This indicates anisotropy of the antiferromagnetic resonance frequency and, by (1), of the limiting velocity. More accurate information regarding the anisotropy of the velocity of domain walls in orthoferrites can be obtained by direct measurements of the value of v_b made, by the method indicated above, on an orthoferrite platelet cut perpendicular to the axis of weak ferromagnetism. But it is then necessary to increase greatly the sensitivity of the apparatus, because the Faraday effect diminishes by almost two orders of magnitude in this case. It should be noted that the presence of anisotropy of the velocity of motion of a domain wall makes our method[7] of measurement of the velocity of a plane domain wall considerably more accurate than the method of collapse of a cylindrical magnetic domain.[5]

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Crystal structure, and magnetic and magnetoelastic properties of UGa_2

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An investigation was made of the temperature dependences of the crystal lattice parameters, saturation magnetization, paramagnetic susceptibility, coercive force, and magnetostriction of single crystals of the intermetallic compound UGa_2. In the magnetically ordered state (T_c = 125°K), the magnetic moment of uranium is 2.71 μ_B and it is due to the partly delocalized 5*f* electrons. Below T_c, the compound UGa_2 experiences a strong orthorhombic distortion of the hexagonal lattice which is due to large magnetostrictive strains ($\lambda \sim 10^{-3}$). There is a considerable magnetocrystalline anisotropy in the ferromagnetic and paramagnetic states. The uniaxial magnetic anisotropy constant is $K_1 = -2\times10^7$ erg/g and the constant representing anisotropy in the basal plane is $K_3 = -0.6\times10^6$ erg/g.

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1. INTRODUCTION

The magnetic properties and crystal structures of uranium compounds are of considerable interest in the physics of magnetism and magnetic materials. Extensive experimental data are now available on the principal magnetic properties (magnetic ordering temperature, saturation magnetization, magnetic structure, etc.) of the compounds of uranium with various elements. However, many important and interesting features of the magnetism of these compounds—such as the nature of the magnetic order, degree of localization of the magnetic moment of the uranium ions, influence of the crystal field on this moment, etc.—are known only partially. This is largely due to the fact that the published investigations of the magnetic properties of uranium compounds have not been sufficiently comprehensive and have been carried out primarily on polycrystalline samples, so that there is little information on such important characteristics as the magnetic anisotropy and magnetostriction.

The compound UGa_2 is attracting considerable attention. It is the only compound of uranium with the hexagonal AlB_2-type structure and ferromagnetic ordering at low temperatures. Measurements of the magnetization, magnetostriction, paramagnetic susceptibility, electrical resistivity, and Young modulus have been carried out[1-10] on polycrystalline samples of UGa_2. However, the magnetic properties obtained for polycrystalline samples can only be regarded as estimates because of the exceptionally strong magnetic anisotropy of this compound (see below). In view of this situation, it seemed desirable to carry out a systematic investi-

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