Experimental test of the one-dimensional theory of motion of domain walls in uniaxial ferromagnets

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The validity of the one-dimensional theory of motion of domain walls in garnet ferrites, in which the effective gyromagnetic ratio is the variable parameter, has been confirmed experimentally for the first time.

A one-dimensional theory of motion of domain walls in uniaxial ferromagnets gives us the following relation for the linear mobility of a domain wall[1,2]:

$$\mu = \alpha^{-1} \gamma (A/K)^{1/2} \equiv \Lambda^{-1} M (A/K)^{1/2}, \tag{1}$$

where

$$\alpha = \lambda \gamma^{-1} M^{-1} \equiv \Lambda \gamma M^{-1} \tag{2}$$

is a dimensional parameter of Hilbert damping, λ is the Landau-Lifshitz damping parameter which is the relaxation frequency, γ is the gyromagnetic ratio, $4\pi M$ is the saturation magnetization, Λ is the reduced Landau-Lifshitz damping parameter which is independent of other parameters of the ferromagnet, A is the exchange constant, and K is the uniaxial anisotropy constant. As the driving field reaches the Walker threshold[2,3]

$$H_W = 2\pi\alpha M \equiv 2\pi\Lambda\gamma \tag{3}$$

the velocity of the domain wall, v, reaches the Walker limit

$$v_W = 2\pi\gamma M \; (A/K)^{1/2}. \tag{4}$$

In fields $H \gg H_W$ the functional dependence $v(H)$ again becomes linear. The differential mobility in this case is[2,4]

$$\mu_0 = \mu \; (1 + \alpha^{-2})^{-1} \equiv \mu \; (1 + M^2/\Lambda^2\gamma^2)^{-1}. \tag{5}$$

Malozemov and Slonczewski[2] have pointed out that the experimental results are in satisfactory agreement with the one-dimensional theory only in the presence of a strong magnetic field or an anisotropy in the plane of the film. They also suggested that this theory may be valid for materials with a large value of γ.

Our study is apparently the first experimental test of the validity of the one-dimensional theory of motion of a domain wall,[1–4] which was developed for uniaxial ferromagnets in the absence of a magnetic field or an anisotropy in the plane of the film. We studied garnet ferrite films of the composition $(Bi, Tm, Gd)_3 (Fe, Ga)_5O_{12}$ with a (111) orientation, in which γ was varied. The theory developed for ferromagnets is also applicable to ferrimagnets if the effective gyromagnetic ratio is used.[6] As the experiment has shown, this ratio for the material under study can be determined from the expression

$$\gamma = \gamma_{Fe} [M_{Tm} - (M_{Fe} - M_{Gd})] / (M_{Fe} - M_{Gd}), \tag{6}$$

where $\gamma_{Fe} = \gamma_{Gd}$ is the gyromagnetic ratio for Fe^{3+} and Gd^{3+} ions, M_{TM} and M_{Gd} are the magnetized parts of the dodecahedral garnet sublattice, for which the Tm^{3+} and Gd^{3+} ions, respectively, are responsible, and M_{Fe} is the total magnetization of the tetrahedral and octahedral sublattices. In the case of gadolinium-containing garnet ferrites $\gamma \to \infty$ in the limit $(M_{Fe} - M_{Gd}) \to 0$, rather than in the limit $M_{Fe} \to 0$, as in the case of other garnet ferrites with a high effective gyromagnetic ratio.[7,8] In the test samples the value of γ was changed by changing the content of Gd^{3+} and Ga^{3+} of the films. We present here the data for samples 1–4, respectively, with the following parameters: $4\pi M = 119$, 130, 145, and 153 G; $A \times 10^7 = 1.97$, 1.97, 1.92, and 1.91 erg/cm; and $H_K = 840$, 890, 710, and 490 Oe.

A single high-speed photography method was used in the experiment to measure the velocity of the domain walls, v, in the domains with a reverse magnetization which were formed upon a pulsed reversal of magnetization of the films that have reached the saturated state.[8,9] Domain walls of this sort have the same chirality[9]; i.e., these walls have no Bloch lines, the presence of which renders the one-dimensional theory invalid.

Direct observation of a domain wall in motion has shown that no magnetic perturbations of any sort are generated near a moving domain wall[10,11] over the entire range of fields studied and that the image broadening of a high-speed domain wall is determined completely by the finite recording time (~ 8 ns).

The driving field is defined as

$$H = H_p - H_{sm}, \tag{7}$$

where H_{sm} is the static field which is applied along the direction of the easy-magnetization axis and which magnetizes the sample to its saturation point, and H_p is a pulsed

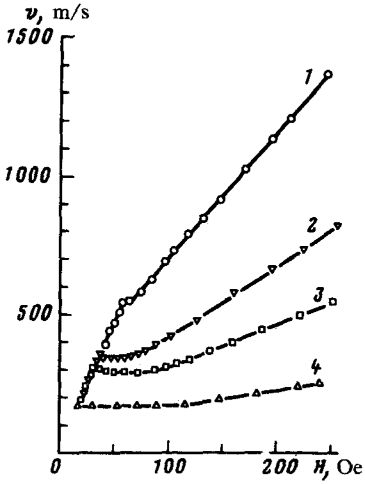

FIG. 1. Typical plots of the velocity of the domain wall versus the driving field (the numbering of the curves is the same as that of the samples).

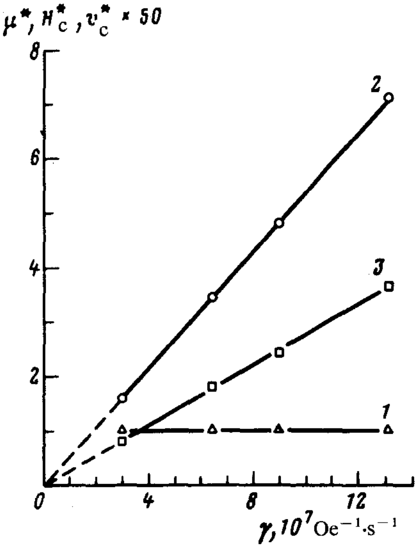

FIG. 2. The relative linear mobility of the domain wall (1), the threshold field (2), and the critical velocity (3) versus the effective gyromagnetic ratio.

magnetization-reversal field which is applied in the opposite direction.

Figure 1 shows typical experimental curves of $v(H)$ measured in fields $H \gtrsim 20$ Oe. For all but sample No. 4, we can single out, as predicted by the theory, two linear parts on these curves, where the slope of the first part is μ (the linear mobility) and that of the second is μ_0. Furthermore the linear mobility of all the samples in fields $H = 1$–20 Oe was measured by the Vella-Coleiro[12] method. The linear mobilities of samples 1–4 are $\mu = 910$, 970, 1020, and 1000 cm/(s·Oe), respectively. The results obtained by using the two methods agree within the error of these measurements. Consequently, the first part on curves 1–3 (Fig. 1) is in fact the initial part, and the value of μ found for it is the linear mobility.

The $v(H)$ curve becomes linear when H reaches H_c. Here we have $v = v_c$. Using the experimental data on μ and μ_0, we determined α from (5) and we then determined γ from (1). We used these values of α and γ to calculate H_W and v_W with the help of relations (3) and (4). A comparison of H_c and H_W and also of v_c and v_W shows that these quantities agree within better than 8%, consistent with the error margin of the measurement of v and H.

The second linear part of the $v(H)$ curve (Fig. 1) is not connected in any way with the magnetization rotation near the moving domain wall,[13] since the threshold field associated with the transition to this part of the curve decreases with increasing value of γ (Fig. 2), while the anisotropy field $H_K = 2K/M$, in contrast, increases.

Figure 2 shows the normalized linear mobility $\mu^* = \mu\Lambda M^{-1}(A/K)^{-1/2}$, the normalized threshold field $H_c^* = H_c/(2\pi\Lambda\gamma_{\rm Fe})$ and the normalized critical velocity $v_c^* = v_c/[2\pi\gamma_{\rm Fe}M(A/K)^{1/2}]$ plotted as a function of γ. We see that μ is virtually independent of γ and that H_c and v_c are related to γ by a linear dependence, consistent with the one-dimensional theory. Note that as γ is increased, the nonlinear part of the $v(H)$

curve (Fig. 1) narrows down, contracting to a point in the limit $\gamma \rightarrow \infty$. At the same time, we have $\mu_0 \rightarrow \mu$.

In summary, we have shown that the one-dimensional theory of motion of domain walls in uniaxial ferromagnets is valid for garnet-ferrite films with a high gyromagnetic ratio.

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