Nonlinear dynamics of a unipolar domain wall

V. S. Gornakov, V. I. Nikitenko, and I. V. Prudnikov

Institute of Solid State Physics, Academy of Sciences of the USSR, 142432, Chernogolovka, Moscow Oblast

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Forced vibrations of 180° Bloch wall in a yttrium iron garnet single crystal have been studied experimentally. A uniform magnetic field oscillating sinusoidally in time excites not only vibrations of the domain wall, at the frequency of the field, but also 2D magnons localized at this wall, over a broad frequency range. In strong fields, the motion of the magnetization in a domain wall becomes random, and nonlinear waves of the soliton type form in the wall.

An emerging trend in the analysis of the dynamic properties of domain walls in magnetically ordered crystals is to use microscopic methods for describing the energy dissipation of moving Bloch walls. These methods involve studying the nonlinear interaction of a wall with various branches of elementary excitations: bulk and surface magnons, phonons, etc.[1,2] So far, however, no one has succeeded in carrying out a direct experimental study of effects of this sort involving 2D magnons and nonlinear waves localized in a domain wall. In the present letter we are reporting the first results of a study of these entities in a single crystal of an yttrium iron garnet containing only a single 180° domain wall. We used induction and magnetooptic methods.

A high sensitivity was achieved in the induction method over the entire frequency range studied through the use of figure-eight wrap-around miniature coils (identical coils for detection and cancellation). They made it possible to automatically cancel the contribution of magnetic noise and the external field to the signal. Since only one domain wall is present, there is no mutual effect of neighboring walls, and there is no contribution to the induction signal from components resulting from a displacement of several domain walls. The sample was cut in the (110) plane and mechanically polished. It was a rectangular plate with dimensions of $10\times0.5\times0.04$ mm. The magnetization M in the domains separated by the Bloch wall ran along the [111] direction and lay in the plane of the sample. The wall ran parallel to the long edge of the sample. The sample was immersed in two uniform magnetic fields: an alternating field $h(t) = h_0 \sin(2\pi\nu_B t)$, directed along M in the domains, and a constant field H, directed normal to the plane of the sample and parallel to M at the center of the wall. The latter field polarized the wall. An SK4-59 spectrum analyzer detected the amplitude of the induction signal, E_0, which is proportional to the amplitude (v_0) of the oscillations in the velocity of the oscillating domain wall. The amplitude v_0 was normalized on the basis of visual measurements of the amplitude of the vibrations of the domain wall, $q_0 (v_0 = 2\pi\nu_B q_0)$. For these measurements we used a polarizing microscope.

Measurements of the $v_0(h_0)$ dependence revealed it to be complex and nonlinear, with several structural features (Fig. 1). Three regions can be distinguished reliably.

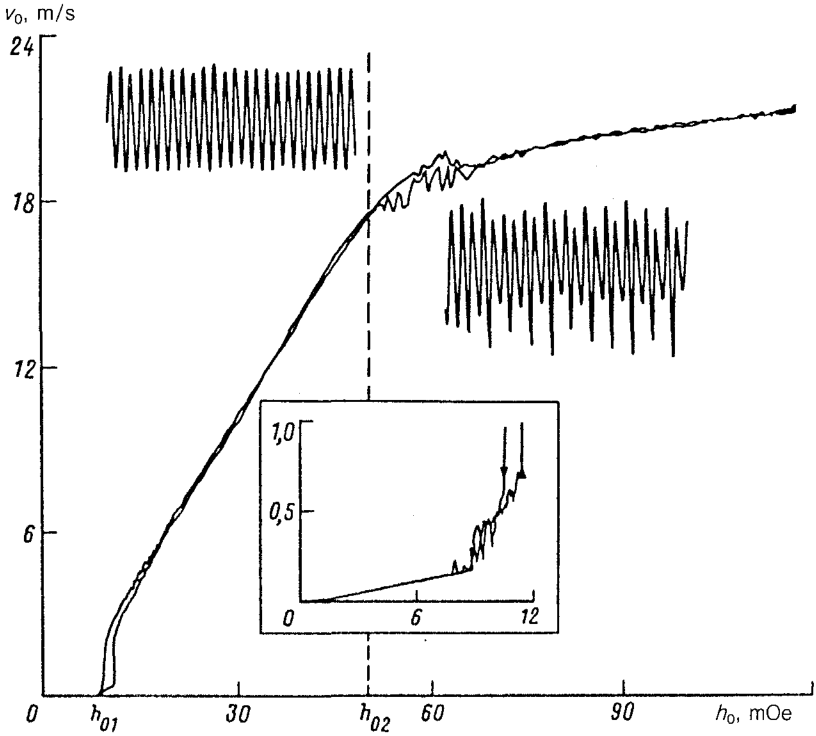

FIG. 1. Vibration amplitude of the domain wall versus the amplitude of the external field ($\nu_B = 0.94$ MHz, $H = 28$ Oe). The two oscillatory insets show the time evolution of the displacement of the domain wall. The one at the upper left corresponds to $h_0 = 34$ mOe, and the lower one at the right corresponds to $h_0 = 152$ mOe. The boxed inset shows the initial part of the curve in the main part of the figure in more detail.

In the first, where h_0 is below a certain critical h_{01}, the induction signal increases slowly and linearly with increasing field. This part of the curve is shown in more detail in the boxed inset. Figure 2 shows vibration spectra of the domain wall for various values of the alternating-field amplitude h_0. We see that there is only a single peak in the signal from the moving domain wall at $h_0 < h_{01}$. This result is evidence that the domain wall is executing exclusively forced harmonic vibrations at the frequency of the external field, ν_B.

The velocity jumps sharply at $h_0 \simeq h_{01}$. If the field is subsequently reduced, there is a clearly defined hysteresis on the plot of $v_0(h_0)$. At $h_0 > h_{01}$, after this sharp jump in the amplitude of the wall vibrations, the $v_0(h_0)$ curve has a second linear region, much larger than that at $h_0 < h_{01}$. The larger slope corresponds to a higher mobility of the wall. Analysis of a Fourier decomposition of the induction signal in these fields reveals, in addition to the main peak, some new peaks at frequencies which are multiples of the frequency of the external field. There are also some small regions with a continuous spectrum. With a further increase in h_0, these latter regions broaden and merge (the hatched regions in Fig. 2). The peaks in this distribution of the vibration ampli-

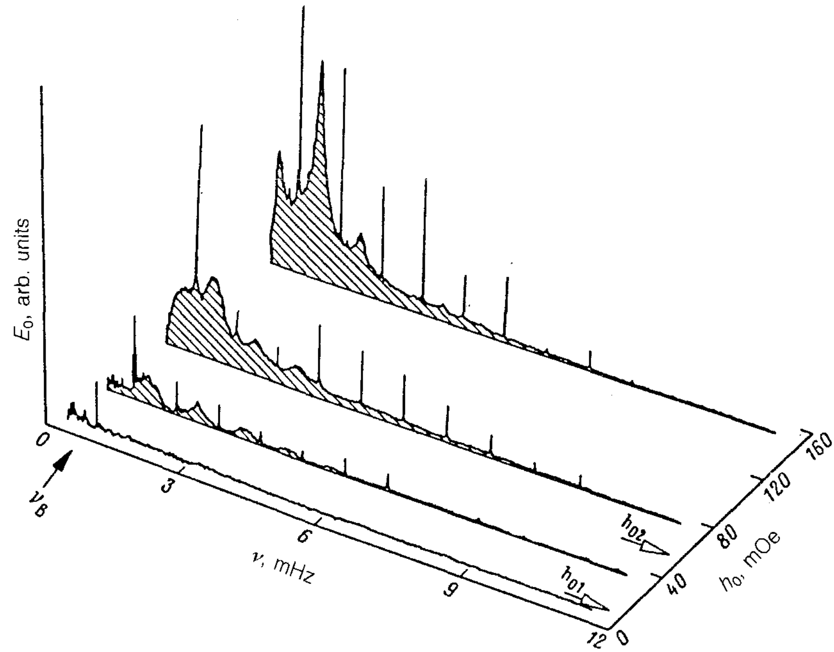

FIG. 2. Evolution of the Fourier decomposition of the vibrations of the domain wall versus the amplitude of the alternating field ($\nu_B = 0.94$ MHz, $H = 28$ Oe). Here E_0 is the amplitude of the induction signal.

tude of the domain wall are not commensurate with the frequency of the exciting field or its harmonics up to the next critical field h_{02}.

Above this field, the $v_0(h_0)$ curve initially becomes nonmonotonic. It then begins to rise monotonically again, but not as steeply as in the preceding region. A recording of the time evolution of the displacement of the domain wall, $q(t)$, in this field (the inset at the right in Fig. 1) shows that the motion is obviously random. Corresponding to a random motion of the domain wall is a qualitatively different Fourier decomposition $E_0(\nu)$. Some low-frequency components (below ν_B) appear in the continuous spectrum; they grow as the field is raised. Vibrations at "half-frequencies" with respect to the harmonics of the field, i.e., at $\nu_n = (n + 1/2)\nu_B$, where $n = 0,1,2,...$, is the index of the harmonic, become progressively more noticeable in the spectrum and eventually predominant (Fig. 2).

Various mechanisms are responsible for the nonlinear behavior of the domain wall. It can be concluded from the weak dependence of v_0 on h_0 at $h_0 < h_{01}$ and from the unsteady, hysteretic transition to vibrations of the domain wall at large distances (Fig. 1) that in weak fields the wall vibrates in the potential relief of randomly distributed bulk and surface defects of the crystal structure. At h_{01}, the wall detaches from the pinning centers, and its motion is determined primarily by the magnetostatic potential well, although this well is modulated by the field of the defects. This effect

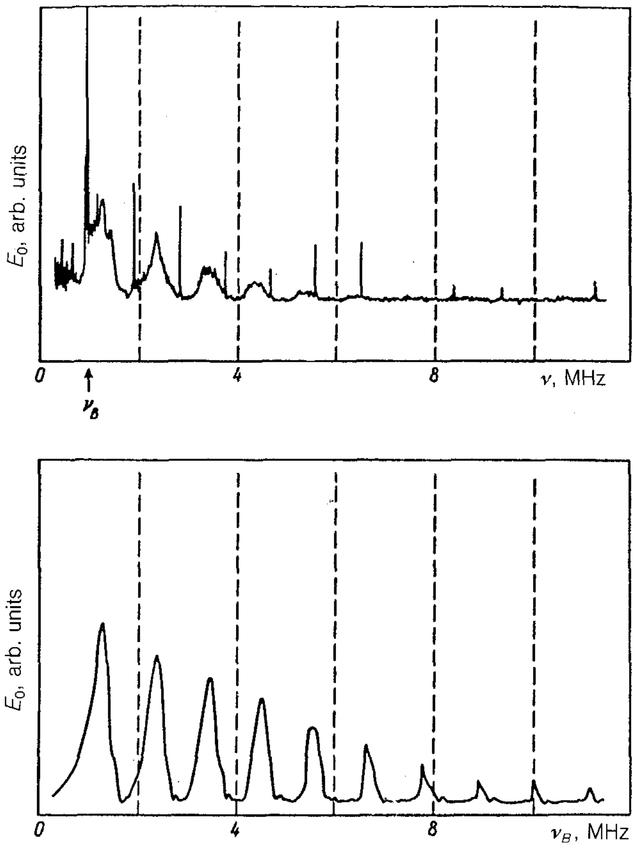

FIG. 3. Upper curve—Fourier decomposition of the signal from forced vibrations of the domain wall ($h_0 = 34$ mOe, $\nu_B = 0.94$ MHz); lower curve—amplitude-frequency characteristic of the wall ($h_0 = 23$ mOe). Here $H = 28$ Oe.

apparently results in the excitation of even harmonics in the vibration spectrum of the wall.

At $h_0 > h_{01}$, the vibrations of the Bloch wall are accompanied by the excitation of 2D magnons in it. Evidence for this conclusion comes from a comparison of the Fourier decomposition of the signal from the vibrating domain wall with its amplitude–frequency characteristic (Fig. 3). This comparison reveals that the continuous spectrum of the Fourier decomposition (the upper curve in Fig. 3) essentially reproduces the amplitude of the wall vibrations as a function of the frequency (the lower curve in Fig. 3). As was shown in Ref. 3, an amplitude–frequency characteristic of this type stems from bending vibrations of the wall, and the peaks on this characteristic correspond to standing waves. A change made in some external parameter (e.g., the field H) which causes a change in the characteristic frequencies of the amplitude–frequency characteristic leads to a corresponding change in the continuous spectrum in the Fourier decomposition. This result is direct proof that flexural waves with a wave vector k perpendicular to M in the domains are excited in the wall in the course of its forced vibrations.

At $h_0 > h_{02}$, the nonlinearity of the wall motion is manifested by the appearance of random vibrations, with an aperiodic $q(t)$ dependence and with a change in the characteristics of the continuous spectrum in the Fourier decomposition of the signal. A one-time photometric study of a domain wall in random motion revealed bursts of a magnetooptic signal, weak in comparison with the photomultiplier noise. These bursts correspond to the onset of nonlinear waves of a soliton type and their motion along the wall.[4] After the field is abruptly turned off, these waves transform into nucleating near-surface subdomains with dimensions from 5 to 10 μm. Their density increases with the field amplitude. At $h_0 < h_{02}$, these nucleating subdomains cannot be detected.

In summary, this study has produced the direct experimental evidence for the existence of various regimes in the motion of a domain wall—regimes which can be controlled through the formation of elementary or nonlinear magnetization excitations in the wall. Upon a change in regime as the amplitude of the external field is raised, the mobility of the wall changes sharply (by more than an order of magnitude).

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