Giant unidirectional anisotropy of domain-wall velocity in thin magnetic films

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Dynamic structural transformations of domain walls have been discovered in discrete time intervals in a narrow range of pulsed magnetic fields. In thin magnetic films with a planar anisotropy, these conversions lead to a pronounced unidirectional anisotropy of the velocity of the domain walls ($V_{\max}/V_{\min} > 4$).

The limiting velocity of domain walls in single-crystal films of iron garnets is known[1,2] to increase substantially if the sample has an orthorhombic anisotropy component, which is seen most obviously in films grown on substrates in the (110) orientation. This effect, which is invariant under a change in the direction of the motion, has been observed repeatedly by indirect methods in experiments on the steady-state motion of domain walls.[3–5] Switching to a study of transient processes by direct experimental methods has revealed several new physical effects which do not conform to the present theoretical understanding.

In the present experiments, we study the dynamics of the domain walls by high-speed image-converter photography with temporal and spatial resolutions ~ 8 ns and ~ 0.3 μm, respectively.[6] The samples are epitaxial films of iron garnets in the (110) orientation. We report results for a sample with the composition $(YGdTbBi)_3(FeAl)_5O_{12}$ with the following parameter values: a thickness $h \approx 10.9$ μm, a saturation magnetization $4\pi M_S \approx 175$ G, a bubble collapse field $H_0 \approx 130$ Oe, a uniaxial anisotropy constant $K_u \approx 4210$ erg/cm^3, an orthorhombic anisotropy constant $K_p \approx 15\,560$ erg/cm^3, and a cubic anisotropy constant $K_1 \approx 4580$ erg/cm^3.

We study the radial expansion of the magnetic bubbles in an essentially uniform pulsed magnetic field H_{pls}, produced by single-layer planar coils. The rise time of the H_{pls} field pulse is no greater than 2 ns; the field strength H_{pls} is varied from 0 to 150 Oe. In its initial state, the sample is in a static bias field $H_b < H_0$, and isolated bubbles exist in it (frame a in Fig. 1A). A field H_{pls} antiparallel to H_b is then applied, and the dynamics of the domain walls of the bubbles is studied at various times τ reckoned from the beginning of the pulse (Fig. 1). For a detailed study of the particular features of the behavior of the individual regions of a domain wall, experiments are carried out with a two-pulse illumination, which makes it possible to record on a single photograph the initial position of the bubble and its shape at an arbitrary time τ (Fig. 1B). Some important distinctions between the conditions of these experiments and those of Refs. 3–5 are the following: 1) Magnetic field pulses with an extremely short rise time (~ 2 ns) are used. 2) The dynamics of the domain walls is studied directly, with a spatial resolution close to the limiting resolution. 3) It is possible to simultaneously study the dynamics of domain walls oriented in an arbitrary way with respect to the

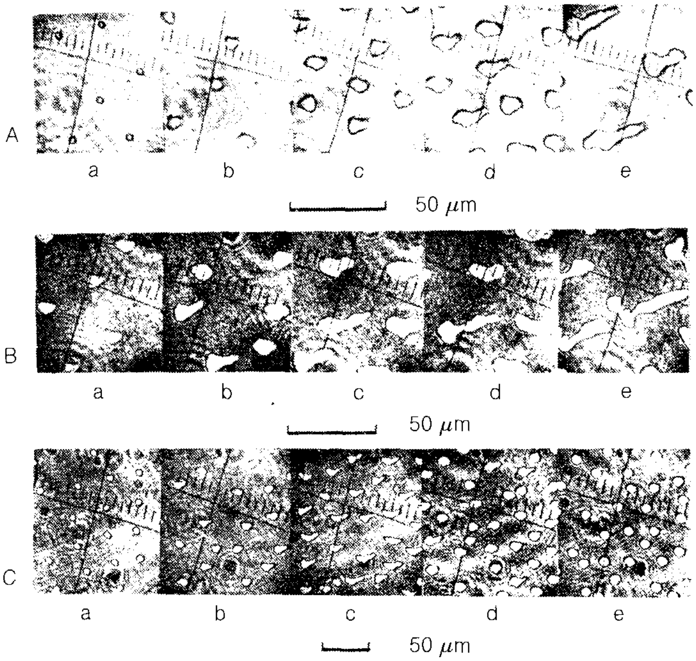

FIG. 1. A: Shapes of domains at various times after the beginning of the magnetic field pulse. The polarizers are completely crossed. $H_B = 128$ Oe; $H_{\rm pls} = 66$ Oe. a—0 ns; *b*—10 ns; c—15 ns; d—25 ns; e—60 ns. B: Distortions in the shape of the magnetic bubbles at various times after the application of the pulsed field $H_{\rm pls}$. Two-pulse illumination was used here. $H_b = 129$ Oe; $H_{\rm pls} = 68$ Oe; $\tau_1 = 0$. a—$\tau_2 = 10$ ns; b—30 ns; c—50 ns; d—70 ns; e—100 ns. C: Dynamic domain configurations which arise in various fields $H_{\rm pls}$ at a time $\tau \approx 30$ ns after the application of the pulsed field. $H_B = 121$ Oe. a—$H_{\rm pls} = 27$ Oe; b—53 Oe; c—64 Oe; d—80 Oe; e—97 Oe.

crystallographic axes. 4) Displacements of individual regions of domain walls can be determined accurately after an arbitrary time interval τ during the application of a single field pulse.

After the application of a field pulse $H_{\rm pls}$, domain walls with any orientation begin to move essentially instantaneously, and during the first few nanoseconds of their motion ($\tau < 10$ ns) they reach such high velocities ($V > 500$ m/s) that it is not possible to record a clear image of a domain wall over the exposure time (~ 8 ns; see the "blurred" regions of the domain walls in frames b–e in Fig. 1A). As early as $\tau \approx 10$ ns, however, the velocity of the domain walls decreases to the point ($V \approx 150$ m/s) that essentially all the domain walls of the magnetic bubbles can be recorded on the photographs (b in Fig. 1A). A study of the particular features of this phenomenon showed that the high velocity of the domain walls ($V > 500$ m/s) at $\tau \gtrsim 10$ ns can generally be maintained for only a single part of a bubble wall (Fig. 1), which is oriented in a certain way with respect to the crystallographic axes (see the inset in Fig. 2), while the velocity of a domain wall in any other orientation stabilizes at ~ 150 m/s. On the photographs with an exposure time ~ 8 ns, the giant unidirectional anisotropy of the wall velocity ($V_{\max}/V_{\min} > 4$) is manifested as a "break" in the domain wall of a bubble (c–e in Fig. 1A). As time elapses ($\tau > 10$ ns), this anisotropy leads to pronounced distortions in the shape of the domains (e in Fig. 1A and c–e in Fig. 1B). The anomalously high velocity of one part of the domain wall persists for only ~ 20 ns after the application of the field pulse; for most of the domains, it then ($\tau > 20$ ns) decreases to a level characteristic of the other parts of the domain wall. For only a few of the magnetic bubbles does the unidirectional anisotropy of the velocity (the "break" in the domain wall) persist for $\tau \gtrsim 50$ ns (e in Fig. 1A and e in Fig. 1B).

A study of the behavior of the distances traversed by the various parts of the domain walls of the bubbles as functions of the time and an analysis of the scatter in the distances traversed by the anomalous sections of a wall over various time intervals τ suggest that there exist discrete time intervals, multiples of $\Delta t \approx 10$ ns, within which the unidirectional velocity anisotropy can be manifested. The decrease in the anomalously high velocity thus occurs at time intervals $\tau \approx 10$, 20, 30 ns, etc.

Since a domain wall in any orientation moves in a nonuniform way over time, the average velocity $\overline{V}$ depends on the averaging time $\Delta\tau$. To estimate the average velocities of the domain walls in the initial stage of their motion, we accordingly carried out the measurements and the calculations with $\Delta\tau \approx 10$ ns. Figure 2 shows the H_{pls} dependence of the minimum and maximum (along the direction of the maximum distortions in the shape of the domains) velocities V of parts of the domain walls of the bubbles.

A characteristic feature of the observed effects is that they occur in a relatively

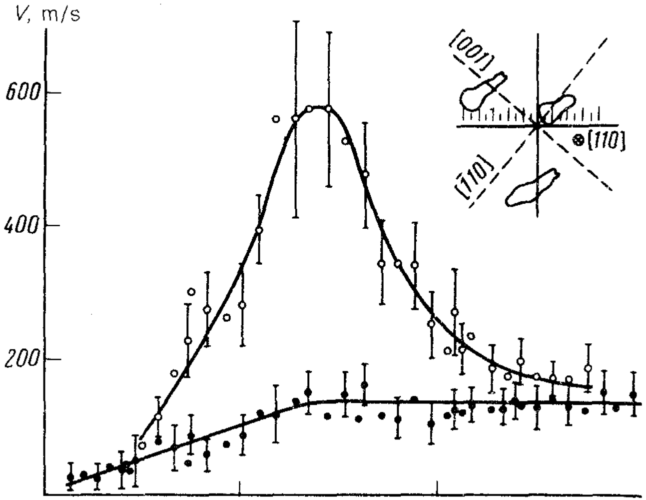

FIG. 2. Maximum velocity of a domain wall in the special direction (O) and minimum velocity (●) versus the strength of the pulsed magnetic field. The inset is a sketch of the domains from frame e in Fig. 1A and also shows the orientation of the most important crystallographic axes in the plane of the sample.

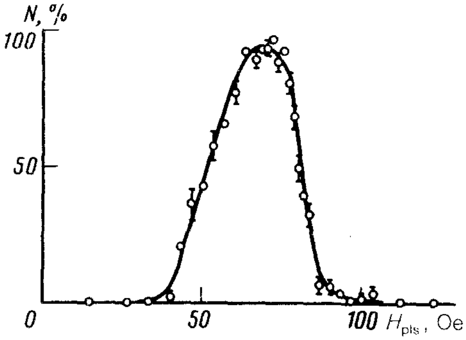

FIG. 3. Number of domains with a unidirectional velocity anisotropy of domain walls (expressed as a percentage of the total number of domains in the field of view) versus the strength of the pulsed magnetic field.

narrow interval of pulsed fields (Figs. 1B and 2). It is clear in Fig. 1B that the number of bubbles for which a unidirectional velocity anisotropy of domain walls is observed depends strongly on the field strength H_{pls}. Figure 3 shows the number of such bubbles, divided by the total number of domains, versus H_{pls}. We see that (Figs. 1C and 3) in fields $H_{pls} \approx 60$–75 Oe essentially all the bubbles exhibit a shape distortion associated with the unidirectional velocity anisotropy of the domain walls.

It can be established that the observed effects are unrelated to a nonuniformity of the pulse field or a time variation of this field. In summary, these experiments have yielded the first observation of dynamic transformations of the structure of domain walls during their motion in a uniform magnetic field.

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