Dynamic domain reorientation in pulsed magnetic fields

B. A. Ivanov, A. S. Logginov,** A. Mazewski,* T. B. Rozanova,** and Stankiewicz*

*Institute of Metal Physics, Academy of Sciences of The Ukraine, 252115, Kiev, the Ukraine; **Moscow State University, 119899, Moscow, Russia; *Institute of Physics, Bialystok Branch of Warsaw University, Poland*

(Submitted 6 July 1992; resubmitted 3 August 1992)
Pis'ma Eksp. Teor. Fiz. **56**, No. 4, 201–204 (25 August 1992)

It has been established experimentally that a pulsed field directed perpendicular to the easy axis of a ferromagnet can cause the reorientation of stripe domains to occur in fields weaker than the anisotropy field H_a but stronger than a certain critical H_k. A theoretical explanation for this result is offered under the assumption that the field pulse excites substantial oscillations with a regular behavior at $H < H_k$ and a quasistochastic behavior at $H > H_k$. The theoretical value $H_k = 0.5H_a$ agrees well with experiment.

When a strong magnetic field $H_\parallel$ is applied to a thin film of a uniaxial magnetic material in a direction parallel to the plane of the film, a stripe domain structure[1] can arise, with a predominant orientation of the domain walls along the field. In this letter we are reporting a study of the possibility of rotating the stripe domain structure by varying the strength and direction of the field in the plane of the film.

1. Experimental procedure. The experiments were carried out on a uniaxial $(BiLu)_3(FeGa)_5(O)_{12}$ film in which the anisotropy field was anomalously low, $H_a \approx 55$ Oe (after a special annealing[2]). The film thickness was 18 μm, and the saturation magnetization was $4\pi M = 40$ Oe. We used both a static field and a pulsed field (the rise time of the pulse was less than 10 ns) in the plane of the film.

The initial stripe domain structure, with essentially plane-parallel domains (Fig. 1a), is easily formed in a static field as the field is reduced in strength from a value $H_\parallel^y > H_a$. If a static field $H_\parallel^x < H_a$ is applied to the stripe domain structure formed in this manner, and if this field is applied in the perpendicular direction in the plane of the film, we do not observe a rotation of the domain structure. All that occurs is a local distortion in shape (Fig. 1b). Reorientation of the stripe domain structure in a static field requires magnetizing the film to saturation in a field $H_\parallel^x > H_a$ and then reducing the strength of this field.

At first glance, it is somewhat surprising to find that a pulsed field is vastly more effective than a static field in reorienting the stripe domain structure.[3] The efficiency of the reorientation of the structure rapidly approaches a maximum if the amplitude of the pulsed field, H_p^x, is greater than a certain H_k. At $H_p^x < H_k$, a reorientation does not occur. The transition from one type of behavior of the orientation of the domain structure to the other occurs quite sharply, in a narrow field interval near $H_p^x = 0.5H_a$. At $H_p^x < 0.4H_a$, the reorientation does not occur (Fig. 1c), while at H_p^x

 0021-3640/92/168198-05$03.00

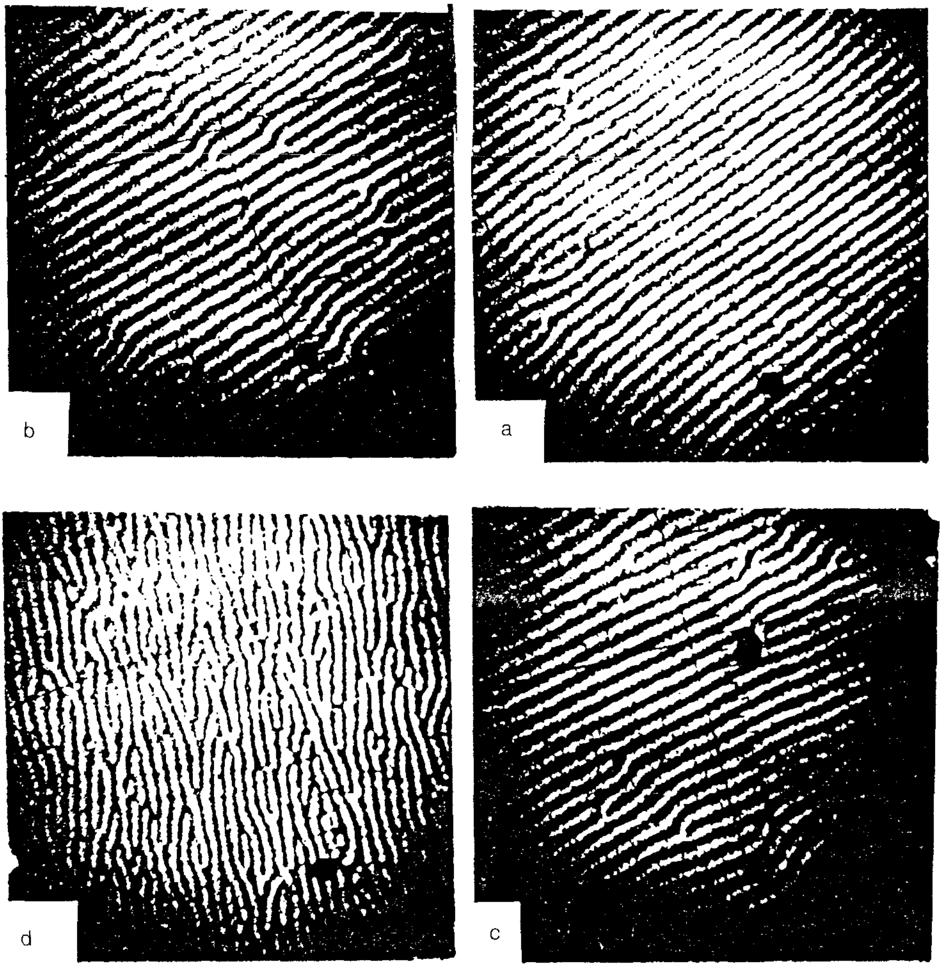

FIG. 1. Reorientation of the strip domain structure. a—Original structure, with a period of 13.6 μm; b—after the quasistatic application and the removal of a field $H_{\parallel}^{x} \simeq 0.8H_a$; c—after a pulse of height $H_{\parallel}^{x} \simeq 0.4H_a$; d—$H_{\parallel}^{x} \simeq 0.6H_a$.

$> 0.6H_a$ it goes essentially to completion (Fig. 1d). The effect is essentially independent of the pulse length Δt between 70 and 300 ns. We believe that these results point to the existence of a high barrier between the stripe domain structures with the different orientations and to the possibility of a dynamic leap across this barrier.

2. Theory. Let us assume that, after the beginning of the pulse, at $t > 0$, the magnetization in each domain varies in accordance with the Landau–Lifshitz equations

$$\dot{\varphi}\sin\theta = \lambda\dot{\theta} + \omega_a(\sin\theta - h\cos\varphi)\cos\theta,$$
$$-\dot{\theta}\sin\theta = \lambda\dot{\varphi}\sin^2\theta + h\omega_a\sin\theta\sin\varphi, \qquad (1)$$

and that the initial conditions correspond to the magnetization direction in the domains at $t<0$ ($\theta \simeq 0$ and $\theta \simeq \pi$). Here $\dot{\theta} = \partial\theta/\partial t$, $\dot{\varphi} = \partial\varphi/\partial t$, $\omega_a = gH_a$, $h = H_{\parallel}^{x}/H_a$, g is the gyromagnetic ratio, λ is a damping constant, the z axis is the easy axis, θ and φ are angular variables, and $M_x + iM_y = M_0 \sin\theta \exp(i\varphi)$. Corresponding to energy minima during a pulse of height $H_{\parallel}^{x} < H_a$ are the values $\varphi = 0$; $\theta_0 = \theta$ and $\pi - \theta_0$, $\sin\theta_0 = h$.

At $\lambda = 0$, Eqs. (1) have the first integral $E(\varphi,\theta) = (\sin\theta - h\cos\varphi)^2 - h^2 \cos^2\varphi$, and there is no difficulty in analyzing the singular points and the substantial oscillations in the (φ,θ) phase plane (Fig. 2). It is easy to see that the topology of the phase trajectories is radically different in the cases $h<0.5$ and $0.5<h<1$. The reason is that the values of E for the cases $\varphi = 0$, $\theta = 0$ and $\theta = \pi/2$ are different: $E(0,\pi/$

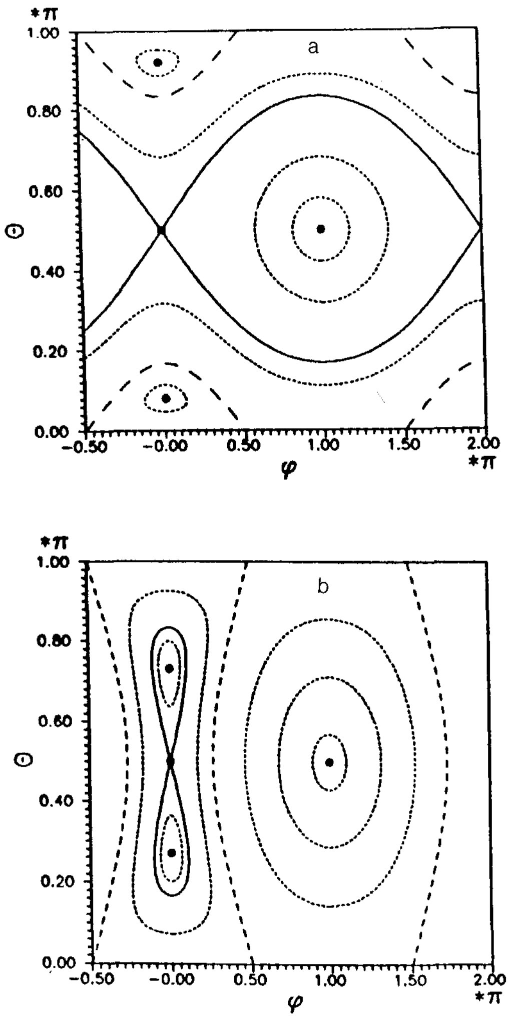

FIG. 2. Phase plane of Eqs. (1) with $\lambda = 0$. a—$H<0.5H_a$; b—$0.5H_a<H<H_a$.

2) $< E(0,0)$ for $h < 0.5$ and $E(0,\pi/2) > E(0,0)$ for $h > 0.5$. In a real situation with $\lambda \neq 0$ but $\lambda \ll 1$, the shape of the phase trajectory in the plane can easily be determined qualitatively [here we allow for the circumstance that the saddle points retain their structure, the minima of $E(\varphi,\theta)$ transform into stable foci, and the maxima transform into unstable foci], or numerical calculations can be carried out (Fig. 3). Let us examine the behavior of the phase trajectories as $t \to \infty$.

If $h < 0.5$, an initial perturbation with $\theta \ll \theta_0$ arrives at a singular point of the focus type with $\theta = \theta_0$, and a perturbation with $\pi - \theta \ll \theta_0$ arrives at a focus with $\theta = \pi - \theta_0$ (Fig. 3a). In weak fields there is thus a "memory" of the initial conditions, and a dynamic magnetization reversal of the given domain is impossible. Consequently, a reorientation of the stripe domain structure due to dynamic effects is also impossible.

If $h > 0.5$, on the other hand, the situation is fundamentally different (Fig. 3b). In

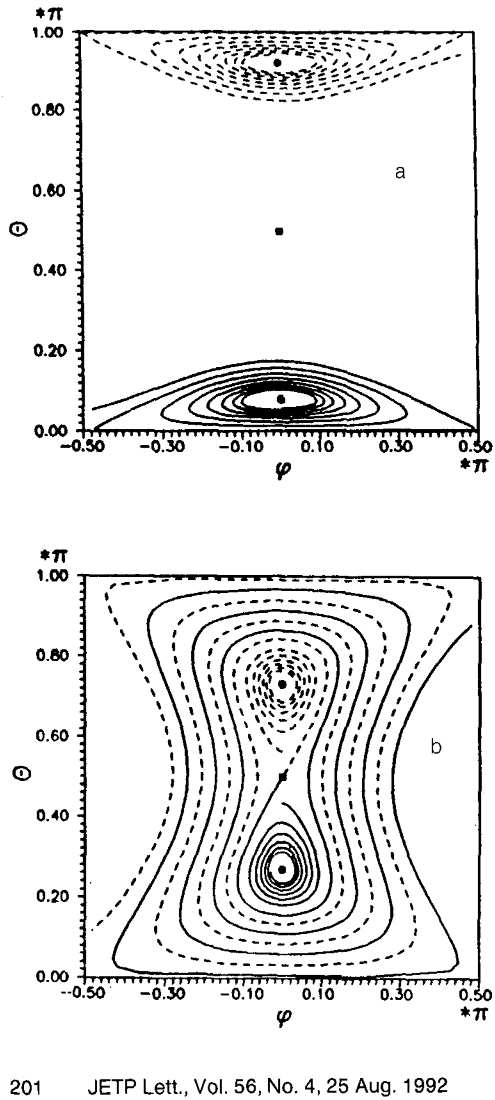

FIG. 3. Phase trajectories of Eqs. (1) for $\lambda = 0.03$. a—$H < 0.5H_a$; b—$0.5H_a < H < H_a$.

this case there is a closed separatrix loop in the region $0<\theta<\pi/2, \ -\pi/2<\varphi<\pi/2$ at $\lambda=0$. This loop emerges from a saddle singular point $\theta=\pi/2$, $\varphi=0$ and circles both energy minima (the stable foci $\varphi=0$, $\theta=\theta_0$ and $\theta=\pi-\theta_0$). At $\lambda\neq 0$, a standard analysis[4] reveals a quasistochastic dynamics: Separatrix lines going into the saddle singular point are infinite, unclosed helices which circle both minima and which form a system of narrow stripes. The width of these stripes is proportional to λ and is small as $\lambda\to 0$ (Fig. 3b). In this case, a rather small change in the initial conditions ($\Delta\theta<\lambda\ll 1$) causes a fundamental change in the magnetization, which reaches a steady state at $t\to\infty$. As $\lambda\to 0$, with a slight uncertainty in the initial conditions, these conditions are thus "forgotten," and it is more appropriate to speak in terms of the probability for reaching some value or other of the magnetization. For both initial conditions ($\theta\simeq 0$ or $\theta\simeq\pi$), the values $\theta=\theta_0$ and $\theta=\pi-\theta_0$ are equally likely to be reached. This circumstance can explain the slight reorientation of the domain structure and the nature of the steady-state structure, consisting of an irregular system of extended domains (Fig. 1d).

If this is indeed the explanation for the observed effects (we see no other possibilities for explaining these facts and the value $H_k\simeq 0.5H_a$), then the leading edge of the pulse would excite highly nonlinear oscillations in the magnetization, with a frequency on the order of $\omega_a\approx 150$ MHz, an amplitude on the order of tens of degrees, and a quasistochastic behavior in these experiments. Although it would be very interesting to observed such oscillations directly, the apparatus would have to have a time resolution better than 1 ns.

We wish to thank A. N. Balbashov for preparing the sample. This study was supported financially in part by grant No. 2-00989-91 of the Committee on Science of the Republic of Poland.

[1]S. K. Chung and M. W. Muller, J. Magn. Magn. Mater. **1**, 114 (1975).
[2]A. Stankiewicz *et al., EMMA '89, Abs., 68,* Rimini, 1989.
[3]A. Stankiewicz *et al., ISMO '91, Abs.,* Kharkov, 1991.
[4]A. A. Andronov, S. É. Bitt, and A. A. Khaĭkin, *Theory of Oscillations*, Nauka, Moscow, 1981.

Translated by D. Parsons