New types of dynamic self-organization of the magnetic moment

F. V. Lisovskiĭ and E. G. Mansvetova
Institute of Radioengineering and Electronics, Academy of Sciences of the USSR, 141120, Fryazino, Moscow Oblast

(Submitted 14 October 1991)
Pis'ma Zh. Eksp. Teor. Fiz. **55**, No. 1, 34–37 (10 January 1992)

New types of dynamic self-organization of the magnetic moment have been observed in thin iron garnet films exposed to unipolar magnetic field pulses. The symmetry of the dynamic and static configurations which arise has been determined. Structural phase transitions between these configurations have been studied.

The domain structure in magnetic thin films with a pronounced "perpendicular" anisotropy ($\beta_u > 4\pi$, where β_u is the uniaxial anisotropy constant) is known to be labyrinthal under ordinary conditions. When a sinusoidal or unipolar pulsed magnetic field is applied to such a film, a self-organization of the distribution of the magnetization vector $\vec{M}$ can occur under certain conditions. This self-organization is seen as the appearance of a definite order in the orientation and/or shape of the domain walls. Typical examples of the configurations which arise in the course of self-organization processes are a stripe domain structure, a hexagonal lattice of cylindrical magnetic domains of circular shape, and a system of concentric annular or spiral domains (Refs. 1–6, for example).

In this letter we are reporting the observation of some new types of self-organization of a domain structure. Figure 1 shows some photographs of these structures, which remind one of textbook's on space-group theory. The experiments were carried out on a thin (8.2-μm) iron garnet film with the composition $(YBi)_3(FeGa)_5O_{12}$ on a $Gd_3Ga_5O_{12}$ substrate in the (111) orientation. The period of the labyrinthal domain structure was 38.6 μm; the collapse field H_c of the magnetic bubbles (the cylindrical magnetic domains) was 18.6 Oe; the magnetization M was 5.4 G; and the quality factor of the material was $(\beta_u/4\pi) \simeq 100$. The film was immersed in a magnetizing field $\vec{H} = H\vec{e}_z$, directed parallel to the normal ($\vec{n}$) to the surface. A pulsed (or sinusoidal) magnetic field with an amplitude $\widetilde{H}$ was produced in the same direction by a plane coil with an inside diameter of 1 mm.

When the pulsed or sinusoidal magnetic field was applied to the film, a self-organization of the distribution of $\vec{M}$ occurred at certain values of the parameters of this field. This self-organization resulted in the formation of a domain structure: the spiral structure, the concentric-ring structure, or the hexagonal lattice of magnetic bubbles. In addition to the known configurations, however, the dynamic structures shown in Fig. 1, a and b, formed under certain conditions. Specifically, they formed in the case of a unipolar field, in narrow intervals of the field amplitude $\widetilde{H}$, the pulse length τ_p, the pulse ring time τ_r, the cutoff time τ_c, and the magnetizing field H. The

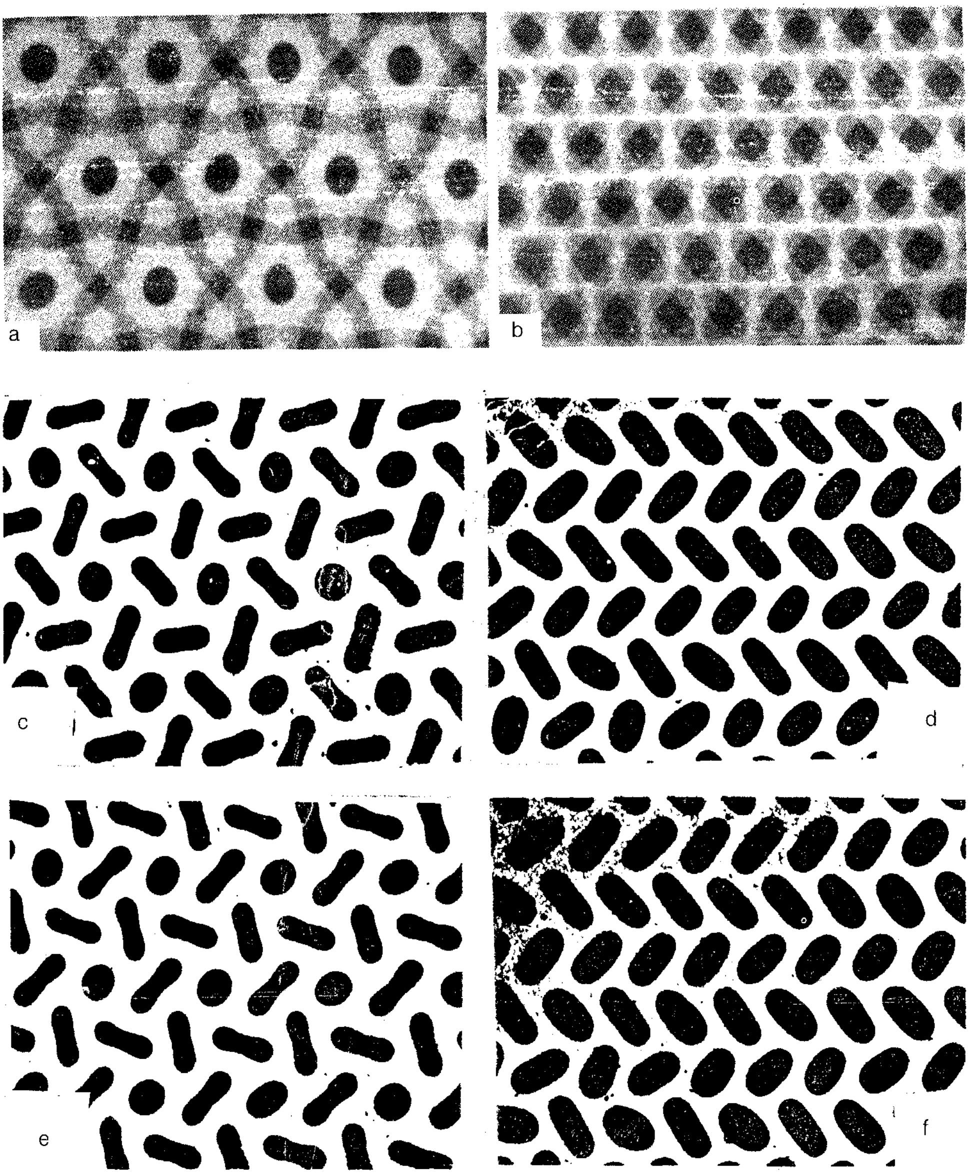

FIG. 1. a,b—Dynamic domain structures; c,f—static domain structures. The symmetry of these structures is described by the following space groups: a) $P31m$; c,e) $P3$; b) $C2mm$; d,f) $P2ab$. $H = 4.6$ Oe, $H = 77$ Oe (a), and 53 Oe (b). The structures in frames e and f were obtained from the structures in frames c and d, respectively, through the application of a single pulse.

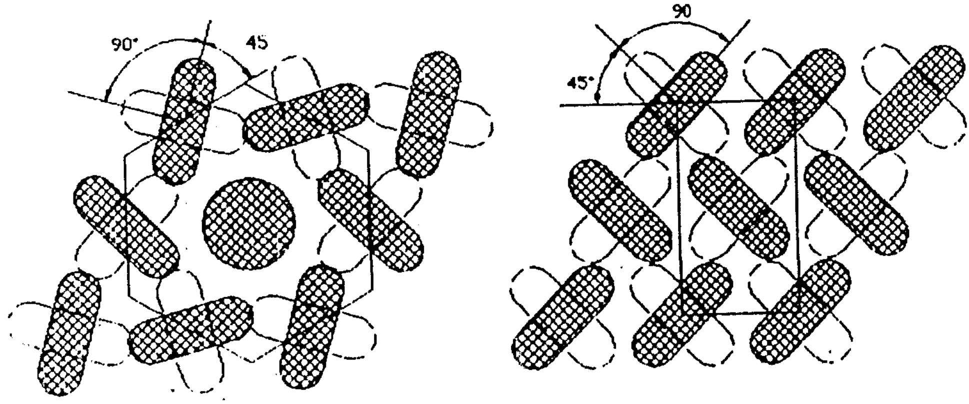

FIG. 2. Schematic diagram of the domain structures.

exposure time for these photographs was 60 ms, substantially longer than the pulse repetition period $T_p = 1$ ms. In other words, the picture which was photographed was an average over 60 pulses. These formations reached their greatest stability in the case with $\tau_p \simeq 4$ μs and $\tau_r \simeq \tau_c \simeq \tau_{p/2}$. A weak magnetizing field ($H \lesssim 5$ Oe) caused a very slight broadening of the stability region of the configuration (Fig. 1a). When the pulsed field was turned off, the domain structure "froze" and acquired the form shown in Fig. 1, c and d. After one more pulse was applied, the latter configurations became the configurations shown in Fig. 1, e and f, respectively. We see that a one-time "shock" leads to a change in the orientation of all the dumbbell-shaped domains.[1)] This change is through an angle of precisely $\pi/2$. The dynamic domain configurations in Fig. 1, a and b, are simply a superposition of the static structures in Fig. 1, c and e, or Fig. 1, d and f, respectively. The fact that dumbbell-shaped domains exist is evidence that vertical Bloch lines are playing a definite role in the observed effects (Ref. 1, for example).

The symmetry of the dynamic domain structures in Fig. 1, a and b, is described by the space groups $P31m$ and $C2mm$, respectively (these are "symmetric phases"). The static configurations in Fig. 1, c and e, and Fig. 1, d and f, are described by groups $P3$ and $P2ab$ ("disymmetric phases"[9]). The symmetry of the hexagonal lattice of magnetic bubbles is characterized by the two-dimensional space group $P6mm$ (see Refs. 10 and 11 regarding two-dimensional space groups). Figure 2 shows the arrangement of domains and the angles characterizing their relative orientation. One possible static configuration is shown by the hatching; another is shown by the dashed curve. We see that certain of the symmetry elements which had been lost are restored in the dynamic structures. The presence of circular magnetic bubbles in the lattices in Fig. 1 a, c, and e, agrees with the symmetry of the local surroundings of bubbles (a sixfold axis).

Structural phase transitions can be induced between the domain structures in Fig. 1, a and b, by a change in the amplitude of the pulsed magnetic field $\widetilde{H}$ (at a constant magnetizing field H) or by a change in the strength of the magnetizing field at a constant value of $\widetilde{H}$ (or both). These are reversible transitions, with essentially no hysteresis. The static configurations (Fig. 1, c–f), on the other hand, undergo a transition to a hexagonal lattice of magnetic bubbles or to a honeycomb domain structure, depending on the direction of the field change, upon a change in the magnetizing field H. These transitions are irreversible.

Reversible phase transitions from a hexagonal lattice of magnetic bubbles (with symmetry space group $P6mm$) to phases with three-dimensional symmetry $P2ab$ or $P3$ can be realized during manual operation of the pulse generator which produces the field $\tilde{H}$ (if the amplitude is chosen appropriately). It thus becomes possible to determine the time over which the phase transition occurs. Observations show that a complete conversion of the type of domain structure, which occurs through the appearance of a nucleating center of the new phase (dumbbell-shaped domains) and the subsequent growth of this center (by virtue of a motion of the phase boundaries), occurs after the application of 50–100 pulses. In other words, the duration of the phase transition is in the interval 0.2–0.4 ms.

The lattice constants of the two-dimensional Bravais lattices, represented in the form $(\vec{a},\vec{b},\gamma)$, where $\vec{a}$ and $\vec{b}$ are primitive translation vectors, and γ is the angle between them, are $(d,d\sqrt{3},\pi/2)$ for the configurations with symmetry groups $C2mm$ and $P2ab$, while they are $(2d,2d,\pi/3)$ for $P31mm$ and $P3$, where d is the on-center distance between nearest domains. [For the ordinary hexagonal lattice of magnetic bubbles, the relation is $(\vec{a},\vec{b},\gamma) = (d,d,\pi/3)$.] The configurations with the symmetry groups $P31m$, $P3$, and $P2ab$ are characterized by two mutually penetrating Bravais lattices, which are displaced with respect to each other along the major diagonal of the unit cell, by distances of $2d\sqrt{3}/3$ and d, respectively.

The processes which occur for the dynamic structures (e.g., with $H=$ const, and as the pulse amplitude $\tilde{H}$ is smoothly reduced from the stability region of the ordinary hexagonal lattice of magnetic bubbles) constitute a chain of structural phase transitions in a system of two-dimensional crystals of the following types: [hexagonal crystal of class 6mm $(a=b=d)$] → [orthorhombic crystal of class $2mm$ $(a=d,\ b=d\sqrt{3})$] → [trigonal crystal of class $3m(a=b=2d)$]. For the "frozen" structures, the chain of transitions is [hexagonal crystal of class $6mm$] → [orthorhombic crystal of class $2mm$ $(a=d,\ b=d\sqrt{3})$] → [trigonal crystal of class 3 $(a=b=2d)$].

These processes are very nonlinear, since they are observed at fields $\tilde{H}$ well above the collapse field. After each pulse, there is a coherent change in the orientation of all dumbbell-shaped domains, through an angle precisely equal to $\pi/2$. This change in orientation is apparently the main reason why the self-organization processes are highly sensitive to the amplitude and length of the pulses and also to the homogeneity and quality of the films. Similar effects have been seen in other films (with different compositions), with a larger value of β_u.

[1] A rotation of dumbbell-shaped domains (without a change in their shape) in a pulsed magnetizing field was observed in Refs. 7 and 8. In our experiments, the process is apparently more complex, since the distribution of the optical density on the photographs in Fig. 1, a and b, does not agree with the hypothesis of a rotation.

[1] A. P. Malozemoff and J. C. Slonczewski, *Magnetic Domain Walls in Bubble Materials*, Academic, Orlando, 1979.
[2] V. K. Vlasko-Vlasov and A. F. Khapikov, Fiz. Tverd. Tela (Leningrad) **32**, 2034 (1990) [Sov. Phys. Solid State **32**, 1183 (1990)].
[3] T. H. O'Dell, *Magnetic Bubbles*, Halsted Press, New York, 1975.
[4] G. S. Kandaurova, Dokl. Akad. Nauk SSSR **308**, 1364 (1989) [Sov. Phys. Dokl. **34**, 918 (1989)].
[5] G. S. Kandaurova and A. É. Sviderskiĭ, Zh. Eksp. Teor. Fiz. **97**, 1218 (1990) [Sov. Phys. JETP **70**, 684 (1990)].
[6] I. E. Dikshteĭn, F. V. Lisovskiĭ, E. G. Mansvetova, and E. S. Chizhik, Zh. Eksp. Teor. Fiz. **100**, 1606 (1991) [Sov. Phys. JETP **73**, 888 (1991)].
[7] J. C. Slonczewski, A. P. Malozemoff, and O. Voegeli, AIP Conf. Proc. **10**, 458 (1973).
[8] F. G. West and D. C. Bullock, AIP Conf. Proc. **10**, 483 (1973).
[9] Yu. A. Izyumov and V. N. Syromyatnikov, *Phase Transitions and Symmetry of Crystals*, Nauka, Moscow, 1984.
[10] S. Bhagavantam and T. Venkatarayudu, *Theory of Groups and Its Applications to Physical Problems*, Andhra University Press, 1962.
[11] M. A. Jaswon and M. A. Rose, *Crystal Symmetry: Theory of Colour Crystallography*, Ellis Horwood Ltd., Chichester, 1983.

Translated by D. Parsons