Dynamic self-organization and symmetry of the magnetic-moment distribution in thin films

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New types of self-organization of domain structures have been observed in thin films of magnetic garnets subjected to a unipolar magnetizing pulse of a certain shape and duration. Results found by high-speed photography are reported. In the course of these experiments, an unusual reaction of elliptical (or dumbell-shaped) domains to the magnetic field pulses was found. The symmetry of the configurations which arise in the course of the self-organization processes has been determined in the theory of two-dimensional space groups. There is a discussion of the possibility that all 17 of the magnetic-moment distributions permitted by this theory can actually be realized.

Analyzing the current trends in synergetics, many specialists (Ref. 1, for example) conclude that the significant progress which has been made toward an understanding of the world of chaos has been accompanied by far more modest success in sorting out the structures which arise in the course of self-organization from chaos. In particular, the search for and the classification of such structures have made almost no use of the symmetry approach which has played such a key role in other branches of physics. Indeed, symmetry considerations have been invoked only as auxiliary considerations in synergetics. (For example, symmetry considerations have been invoked in the identification of a bifurcation as a transition with a spontaneous symmetry breaking, in a group-theory approach to the analysis of invariant transformations of systems of equations of the diffusion type, and in the interpretation of self-organization processes involving the formation of stable or metastable dissipative structures as nonequilibrium phase transitions.[1–4])

Although magnetically ordered media are classic examples of dissipative systems (the Landau-Liftshitz equation with a relaxation term is invariant under time reversal and is always nonlinear), they escaped attention in the field of synergetics for a fairly long time. Recent experiments have now established that applying a sinusoidal or unipolar pulsed magnetic field to a magnetic thin film with a strong perpendicular anisotropy of the easy-axis type ($\beta_u > 4\pi$, where β_u is the uniaxial anisotropy constant) may, under certain conditions, result in a self-organization of the distribution of the magnetization vector **M**. Ordinarily, the domain structure in such a film is labyrinthine. This self-organization is seen as an ordering of domain walls. Typical examples of the configurations formed in the course of the self-organization are a stripe domain structure, a hexagonal lattice of cylindrical magnetic domains with a generatrix which is a circle, an ellipse, or an oval with a constriction (a "dumbell"), and a system of concentric annular or helical domains.[5–20]

Among the various possible distributions of the vector **M** in a magnetic sample of finite dimensions, one can distinguish a so-called ground state, which corresponds to an absolute minimum of the thermodynamic potential for the given external conditions. In general, however, there exists an infinite set of metastable states corresponding to a relative minima of the thermodynamic potential. Under certain conditions, these metastable states can also be realized in the magnetic material, possibly during self-organization processes. The number of states having a spatial symmetry is undoubtedly finite, but so far we do not have a general classification of these symmetric configurations. All that we find in the literature are isolated attempts to solve the problem partially (e.g., in Ref. 21, where a symmetry analysis of possible types of domain walls in ferromagnets and ferrimagnets was carried out). In sufficiently thin films, the situation is simplified because the domain structures run all the way through the film, and in many cases they can be treated as quasi-two dimensional. It thus becomes possible to use two-dimensional space groups for a symmetry classification. In this approach, the internal structure of the domain walls is ignored, and these walls are treated as structureless geometric surfaces running perpendicular to the large planes of the film, separating neighboring regions of the magnetic material which are uniformly magnetized with antiparallel vectors **M**. The approximation of "geometric" domain walls appears to be completely legitimate for analyzing possible symmetry types of domain structures [as in the case of (for example) crystalline solid solutions, in determining the symmetry one need not distinguish between the structures of the inner electron shells of atoms in identical coordinations]. In the two-dimensional model of domain structures, the isolated domains from which the "motifs" of the Bravais lattices are formed should also be regarded as structureless plane elements with a magnetization $-2\mathbf{M}$ which is "floating" in a homogeneous medium with a magnetization $+\mathbf{M}$.

In this paper we are reporting the observation of new types of self-organization of domain structures in thin films of magnetic garnets induced by a unipolar pulsed magnetic field of a certain shape and duration. The symmetry of the configurations which arise in the process is determined in the theory of two-dimensional space groups. We discuss the possibility that all 17 of the magnetic-moment distributions allowed by this theory are realized. Some of these results were published previously in Ref. 22.

1. REALIZATION OF A SELF-ORGANIZATION PROCESS; EXPERIMENTAL CONDITIONS

The experiments which were carried out to observe self-organization of domain structures used a thin (8.2-μm) film of the iron garnet $(YBi)_3(FeGa)_5O_{12}$ on a $Gd_3Ga_5O_{12}$ substrate in the (111) orientation. The period of the labyrinthine domain structure was 54.3 μm, the collapse field of the cylindrical magnetic domains, H_c, was 18.6 Oe, the magnetization M was 5 G, and the quality factor of the material was $(\beta_u/4\pi) \approx 100$. The film was in a magnetizing field $\mathbf{H} = \mathrm{H}\mathbf{e}_z$, oriented parallel to the normal ($\mathbf{n}$) to the surface. The pulsed (or sinusoidal) alternating magnetic field, $\widetilde{\mathbf{H}}$, in the same direction, was produced by a ten-turn plane coil with an inside diameter of 1 mm.

During the application of the pulsed or sinusoidal magnetic field to the film, for certain field parameter values, a self-organization of the distribution of $\mathbf{M}$ occurred. This self-organization was accompanied by the formation of domain structures which were helices, concentric rings, or a hexagonal lattice of cylindrical magnetic domains. However, along with the known configurations, the dynamic structures shown in Fig. 1, a and b, formed during the application of a unipolar pulse over certain ranges of the field amplitude ($\widetilde{H} \approx 50$–90 Oe), the pulse length ($\tau_p \approx 3$–5 μs), the rise time ($\tau_r \approx 0.5$–2.5 μs), the decay time ($\tau_d \approx 0.5$–2.5 μs), and also the magnetizing field ($H \approx 0$–10 Oe). The exposure time in the photography (≈ 60 ms) was considerably longer than the pulse repetition period $T_p = 1$ ms; in other

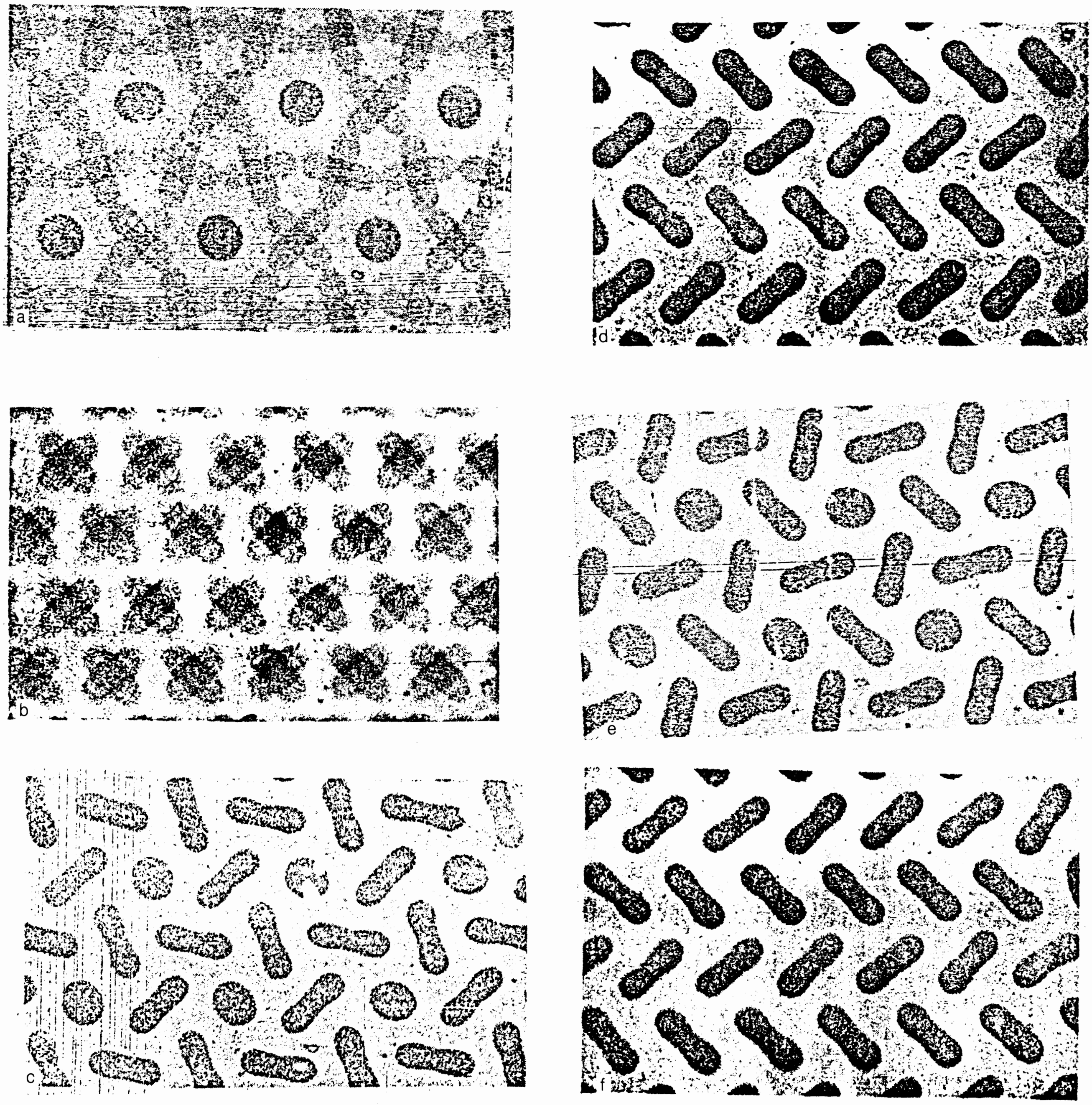

FIG. 1. Photographs of (a, b) dynamic and (c–f) static domain structures which arise in the course of self-organization in an iron garnet film. $H = 4.6$ Oe. a—$\widetilde{H} = 77$ Oe; b—53 Oe. The structures in frames a and f were obtained from those in frames c and d, respectively, by the application of a single pulse, with $\tau_p \approx 4$ μs and $\tau_r \approx \tau_d \approx 2$ μs.

words, the picture which was recorded was an average over 60 pulses. For the domain structures of the type in Fig. 1b, the greatest stability was found for triangular pulses with $\tau_p \approx 4\ \mu s$ and $\tau_r \approx \tau_d \approx 2\ \mu s$. The configurations of the type of Fig. 1 were maximally stable for pulses of approximately the same length, but with a slightly different shape: asymmetric double-humped pulses (with a small additional maximum on the decay of the initial triangular pulse). The regions in which the structures of the two types exist overlap, however. The domain structures in Fig. 1b exist over a wider region in the space of pulse parameters, and they are less sensitive to the shape of the pulses. A weak magnetizing field ($H \lesssim 5$ Oe) causes a negligible broadening of the stability region of the configurations in Fig. 1a.

As the temporal parameters of the pulses are changed away from their optimum values, the stability is progressively degraded (ordered structures of the types in Fig. 1, a and b, appear on a progressively smaller area of the sample and have progressively shorter lifetimes under dynamic conditions). Eventually, the stability is lost completely. Particularly unfavorable factors for self-organization are short rise times and/or short decay times. For small pulse lengths and/or low pulse heights, self-organization is not observed, because the reorientation of the major axes of the elliptical domains ceases to occur, and also because the amplitudes of the domain-wall oscillations are small. Large-amplitude (or long) pulses cause a transition to a chaotic motion and prevent an ordering of domains into regular lattices.

In the region in which they exist, the basic types of instability of the dynamic structures in Fig. 1, a and b, are as follows: spontaneous transitions of one configuration into another (Sec. 3), a displacement of ordered domain structures by a labyrinthine structure (which forms as the result of a loss of stability with respect to a transition of one of several elliptical domains into a stripe domain), a "twinning," by which we mean the appearance of several ordered macroscopic regions differing in the orientation of their symmetry axes, and random hops of circular-cylinder magnetic domains from their original positions to neighboring positions, accompanied by a change in the structure of the "neighborhood" of elliptical domains.

These processes are very nonlinear, since they observed at fields $\widetilde{H}$ which are considerably higher than the static collapse field of a magnetic bubble.

The spatial periods of the domain structures in Fig. 1 in their stability region depend only slightly on the pulse parameters. The average on-center distances between neighboring domains are 80 and 90 μm for the configurations in Fig. 1, a and b, respectively. These distances are considerably larger than both the period of the equilibrium stripe domain structure (54.3 μm) and the period of the closest-packed hexagonal lattice of magnetic bubbles (62 μm).

When the magnetic field is turned off, the domain structures "freeze" and acquire the shape shown in Fig. 1, c and d. After one additional pulse is applied, these structures become the configurations in Fig. 1, e and f, respectively. We see that a single "shock" effect causes changes of exactly $\pi/2$ in the orientation of the major axes of the dumbbell-shaped domains. The dynamic domain configurations in Fig. 1, a and b cease to be a simple superposition of the static structures in Fig. 1, c and e, or Fig. 1, d and f, respectively. A rotation of isolated dumbbell-shaped domains induced by a train of magnetizing-field pulses has been observed previously.[23–25] The investigators attributed the effect to vertical Bloch lines. Under our photography conditions, however, the rotating dumbbell-shaped domains should have produced a half-tone image in the form of a circle on the photographs in Fig. 1, a and b. This did not happen. It follows that the reorientation of the dumbbell-shaped domains through $\pi/2$ occurs differently in our case. Concrete data on this effect were found from experiments carried out by high-speed photography (Sec. 2).

The reorientation of the dumbbell-shaped domains is accompanied by a noticeable aftereffect. This effect was found in the course of experiments in which pairs of successive pulses (identical in shape), separated by a variable time interval τ_{12}, were used to induce the self-organization of the domain structures. It was found that at $\tau_{12} \geqslant 3\tau_p$ the visual shape of the dynamic domain structures was the same as that of the static configurations. The reason was that the successive aftereffects of each pair of pulses caused the major axes of the dumbbell-shaped domains to undergo an orientation change of $\pi/2$ twice. In other words, they rotated back to their original position. If the second pulse of a pair arrived after a delay of less than $3\tau_p$, the motion of the domains became chaotic, and ordered dynamic domain structures did not form.

2. EXPERIMENTS INVOLVING HIGH-SPEED PHOTOGRAPHY OF DYNAMIC DOMAIN STRUCTURES

The experiments were carried out on an apparatus similar to that described in Ref. 26, with light applied in two flashes (or one), ≈ 10 ns long. To keep the dumbbell-shaped domains in their original orientation in the course of the photography, we used a train of two triangular magnetic-field pulses ($\tau_p = 4\ \mu s$, $\tau_r = \tau_d = 2\ \mu s$), with a delay of $\tau_{12} = 200\ \mu s$ between the pulses and with a repetition period $T_P = 1$ ms. The first flash of light was applied just before the beginning of the pair of magnetic-field pulses. This flash fixed the (quasistatic) original configuration. The second flash was applied at a variable time τ after the beginning of the first pulse of the pair. Figures 2 and 3 show series of photographs of dynamic domain structures of the types in Fig. 1, a and b, taken for various values of the delay (τ) between the beginning of the first pulse of the pair and the second light flash.[1)]

The high-speed photography showed that no qualitative changes occurred in the domain structures over a large fraction of the duration of the magnetic-field pulse. All that we observed was a decrease in the dimensions of the domains, without any significant change in their shape. Dumbbell-shaped distortions began to appear in the domains at $\tau \gtrsim 3.3\ \mu s$. The domains acquired a more developed shape at roughly the end of the magnetic-field pulse (see Figs. 2b and 3b for $\tau = 3.8$ and $3.4\ \mu s$, respectively). After this event, the length of the dumbbell-shaped domains begins a rapid decrease, while the width of these domains increases. In other words, the constrictions are annihilated (Figs. 2c and 3c for $\tau = 4.4$ and $4.6\ \mu s$, respectively). As a result, the extended domains (after the end of the magnetic-field pulse) become nearly square (Figs. 2d and 3d for $\tau = 5.2$ and $5.0\ \mu s$, respectively). These nearly square domains then begin to lengthen along the direction perpendicular to the major axis of the elliptical domains in the original domain structure, as can be

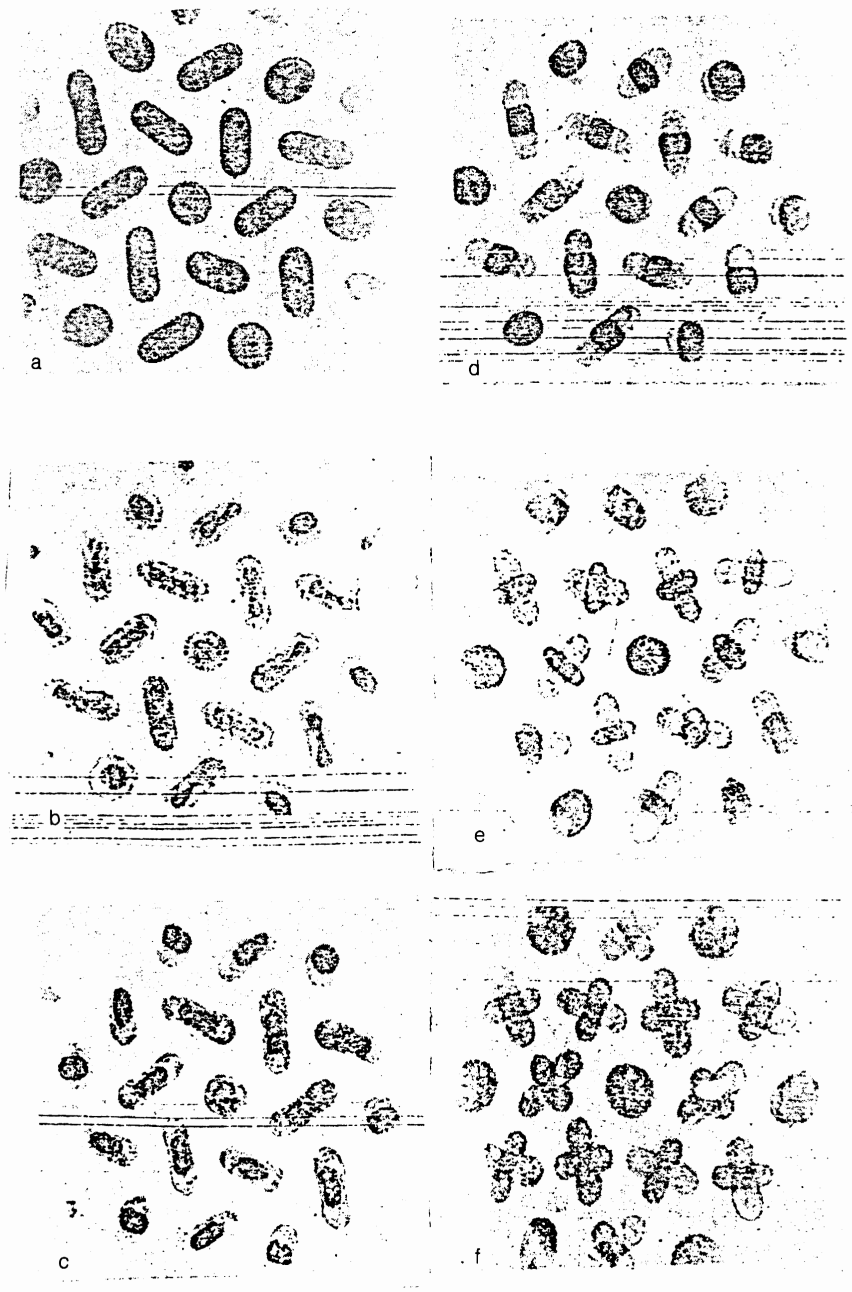

FIG. 2. Photographs of dynamic domain structures obtained by high-speed photography for a configuration of the type in Fig. 1a. The exposure time was 10 ns. The delay times between the beginning of the magnetizing-field pulse and the second light flash for photographs a–f were 0, 3.8, 4.4, 5.2, 7.2, and 9.4 μs, respectively. The parameters of the magnetic-field pulses were the same as for Fig. 1a.

seen in Figs. 2e and 3e ($\tau = 7.2\,\mu$s). Later on, the increase in the domain size occurs in such a way that the shape of the domains initially goes through a stage of small dumbbell-shaped distortions (Fig. 2f, $\tau = 9.4\ \mu$s; Fig. 3f, $\tau = 9.8\ \mu$s) and then asymptotically approaches an elliptical shape. These circular-cylinder magnetic domains in a structure of the type in Fig. 1a cause essentially no change in the shape of the domain walls in any stage of the compression-expansion cycle (Fig. 2).

Using the results of the high-speed photography, we can find the time evolution of the displacements (R) of the domain walls from their equilibrium positions along the directions corresponding to the local symmetry planes (along the principal axes of the ellipses). The results found for the structures of the types in Fig. 1, a and b ($\tau_p = 4\ \mu$s, $\tau_r = \tau_d = 2\,\mu$s), are shown in Figs. 4a and 5b (the asterisks, triangles, and circles refer to the major and minor axes of the elliptical domains in the original state and the diameter of a circular-domain, respectively). The experimental data were approximated and smoothed by the method of cubic splines with a mesh spacing $\Delta\tau/300$ on a computer of the IBM-PC-XT type, with the help of a program written by O. A. Byshevskiĭ–Knopko. After the smoothing, the approximating curves were differentiated numerically in order to deterime the instantaneous velocity V of selected regions of domain walls. Curves of $V(\tau)$ are given in Figs. 4b and 5b. We see that at the front of the magnetizing-field pulse all parts of the domain wall are moving at the same velocity. The presence of circular-cylinder domains does not cause any important changes in the dynamic reaction of the elliptical domains (compare Figs. 4 and 5). The maximum velocity of the domain walls in these experiments did not exceed 5 m/s.

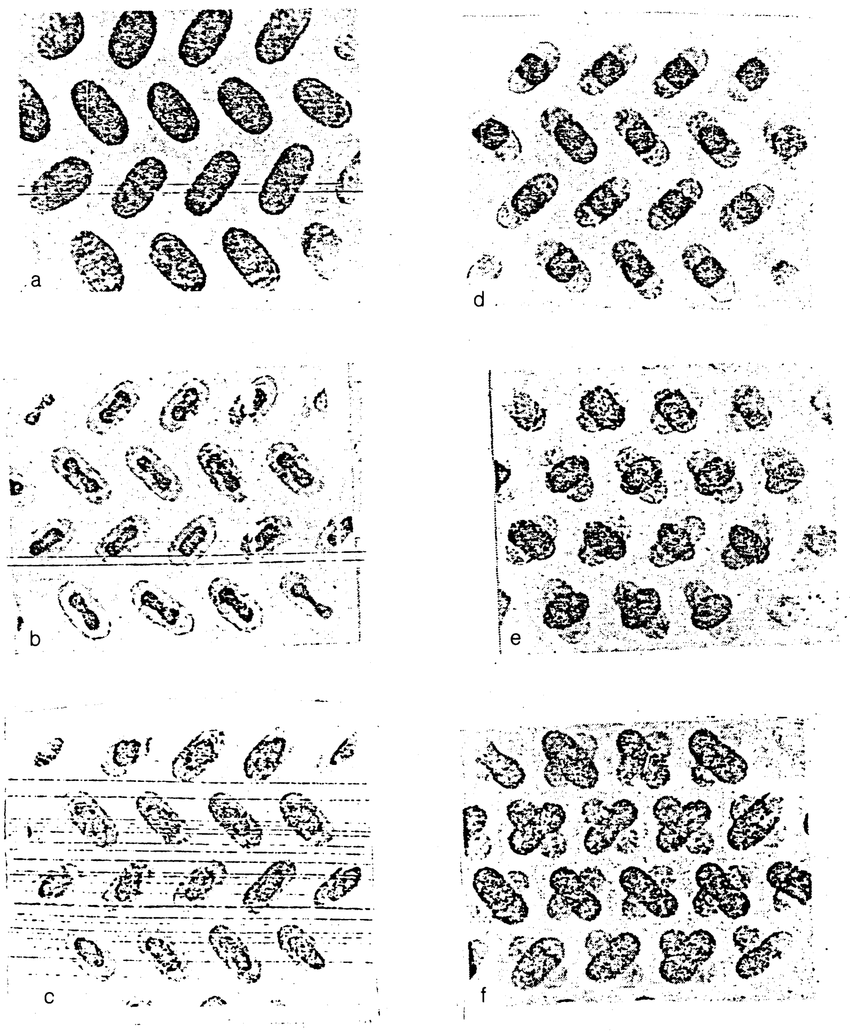

FIG. 3. Photographs of dynamic domain structures obtained by high-speed photography for a configuration of the type in Fig. 1b. The exposure time was 10 ns. The delay times between the beginning of the magnetizing-field pulse and the second light flash for photographs a–f were 0. 3.4, 4.6, 5.0, 7.2, and 9.8 μs, respectively. The parameters of the magnetic-field pulses were the same as for Fig. 1b.

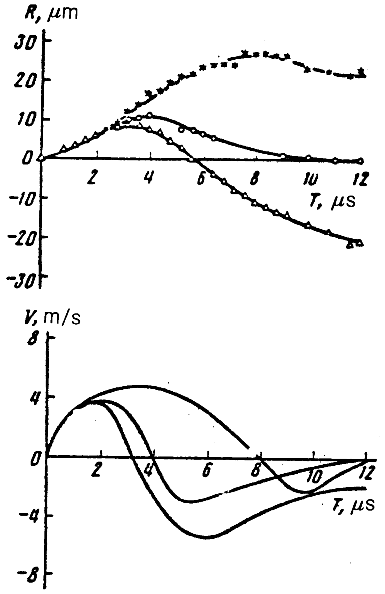

FIG. 4. Time evolution of the displacement R and the velocity V of the domain walls in a structure of the type in Fig. 1a O–For circular-cylinder domains; *, Δ–for elliptical (dumbbell-shaped) domains, along the original major axis and the original minor axis, respectively.

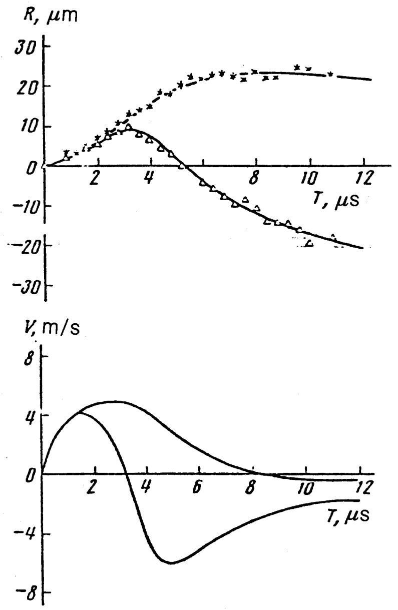

FIG. 5. Time evolution of the displacement R and the velocity of V domain walls in a structure of the type in Fig. 1b. *, Δ–For elliptical (dumbbell-shaped) domains along the original major axis and along the original minor axis, respectively.

Analysis of the results found by high-speed photography of the dynamic structures shows that the observed behavior of the dumbbell-shaped (or elliptical) domains is fundamentally different from the behavior which has been found previously (as described in Refs. 5 and 23–25, for example). Ordinarily, dumbbell-shaped domains rotate in the manner of a propeller under the influence of a train of magnetizing-field pulses. The use of high-speed photography revealed that a rotation through a certain angle in one direction occurs during each pulse (in the domain compression phase), while in the time interval between pulses there is a rotation through a smaller angle, in the opposite direction (during expansion of the domains). In the opinion of Malozemoff *et al.*[5,23,24] and West and Bullock,[25] the net rotation angle in each pulse of the train differs from zero only if a domain does not reach its equilibrium position during the pulse and if the coercive force suppresses the rotation in the opposite direction during the time interval between pulses (for sufficiently long pulses, the net rotation angle vanishes). For short pulses, a small additional rotation in the same direction as during the pulses is observed in the time intervals between pulses. Under all of the conditions used in Refs. 5 and 23–25, however, the net rotation was always less than $\pi/2$. The effects described in Refs. 5 and 23–25 are related to a deviation of rigid circular-cylinder domains (i.e., of domains whose wall contains a large number of vertical Bloch lines) during a translational motion due to gyrotropic forces. Since the ends of an extended domain, which are equivalent to circular-cylinder domains, move toward each other (away from each other) during the compression (expansion) of an extended domain, a pair of forces arises which tends to rotate the domain. The sign of the moment of this pair is determined by whether the domain is being compressed or is expanding.

The role played by vertical Bloch lines is not as obvious here as in the experiments of Refs. 5 and 23–25. This assertion is based on an analysis of some additional experiments which we carried out to study the reaction of a labyrinthe domain structure in the same film to a train of magnetizing-field pulses with parameters such that self-organization accompanied by the formation of structures of the type in Fig. 1 did not yet occur. For this purpose, we used pulses of relatively small height (~ 10 Oe). Under these conditions, during the oscillations of the domain walls we clearly observed nodes, which are usually linked with the appearance of regions with a large effective mass in domain walls, because of a clustering of vertical Bloch lines.[27] However, direct visual observations revealed a drift of these oscillation nodes. In other words, these nodes were not completely pinned (Ref. 27, for example). After the pulse, the strip domains did not acquire the numerous lateral outgrowths which are characteristic of the presence of clusters of vertical Bloch lines, although we used films with a high quality factor. In such films, the energies of the Bloch and Néel domain walls differ only slightly, so we would expect a massive generation of vertical Bloch lines in the course of the motion. These facts suggest that if vertical Bloch lines do form in our experiments then they are apparently very dynamic formations, which annihilate as the domain structure relaxes to an equilibrium state.[2)] Possibly of more importance for explaining the reorientation of the major axes of the elliptical domains is that pronounced dumbbell-shaped distortions of the domain walls grow during the stage of compression of these domains (Figs. 2b and 3b).

Observations of the behavior of the dumbbell-shaped domains during the compression stage (Figs. 2, b and c, and 3, b and c) show that their conversion to elliptical domains occurs very rapidly (over a time $\sim 1\,\mu$s) and is accompanied by an abrupt increase in the width of the domains. The conditions here are consistent with a shock excitation of compression-extension pulsations (which are not cylindrically symmetry) along two mutually perpendicular directions.[3)]

Direct visual inspection reveals cross-shaped "dynamic" domains not only when these domains are combined in ordered lattices of the types in Fig. 1, a and b, but also when they are in disordered arrays, and even in the case of isolated domains. Furthermore, if the parameters of the magnetic pulse are close to these required for the formation of domain structures of the type in Fig. 1, then the ends of the isolated stripe domains also tend to undergo periodic changes $\pi/2$ in orientation after each magnetizing-field pulse. The switching of the orientation of the major axes of elliptical domains as the result of a single applied pulse is thus an individual, rather than domains collective, effect. In periodic domain structures (lattices) there is simply a mutual ordering of the axes of the elliptical domains in accordance with the symmetry. In addition, it is the symmetry of the local surroundings which is responsible for the circular shape of a certain fraction of the domains in a configuration of the type in Fig. 1a and thus responsible for the dynamic reaction distinct from that of elliptical domains.

Some experiments using high-speed photography were reported in Refs. 28 and 29. It was found there that circular-cylinder domains subjected beforehand to a nonuniform pulse of magnetizing field become elliptical domains during both expansion and compression. The positions of the major axes of the ellipses in these two cases are mutually orthogonal. Kochan *et al.*[28] and Malozemoff and Maekawa[29] make a fairly convincing case that the reason for the observed effect is the existence of low-mobility regions on two opposite sides of a domain wall. This low mobility results from the formation of clusters of vertical Bloch lines upon the rupture of horizontal Bloch lines during motion driven by the nonuniform magnetizing field. However, it is not difficult to see that this mechanism would not be valid for the processes we observe, since in our case (as was shown above) there is essentially no significant difference in the mobilities of the various regions of the domain wall (at least in the compression stage; Figs. 4a and 5a). Furthermore, in contrast with the case studied in Refs. 28 and 29, the elliptical shape of the domains is stable in the static sense. Nevertheless, vertical Bloch lines may still play a definite role in our experiments, in particular, in the stage in which the elliptical domains acquire dumbbell-shaped distortions.

3. SYMMETRY ANALYSIS OF THE DOMAIN STRUCTURES WHICH ARISE IN THE COURSE OF THE SELF-ORGANIZATION

The photographs in Fig. 1 clearly reveal a high degree of translational and orientational order of the domains in the structures which arise in the course of the self-organization. Accordingly, a symmetry analysis is not only justifed but in fact necessary for describing and classifying these stuctures. Drawing on the arguments in the introduction to this paper, we can think of the domain structures as a set of plane geometric figures. We can then use the methods of the theory of two-dimensional space groups (Refs. 30–33, for example). According to the results of this theory, there are 17 such groups. The regularly repeating motifs corresponding to these groups are shown in Fig. 6 (oblique-angles and rectangular systems) and Fig. 7 (square and regular triangular or hexagonal systems). Also shown in these figures are the symbols of the space groups.[4)] Each pattern is obtained by applying all the symmetry operators of the given group to the same asymmetric motif-forming element (prototype) shown in Fig. 8a. In ordered domain structures, these prototypes may be an isolated circular-cylinder domain (Fig. 8b), an isolated elliptical (or dumbbell-shaped) domain (Fig. 8c), a combination of the two (Fig. 8d), or more-complex clusters of domains of various shapes. A helical domain can serve as a very simple domain analog of the abstract prototype in Fig. 8a.

To determine the symmetry of the domain structures observed in the present experiments, we turn to Fig. 9. Shown here are schematic diagrams of the spatial arrangements of the domains and the values of the angles characterizing their relative orientation. One possible static configuration is shown by the hatching, and another by the stippling. We see (cf. Figs. 6 and 7) that the symmetry of the dynamic domain structures whose photographs are shown in Fig. 1, a and b, is described by the space groups *P6mm* and *Cmm2*, respectively (symmetric phases), while the static configurations in Fig. 1, c, e and d, f, are described by the

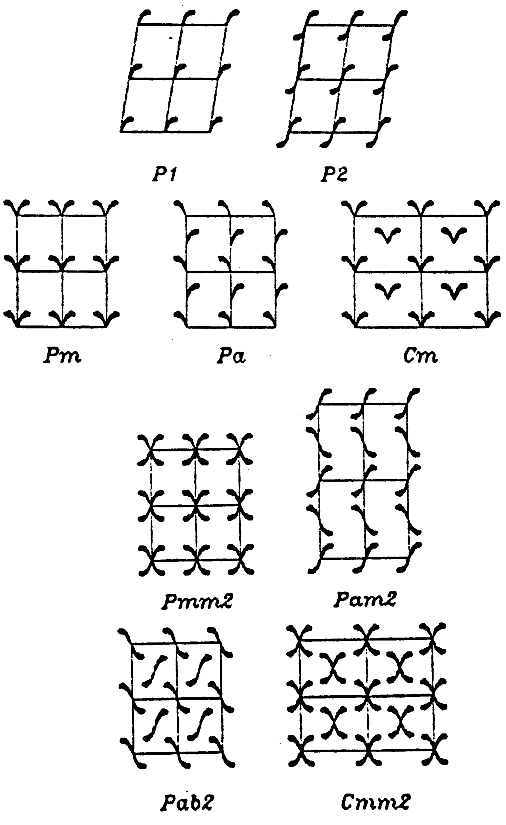

FIG. 6. Abstract motifs corresponding to an oblique-angle symmetry ($P1$, $P2$) and to a rectangular symmetry (Pm-$Cmm2$) of the two-dimensional space groups.

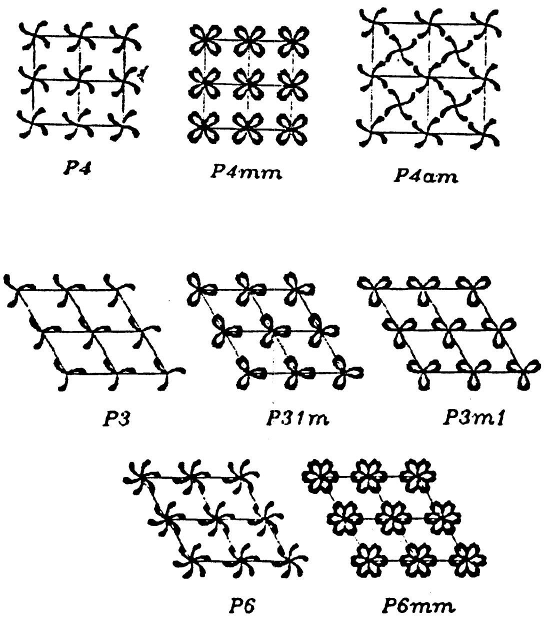

FIG. 7. Abstract motifs corresponding to a square symmetry ($P4$-$P4am$) and to a hexagonal symmetry ($P3$-$P6mm$) of the two-dimensional space groups.

groups *P6* and *Pab2* (disymmetric phases[31,34]). Some of the missing symmetry elements are restored in the dynamic structures. The presence of circular-cylinder domains in the lattices in Figs. 1, a, c, and e, agrees with the symmetry of the surroundings of the latter (a sixfold axis). An error was made in Ref. 22 in the determination of the symmetry of the structures in Fig. 1, a, c, and e.

For configurations with the symmetry groups *Cmm2*, *Pab2*, *P6mm*, and *P6*, the parameters of the two-dimensional Bravais lattices written in the form (a,b,γ), where **a** and **b** are the basic translation vectors, and γ is the angle between them, are $(d,d\sqrt{3},\pi/2)$ for the first pair and $(2d,2d,\pi/3)$ for the second. Here d is the on-center distance between nearest domains [for the ordinary hexagonal lattice of cylindrical domains whose Bravais cell is shown in Fig. 8b, we have $(a,b,\gamma) = (d,d,\pi/3)$]. The Bravais unit cells are

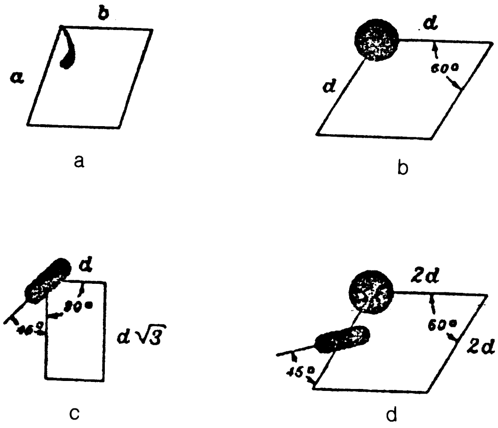

FIG. 8. Bravais lattices with (a) abstract and (b,d) domain motif-forming elements (prototypes).

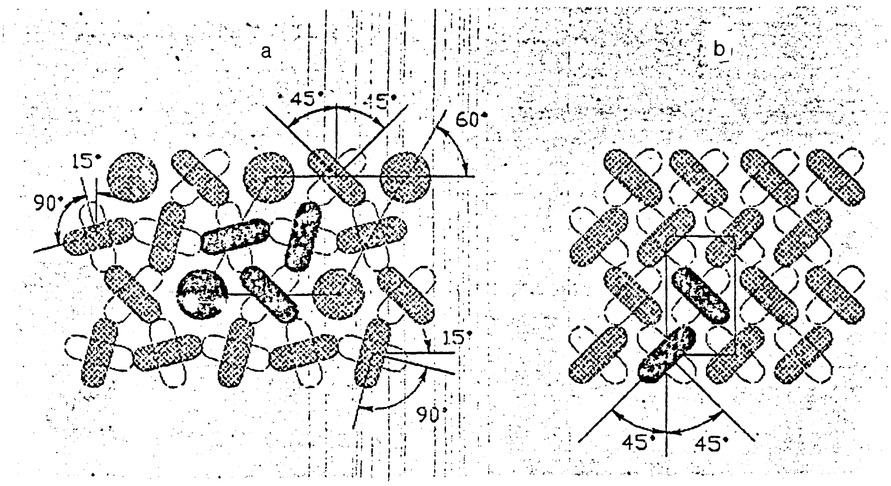

FIG. 9. Schematic diagram of the domain structures of the types in Fig. 1, a and b.

shown by the light solid lines in Fig. 9; the heavy lines show clusters of domains associated with each site of the Bravais lattices. For dynamic domain structures with the symmetry group *Cmm2* (Fig 9b), the Bravais cell is centered. The motif-forming elements (prototypes) for the structures in Fig. 1, a, c, e, and Fig. 1, b, d, f, are shown along with the corresponding Bravais cells in Fig. 8, c and d.

Structural phase transitions may occur between the domain structures in Fig. 1, a and b. These transitions would be induced by either a change in the amplitude of the pulsed magnetic field $\widetilde{H}$ (at a constant value of the magnetizing field H) or a change in the direction of the magnetizing field at a constant value of $\widetilde{H}$ (or both). These transitions are reversible and occur with essentially no hysteresis. A structure of the type in Fig. 1a becomes a structure of the type in Fig. 1b either through an increase in the magnetizing field or a decrease in the amplitude of the pulsed magnetic field. In general, the difference between the energies of the structures of these two types is so small that they can coexist (Fig. 10) and can convert spontaneously into each other.[5)] In contrast, the static configurations (Fig. 1, c–f) convert into either a hexagonal lattice of circular cylindrical magnetic domains or a honeycomb domain structure, depending on the direction in which the field strength is changed, upon a change in the magnetizing field H. These transitions are irreversible.

Reversible phase transitions from a hexagonal lattice of cylindrical domains (with symmetry space group *P6mm*) to phases with the spatial symmetry *Pab2* or *P6* can occur during manual triggering of the pulse generator which produces the field $\widetilde{H}$ (if the amplitude is chosen appropriately). It thus becomes possible to determine the time taken by the phase transition. Observations show that a complete transformation of the type of domain structure, which occurs through the appearance of a seed of the new phase (dumbbell-shaped domains) and the subsequent growth of this region (as a result of the motion of the interface), occurs after the application of 50 to 100 pulses. In other words, the duration of the phase transition is 0.2 to 0.4 ms. The process by which a hexagonal lattice of cylindrical domains is transformed into a domain structure of the type in Fig. 1c is illustrated by the photographs in Fig. 11. Regardless of whether the generator is triggered manually or automatically, a phase transition of this sort occurs only if the original lattice of cylindrical domains does not have the closest possible packing (Sec. 1). Nor does a transformation of the type of domain structure occur if the alternating magnetic field is sinusoidal; all that

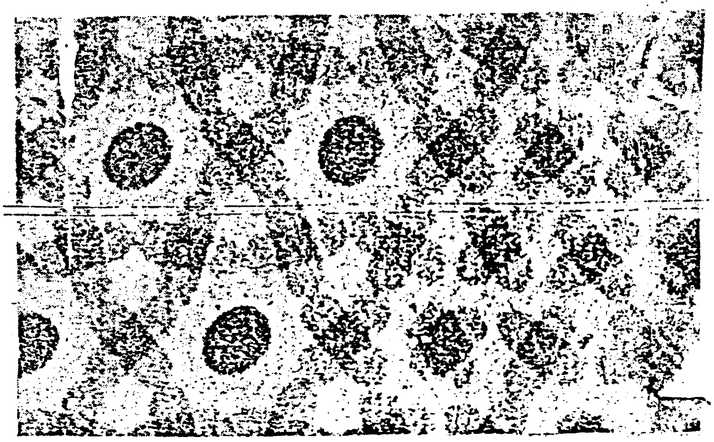

FIG. 10. Photograph of coexisting domain structures of different types.

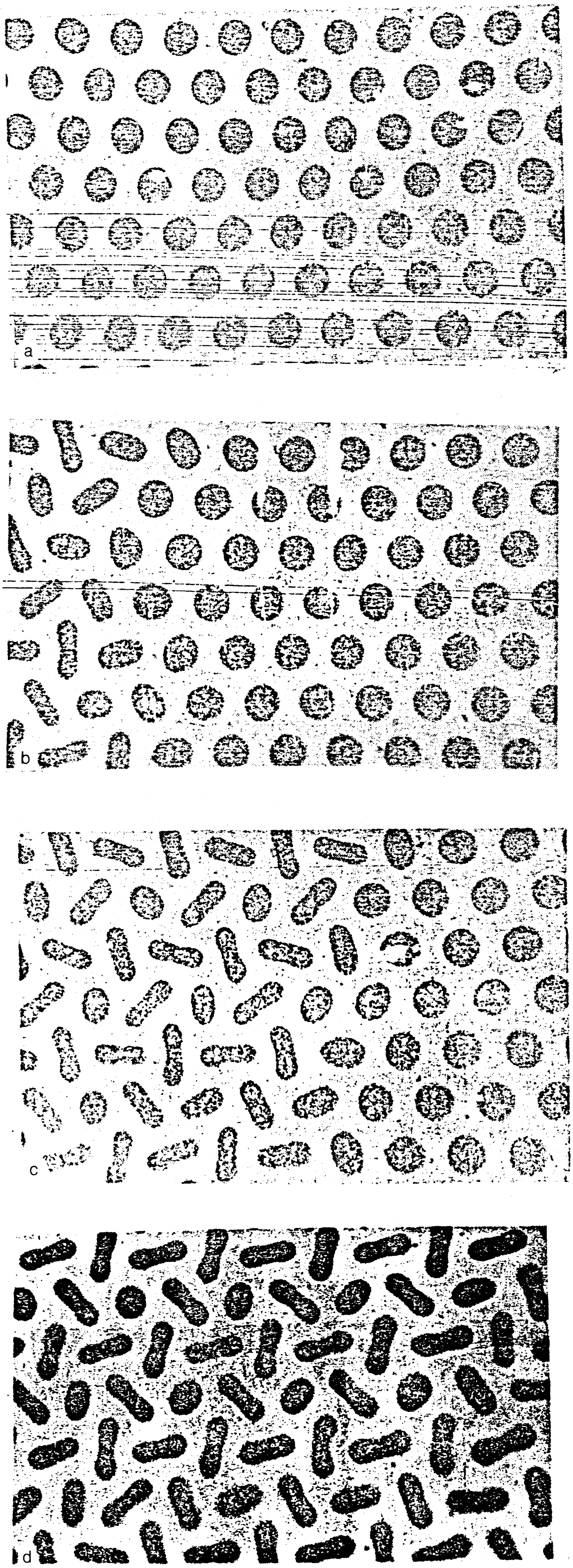

FIG. 11. Transformation of a hexagonal lattice of circular-cylinder (a) into a structure of the type shown in Fig. 1c after the application of (b) 30, (c) 38, and (d) 45 magnetizing-field pulses.

we observe in this case are radial vibrations of the domains.

The processes which occur for the dynamic domain structures (at constant H, as the pulse height $\tilde{H}$ is reduced smoothly from the region corresponding to stablility of a hexagonal lattice of circular cylindrical domains) constitute a chain of structural phase transitions in a system of two-dimensional crystals: [$6mm$ hexagonal crystal $(a = b = d)$] $\rightarrow$ [$mm2$ orthorhombic crystal $(a = d, b = d\sqrt{3})$] $\rightarrow$ [$6mm$ hexagonal crystal $(a = b = 2d)$]. For the "frozen" structures, these processes correspond to the chain of transitions [$6mm$ hexagonal crystal] $\rightarrow$ [mm2 orthorhombic crystal $(a = d, b = d\sqrt{3})$] $\rightarrow$ [6 hexagonal crystal $(a = b = 2d)$].

4. DISCUSSION OF RESULTS

We can conclude that a self-organization of the distribution of the magnetization vector can occur in uniaxial magnetic films with a strong perpendicular anisotroy under certain conditions. This self-organization is accompanied by the formation of domain structures whose symmetry is described by the two-dimensional space groups *P6mm*, *P6*, *Cmm2*, and *Pab2*. Can domain structures with a different spatial symmetry arise under the same (or similar) experimental conditions? A partial answer to this question can be found by analyzing the photographs in Figs. 1–3. We see that in some cases the angles between the lines connecting the centers of neighboring domains differ from $\pi n/3$, where n is an integer. Such distortions of the Bravais lattices can be made regular by applying a static magnetic field $\mathbf{H}_\perp$ of low strength ($\leqslant 100$ Oe) in the plane of the large surface of the film, along a direction which does not lie in the symmetry planes of the original Bravais lattice. Since the original domain structures and the external agent have no common symmetry elements, the Bravais unit cells become oblique-angle cells in both cases (with $a \approx b \approx 2\tilde{d}$, $\gamma = 2\pi/3 + \varepsilon$ and $a \approx b \approx \tilde{d}$, $\gamma = 2\pi/3 + \varepsilon$ for the structures in Fig. 1, a and b, respectively; here $a \neq b$, $0 < |\varepsilon| \ll 1$, and $\tilde{d}$ is the average on-center distance between neighboring domains). The symmetry of such domain structures is described by space group P2, under both static and dynamic conditions.[6)]

In iron garnet films in a field $\mathbf{H}_\perp$, it is a simple matter to produce an ordered stripe domain structure in the course of self-organization. After the field $\mathbf{H}_\perp$ and the pulsed field are turned off, either this structure freezes, or the profile of the domain walls acquires sinusoidal distortions. In the latter case, outgrowths can even arise at the crests of the "sine wave" (see, for example, the photographs in Fig. 6 in Ref. 37). The space groups which describe the symmetry of these distributions are *Pmm2* and *Pam2*, respectively. The Bravais cells are rectangular with $a = d$, and b arbitrary, for a regular stripe domain structure,[7] while they are $a = d$, $b = \Lambda$ for a stripe domain structure with sinusoidally distorted domain walls (or with outgrowths). Here d is the period of the domain structure, and Λ is the period of the sinusoidal distortions along the domain wall.

Before we discuss the possibility that doubly periodic domain structures with a symmetry characterized by other plane space groups would arise in the course of self-organization, we would like to point out that in any real domain structure all the shortest distances between the domain walls of any two neighboring domains must be approximately the same. In the absence of a magnetizing field, these distances must be equal to the average width of the domains, since it is in this case that the energy of the demagnetizing and fringing fields is minimized.[8)] In this regard, the domain structures differ from motifs of abstract plane geometric figures. In the latter case, the distances between these motifs in the Bravais cells can be arbitrary (Figs. 6 and 7).

Spatial distributions of the magnetization vector corresponding to the groups *P1*, *Pm*, *Pa*, and *Cm* with noncentrally symmetric elements in the motifs could probably be realized only in domain structures with helical domains. Whether such domains could become ordered in the course of a self-organization in a uniform magnetizing field looks extremely problematical. On the other hand, Kandaurova and Sviderskiĭ[18] have succeeded in producing a quasiordered one-dimensional chain of helical domains in a static, nonuniform (quadrupole) magnetic field which was produced.

It would appear to be extremely difficult to produce domain analogs of the abstract motifs for the space groups *P3*, *P3m1*, and *P31m*, with an equilateral-triangle Bravais cell, because the shortest distance between the domain walls of any two (unipolar) neighboring domains must be held constant (as discussed above). Doubly periodic domain structures with square Bravais lattices, on the other hand, may in principle be realized—under dynamic self-organization conditions close to those in our own experiments. If we choose a cluster of two circular and two elliptical domains as the motif-forming element, and if we place the former at a corner and the center of the square and the latter (with major axes making angles of $+\pi/4$ and $-\pi/4$ with the horizontal direction) at the centers of the sides of the square closest to the corner selected, then translations of such a cluster would lead to a motif with a symmetry described by group *P4*. Under dynamic conditions, which a periodic reorientation of the major axes of the elliptical domains through $\pi/2$, the symmetry of such a domain structure would arise to *P4mm* (Fig. 12). However, domain structures with a square Bravais lattice would face strong competition from structures with a hexagonal (equilateral-triangle) lattice. As a result, structures with a square lattice could apparently be

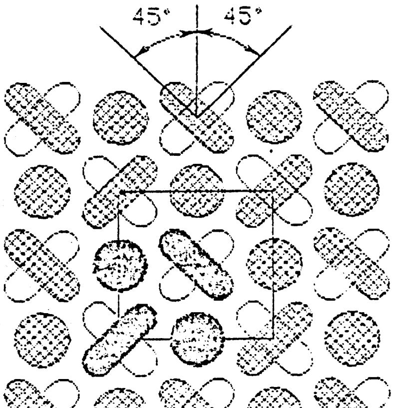

FIG. 12. Schematic diagram of a possible domain structure with a square Bravais unit cell.

produced only if additional stabilizing factors are present [e.g., a magnetocrystalline anistropy, obtained through the use of films whose normal is oriented along a fourfold crystallographic symmetry axis, i.e., a (001) axis].

We would like to call attention to one nontrivial aspect of the self-organization processes which we have observed. Upon a bifurcation corresponding to a transition from a hexagonal lattice of circular cylindrical domains to structures of the type in Fig. 1, c or d, which can exist in two modifications, "right-handed" and "left-handed" (cf. Fig. 1 e and f), there is a spontaneous symmetry breaking. Ordinarily, a symmetry breaking of this sort is irreversible: When the system is in one of the two possible states, it cannot undergo a transition to the dual state. In our case, each magnetic-field pulse sends the system from one modification to the other, thereby making the bifurcation process reversible.

In an earlier paper[20] on the dynamic formation of helical domains, it was pointed out that a self-organization accompanied by the formation of these metastable (reflexive) domain structures occurs during shock (pulsed) excitation only if the amount of energy pumped into the system per pulse lies in a certain interval. The lower boundary of this interval corresponds to the threshold for the occurrence of self-organization, and the upper boundary to a transition to a chaotic (turbulent) behavior. This situation can also be seen clearly in the experiments which we are describing in the present paper (Sec. 1), with one important distinction. In the stage in which structures of the type in Fig. 1 form from a hexagonal lattice of circular-cylinder domains, the energy of each magnetizing-field pulse is expended both on moving the phase front between regions in the original and new states and on reorienting the elliptical domains in the new phase, i.e., on energy transitions between states differing in chirality (Figs. 1 and 11). After the phase transition has been completed, the first mechanism for energy conversion drops out of the picture, so the optimum conditions for the stage of the formation of the dynamic structures in Fig. 1, a and b, and those for the stage in which these structures are held stable should in general be different. This difference can be seen fairly clearly in our experiments. For the same reason, the region of stable formation of domain structures of the types in Fig. 1, a and b, in the space of the parameters of the magnetic-field pulses is always far narrower than the region in which such structures exist stably.

A self-organization of domain structures analogous to those described in this paper has also been observed in (111)-orientation films of other compositions, e.g., $(LuBi)_3(FeGa)_5O_{12}$ and $(TmBi)_3(FeGa)_5O_{12}$. These films have had a large value of β_u, a low defect concentration, and highly uniform parameters in the large plane. The latter condition is particularly necessary for the existence of domain structures of the type in Fig. 1a. The structure in Fig. 1b is more "tolerant" of inhomogeneities of the film in the large plane and also (up to a certain point) of defects. The orthorhombic component of the magnetic anisotropy is a negative factor for self-organization (accompanied by the formation of structures of the type in Fig. 1). It is for this reason that self-organization did not occur in films with the (110), (112), and (210) orientations.

The mechanism for the formation of the ordered domain structures which we observed is not yet clear. As we mentioned back in Sec. 2, the unusual reaction of the elliptical domains to an external agent in the form of a train of magnetizing-field pulses and also other aspects of the behavior of the moving domain walls in these films indicate that an approach starting with the assumption that some number of "through" vertical Bloch lines arise in a domain wall apparently does not work in our case (that approach is the one which has customarily been taken to explain various anomalies in the dynamic behavior of cylindrical magnetic domains; Refs. 5 and 6, for example). These arguments do not, however, rule out the possibility that clusters of nested Bloch half-loops form in the domain walls of elliptical domains as they are compressed (or stretched).[9)] Such clusters would not alter the topological index of the wall and would not give rise to gyrotropic forces which would tend to rotate the elliptical domains.

The effect of magnetostriction on the processes observed in these experiments is probably negligible. The example of the elliptical vibrations of a drop of incompressible liquid which we discussed in Sec. 2 is simply a mechanical analog. Nevertheless, there are cases in which a magnetoelastic coupling can be the primary reason for the occurrence of self-organization, e.g., in magnetic materials with an easy-plane anisotropy.[39]

[1)]The extended initial domains on the photographs taken by high-speed photography range in shape from ellipses (or ovals) to dumbbells with various constriction depths. Additional studies showed that the elliptical shape is the equilibrium shape, but the time scale of the relaxation of the dumbbell-shaped domains to elliptical shapes may be either fairly short (milliseconds) or fairly long (seconds). Longer relaxation times are observed for the domain structures in Fig. 1, c and e.

[2)]The probability for annihilation of vertical Bloch lines in films with a high quality factor may be fairly high.

[3)]Elliptical vibrations of a drop of an incompressible liquid in a state of weightlessness constitute acoustic analogs of such a mode.

[4)]Another system of symbols is sometimes used for two-dimensional space groups. In this other system, the type of Bravais lattice is given by a lower-case letter *p* or *c*, the grazing-reflection plane is specified by a lower-case *g*, and "redundant" information on the symmetry axes of planes is omitted.[30,32]

[5)]It follows from Fig. 10 that the appearance of a "seed' for the transition from a lattice of elliptical domains (of the type in Fig. 1b) to a mixed domain structure (of the type in Fig. 1a) is accompanied by the transformation of one of these domains into a circular domain and by a change of $\pi/6$ in the orientation of the four nearest elliptical domains (the orientation of the two closest domains does not change).

[6)]The hexagonal lattice of circular cylindrical domains which is nucleated in the course of orientational phase transitions from a uniform state to a magnetically nonuniform state in a field $\mathbf{H}_\perp$ also has a slightly distorted Bravais lattice.[35,36] In other words, it is characterized by space group P2.

[7)]Strictly speaking, the symmetry of a regular stripe domain structure with parallel boundaries is described by the one-dimensionally periodic group G_1^3, the "border" group.[38]

[8)]In other words, the domain structures "abhor a vacuum," although a vacuum is completely acceptable in (for example) the lattices of single crystals.

[9)]Somewhat loosely speaking, each such half-loop might be thought of as a combination of two "nonthrough" vertical Bloch lines, which are closed by a segment of a horizontal Bloch line.[5]

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