Formation of reflexive domain structure by monopolar and cyclic magnetization of uniaxial magnetic films

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Results are reported of an experimental study of the formation, in uniaxial iron garnet films, of reflexive domain structures with singular magnetic defects such as spiral and concentric annular domains in an object acted upon by a harmonic or unipolar pulsed magnetic field. Possible types of magnetic stripe-domain structure defects are classified on the basis of the Burgers and Frank vectors. A theory describing the static properties of spiral and concentric ring domains is developed.

Inhomogeneous magnetic states characterized by partial or total absence of order of the domain-wall (DW) arrangement [quasiordered or disordered domain structures (DS)] are presently attracting great interest in addition to ideally ordered domain structures such as magnetic bubble domains (MBD) or stripe domains with parallel domain walls (DW). In uniaxial films with easy magnetization axes (EMA) along the normal **n** to the surface, such a randomization is caused by an anisotropy that excludes the existence of a preferred direction in the basal plane, and also by entropy effects.[1,2] A well-known example of total "orientational" chaos is the so-called maze DW in iron-garnet films.

A change from a regular stripe DW to chaos can be effected by introducing randomly[1)] into the initial structure magnetic defects constituting in general combinations of magnetic dislocation and disclinations. Such a process takes place, for example, when a DW is generated by a second-order or by a nearly second-order phase transition.[2] We shall show in the present paper that multiple magnetic defects of a definite type in a stripe DW can be generated also by unipolar (pulsed) or cyclic (say, harmonic) magnetization of uniaxial magnetic film, provided the magnetization procedure is repeated enough times.

INTRODUCTION

An isolated magnetic defect moving along a closed contour $\mathscr{L}$ in a stripe DW produces a circulation $\oint_{\mathscr{L}} \nabla_k \mathbf{u} dx_k$, [$x_k$ are the Cartesian coordinates and the vector **u** describes the displacement of a point with a specified direction of the magnetization vector **M** from its position in a regular DW with period d]. This circulation is equal to $\mathbf{B} + 2\pi[\mathbf{\Omega},\mathbf{r}_\perp]$, where $2\pi\mathbf{\Omega}$ is the Frank vector parallel (or antiparallel) to the normal **n** to the film surface, **r** is the distance to the defect axis, **B** is the Burgers vector parallel to the film surface ($|\mathbf{B}| = Nd$), and N and 2Ω are non-negative integers. Magnetic dislocations have values $\Omega = 0$ and $N \neq 0$; magnetic disclinations have $\Omega \neq 0$ and $N = 0$ [for $\Omega = 1$ and $N = 0$ we have a system of concentric ring domains (CRD)]; N-arm spiral domains (SD) have $\Omega = 1$ and $N \neq 0$ (the helicity is determined by the direction of $[\mathbf{B}\times\mathbf{\Omega}]$); magnetic defects can generate also more complicated DS. Investigations of stripe DS with magnetic dislocations are reported in Ref. 3.

Rather unexpected results were obtained recently in investigations of the behavior of DS of uniaxial magnetic films in pulsed or low-frequency ($f \lesssim 1$ MHz) harmonic magnetic fields $\widetilde{H}$ parallel to the EMA and of intensity close to that of the field H_s that annihilates the DS in a quasistatically magnetized sample.[4–14] It was found that similar nonstationary actions produce in an initially maze DS a dynamic selection of the CRD and SD,[2)] i.e., of magnetic defects with $\Omega = 1$ and $N = 0, 1, 2,\ldots$.

This was first reported in Refs. 4–6, where formation of CRD ($f = 120$ to 200 GHz) and SD ($f = 200$ Hz to 6 kHz) was observed in an alternating meander-type magnetic field in a $(YSm)_3(FeGa)_5O_{12}$ iron-garnet film and in an amplitude range $\widetilde{H} \approx (0.75–0.9)H_s$. SD of either chirality was observed. No SD or CRD was observed in this sample when the meander was replaced by a harmonic signal. In another film with composition $(TmBi)_3(FeGa)_5O_{12}$ the situation was reversed: SD were generated only by a harmonic magnetic field at frequencies from 120 Hz to 30 kHz at $\widetilde{H} \approx (0.6–0.7)H_s$ (Refs. 5–9). No CRD formation was observed. At the low-frequency end of the employed frequency range, the SD had small numbers of turns and large cores; at higher frequency the number of turns tended to increase and the core tended to decrease. The SD acquired a sectorial close-packing structure.

The helicity of the produced SD was arbitrary, but when a magnetizing field H_0 was applied one of the helicities became dominant, and the reversal of the sign of the field H_0 reversed the direction of the helices.[5–9] It was noted[4,9] that the a magnetizing field of the same direction can produce opposite predominant helicities in different samples. The lifetimes of the SD and the CRD ranged from 1 to 10 s, i.e., exceeded by several orders the period of variation of the magnetic field. In addition of the simple helices we observed also two-arm SD; a static magnetic field applied parallel to a the developed film surface suppressed the formation of dynamic SD and CRD.[9]

In Refs. 4–9 the described effect was interpreted as self-organization in a system of randomly moving DW, leading to formation of dynamic SD and CRD which are analogs of dissipative structures in the distributed active media. The quasiperiodic creation and annihilation of SD, the propagation of wavelike perturbations inside the helices, the translational displacements of random SD, and the rotation of helices with few turns in a direction opposite to the turning direction were all included by the authors in a common class of self-sustaining wave processes[3)] in nonlinear media (see, e.g., Ref. 15). Such a treatment, however, is not quite accurate for the following reasons.

The stability of dissipative structures and self-sustaining waves is ensured by constant influx of energy from the outside; they should vanish when the energy input is stopped. However, as shown above, spiral and annular concentric domains are statistically stable (albeit also metastable) configurations, namely—magnetic defects with Frank number $\Omega = 1$ and Burgers-vector modulus equal to Nd ($N = 0, 1, \cdots$), which do not vanish after the alternating magnetic field is turned off. These structures, in accord with the terminology of Ref. 16, must be regarded as reflexive. Being in a state between thermodynamic equilibrium and dissipation, such states can be formed by pumping energy into the system as in dissipative structures, but differ from the latter in that they are (fully or partially) preserved after the external action is turned off. Reflexive DS, naturally, are metastable and can (at temperatures different from absolute zero) relax to thermodynamic equilibrium, but the characteristic of relaxation times are usually quite long.

Note that in magnetic films the transition from the dynamic regime of formation of reflexive spiral DS to the truly self-sustaining-wave regime [with coherent excitations such as leading center, reverberator (spiral waves[4]) and others] can apparently be achieved by increasing the amplitude of the alternating magnetic field H above the DS suppression field H_s, as demonstrated by the experiments described in Refs. 8 and 10.

One more argument against the self-sustaining character of the SD formed by an alternating magnetic field at $\tilde{H} < H_s$ is the result of experiments on the production of SD by a sequence of monopolar short ($\tau_p \approx 1$–$10\,\mu$s) magnetic-field pulses.[11–14] It turns out that SD are produced[5)] at any pulse-repetition period T_p that satisfies the condition $T_p \gtrsim 2\tau_p$ (including repeated manual startup of the pulse generator); formation of the largest possible SD in a given sample calls for a definite number of pulses (usually from 10^2 to 10^3). Although dissipative structures can exist also when energy is pumped into the medium, they are limited by a critical pulse-repetition period $T_p^{(cr)}$; no self-sustained waves can be produced[19] at $T_p > T_p^{(cr)}$.[19]

Under definite (unfortunately not yet clear) circumstances SD can be formed in high-Q films from an isolated MBD[20] or from a saturated state[20,21] when the magnetizing-field intensity is quasistatically decreased; this also refutes the self-sustaining-wave hypothesis for SD and CRD in the presence of an alternating magnetic field.

To complete the brief survey of the presently available methods of producing magnetic defects such as SD and MBD, we mention reports[22,23] of generation of a system of annular domains by a strong local microwave magnetic field in the presence of a magnetization field close to the MBD collapse field (see also Ref. 24).

THEORY

1.1. General premises

The magnetization distribution in reflexive DS far from singularities can be described by an approach based on the WKB method, introducing a local transverse wave vector $\mathbf{k}_\perp(\mathbf{r}_\perp) \equiv \mathbf{k}(\mathbf{r}_\perp) = \nabla\Phi(\mathbf{r}_\perp)$ (Φ is the "phase" variable) that varies slowly over distances $\sim 2\pi/k = d$. We shall illustrate this below using as an example the "critical" stripe DS present in auniaxial ferromagnetic films near the Curie temperature, when the spatial dependence of the magnetic moment is described by rather simple analytic expressions.[1–3,25,26]

The free energy of the film in the vicinity of a spontaneous PT near the Curie point can be written in the form

$$F = M_0^2 \int dv \{ {}^1/_2\alpha(\nabla_i m_k)^2 - {}^1/_2\xi m^2 + {}^1/_2\beta_u m_\perp^2 + 1/4\delta m^4 - \mathbf{hm} - {}^1/_2\mathbf{h}_D\mathbf{m} \}. \qquad (1)$$

Here $\mathbf{m} = \mathbf{M}/M_0 = \mathbf{m}_\perp + m_z\mathbf{e}_z$, $\mathbf{h} = h_z\mathbf{e}_z/M_0$, and $\mathbf{h}_D = \mathbf{H}_D/M_0$ are the normalized magnetization, external magnetic field, and magnetostatic field respectively (the z axis is assumed to be along the normal $\mathbf{n}$ to the film surface, parallel to the EMA), δ and α are the homogeneous and inhomogeneous exchange constants, $\xi = \delta\tilde{M}^2(T)/M_0^2$, $\tilde{M}(T)$ is the equilibrium value of the magnetization at the temperature T in an unbounded medium, β_u is the uniaxial-anisotropy constant, and $M_0 = \tilde{M}(T=0)$.

The behavior of the magnetization vector in the critical DS is described by the equation of motion

$$\gamma\dot{\mathbf{M}} = -\frac{\delta F}{\delta \mathbf{M}}, \qquad (2)$$

where γ is a kinetic coefficient, and by the magnetostatics equations with boundary conditions on the film surfaces ($z = \pm l_z/2$):

$$\nabla_z\mathbf{M} = 0, \quad H_{Dz}^{(i)} + 4\pi M_z = H_{Dz}^{(e)}, \quad \mathbf{H}_{D_\perp}^{(i)} = \mathbf{H}_{D_\perp}^{(e)}, \qquad (3)$$

where $\mathbf{H}_D{}^{(i)}$ and $\mathbf{H}_D{}^{(e)}$ are the demagnetizing and scattering fields.

We confine ourselves to thick $l_z \gg \alpha^{1/2}$) films with large uniaxial anisotropy ($\beta_u \gg 4\pi$, δh^2) in a narrow temperature interval near the Curie point T_0 of an infinite sample, in which the following relations are satisfied:

$$|\mathbf{m}_\perp| \ll |m_z| \ll 1, \quad \xi = \xi'(T_0 - T), \qquad (4)$$

where

$$\xi' = \left.\frac{\partial\xi}{\partial T}\right|_{T=T_0}.$$

In this case Eqs. (2) and (3) reduce to the following system for the homogeneous $m_0 = m_{0z}$ and in homogeneous $\tilde{m}_z$ components of the magnetization m_z:

$$h_z = (4\pi + \delta m_0^2 - \xi) m_0, \qquad (5)$$

$$\mu_\perp \nabla_\perp^2 [\alpha\nabla_\perp^2 \tilde{m}_z + \xi\tilde{m}_z - \delta\tilde{m}_z^3 - \gamma\dot{\tilde{m}}_z] - 4\pi\nabla_z^2\tilde{m}_z = 0, \qquad (6)$$

where

$$\mu_\perp = 1 + 4\pi\beta_u^{-1}.$$

The solution of Eq. (6) for a regular striped DS with fixed value of the wave vector $\mathbf{k}$ is

$$m_z(\mathbf{r}) = m_{0z} + (m_z(\mathbf{r}_\perp) + m_z^*(\mathbf{r}_\perp))\cos\left(\frac{\pi z}{l_z}\right)$$

$$= A_0 + (Ae^{i\Phi} + A^* e^{-i\Phi})\cos\left(\frac{\pi z}{l_z}\right), \qquad (7a)$$

where

$$A_0 \approx m_0, \quad |A|^2 = (4/9\delta)\,[\tilde{\xi} - \xi_c - \alpha k^{-2}(k^2 - k_c^2)^2] \geqslant 0, \quad \Phi = (\mathbf{kr}_\perp),$$

$$\tilde{\xi} = \xi - 3\delta m_0^2, \quad k_c = (4\pi^3/\mu_\perp \alpha l_z^2)^{1/4}, \quad \xi_c = 2\alpha k_c^2. \qquad (7b)$$

1.2. Magnetic defects of the type of concentric ring and spiral domains

The solution of Eq. (6) for an N-arm spiral domain in the vicinity of a spontaneous PT line is best sought in terms of cylindrical coordinates $(r_\perp,\Phi)$, i.e.,

$$m_z(r_\perp,\ \Phi)$$
$$=A_0+\{A(r_\perp)\cos(\pi z/l_z)\exp[i(N\Phi+\tilde\Phi(r_\perp))]+\text{c.c.}\},\quad (8)$$

where A and $\tilde\Phi$ are real functions and $\Phi=\tan(y/x)$; the case $N=0$ corresponds to the CRD system.

Substituting (8) in (6) we obtain the following set of equations for the functions $A(r_\perp)$ and $\Phi(r_\perp)$:

$$\alpha\Big[A_{r_\perp r_\perp r_\perp r_\perp}+\frac{2}{r_\perp}A_{r_\perp r_\perp r_\perp}-\Big(\frac{2N^2+1}{r_\perp{}^2}+6\tilde\Phi^2_{r_\perp}\Big)A_{r_\perp r_\perp}$$
$$+\Big(\frac{2N^2+1}{r_\perp{}^3}-6\tilde\Phi^2_{r_\perp}r_\perp^{-1}-12\tilde\Phi_{r_\perp}\tilde\Phi_{r_\perp r_\perp}\Big)A_{r_\perp}$$
$$+\Big(\tilde\Phi^4_{r_\perp}+\frac{2N^2+1}{r_\perp{}^2}\tilde\Phi^2_{r_\perp}-\frac{6}{r_\perp}\tilde\Phi_{r_\perp}\tilde\Phi_{r_\perp r_\perp}-4\tilde\Phi_{r_\perp}\tilde\Phi_{r_\perp r_\perp r_\perp}$$
$$-3\tilde\Phi^2_{r_\perp r_\perp}+\frac{N^4-4N^2}{r_\perp{}^4}\Big)A\Big]+\Big(\xi-\frac{9}{4}\delta A^2\Big)$$
$$\times\Big[A_{r_\perp r_\perp}+\frac{1}{r_\perp}A_{r_\perp}-A\Big(\frac{N^2}{r_\perp{}^2}+\tilde\Phi^2_{r_\perp}\Big)\Big]+\alpha k_c{}^4A=0.\quad (9a)$$

$$\alpha\Big[4\tilde\Phi_{r_\perp}A_{r_\perp r_\perp r_\perp}+6\,(\tilde\Phi_{r_\perp r_\perp}+\tilde\Phi_{r_\perp}r_\perp^{-1})\,A_{r_\perp r_\perp}$$
$$+\Big(4\tilde\Phi_{r_\perp r_\perp r_\perp}-6\tilde\Phi_{r_\perp r_\perp}r_\perp^{-1}$$
$$-2\frac{2N^2+1}{r_\perp{}^2}\tilde\Phi_{r_\perp}-4\tilde\Phi^3_{r_\perp}\Big)A_{r_\perp}$$
$$+\Big(\tilde\Phi_{r_\perp r_\perp r_\perp r_\perp}+2\tilde\Phi_{r_\perp r_\perp r_\perp}r_\perp^{-1}$$
$$-\frac{2N^2+1}{r_\perp{}^2}\tilde\Phi_{r_\perp r_\perp}+\frac{2N^2+1}{r_\perp{}^3}\tilde\Phi_{r_\perp}$$
$$-2\tilde\Phi^3_{r_\perp}r_\perp^{-1}-6\tilde\Phi^2_{r_\perp}\tilde\Phi_{r_\perp r_\perp}\Big)A\Big]$$
$$+\Big(\xi-\frac{9}{4}\delta A^2\Big)\Big[\Big(\tilde\Phi_{r_\perp r_\perp}+\tilde\Phi_{r_\perp}r_\perp^{-1}\Big)A+2\tilde\Phi_{r_\perp}A_{r_\perp}\Big]=0,\quad (9b)$$

where the subscripts number the derivatives of the functions A and $\tilde\Phi$ with respect to the radius $r_\perp$.

The solution of the system (9) far from the core of the defect $(r_\perp\to\infty)$ is

$$A(r_\perp)=A[1-4\alpha/(27\delta A^2r_\perp{}^2)+O(r_\perp{}^{-3})],\quad (10a)$$
$$\tilde\Phi_{r_\perp}=k_c[1-(2N^2+1)/(4k_c{}^2r_\perp{}^2)+O(r_\perp{}^{-3})],\quad (10b)$$

where $A^2=4(\xi-2\alpha k_c^2)/(9\delta)$.

Substituting (8) and (19) in the equation of state (2), we obtain the magnetostatic potential Ψ of a ferromagnetic plate with a SD in the form

$$\Psi(r_\perp)=-\frac{4\pi^2}{l_zk_c{}^2}A\Big[1+\frac{4\alpha k_c{}^2}{27r_\perp{}^2k_c{}^2\delta A^2}+i(k_cr_\perp)^{-1}+O(r_\perp{}^{-3}\Big]$$
$$\times\exp[i(N\Phi+\tilde\Phi(r_\perp))]\sin\frac{\pi z}{l_z}+\text{c.c.}\quad (11)$$

The free energy F of a magnet with an SD can be represented with the aid of (8), (10), and (11) in the form

$$F=-{}^9/_{16}\delta A^4M_0{}^2V+E_D+\pi\alpha l_zA^2M_0{}^2\ln(R_\perp/r_{\perp0})+O(R_\perp{}^{-1}),\ (12)$$

where $r_{\perp0}$ is the dimension of the disclination core, $R_\perp$ is the transverse dimension of the film, and E_D is the energy of the disclination core. The first term in (12) is equal to the energy of a stripe DS in the absence of defects, and the third describes the energy of the long-range "elastic-stress" fields due to the presence of a magnetic disclination.

The DS generated in a spontaneous phase transition in a magnetic film that is isotropic in a developed plane is the analog of a two dimensional "liquid crystal," and one of the elastic moduli of the DS vanishes (see Refs. 1 and 2). The energy of the long-range fields of the "elastic stresses" depends logarithmically on the transverse dimension $R_\perp$ of the film (cf. Ref. 27). If the film is large enough the energy of a single spiral (magnetic disclination) is high, and therefore single magnetic disclinations are rarely formed in DS. What is formed most frequently is a system of magnetic disclinations; the system has finite energy if the sum of the Frank vectors $\Sigma_i\Omega_i$ is zero. Note that in contrast to the disclination-core energy E_D and the corrections to the free energy $O(R_\perp{}^{-1})$, which are functions of N, the energy of the long-range "elastic stresses" fields connected with the disclination does not depend on the number of arms of the spiral.

If the magnetic anisotropy β_p in the developed plane of the film differs from zero, we introduce for the investigation of the magnetic defects of the DS the displacement $u_x\equiv u(x,y)$ of a point with a given value of the magnetization from its position in the regular DS. Considering for the sake of argument a biaxial ferromagnetic film with a DS, we add to the free-energy density a term $\Delta F=\frac{1}{2}\beta_pM_x^2$, where β_p is the rhombic anisotropy constant $(0<\beta_p\ll\beta_u)$. We write for the free-energy "elastic" part connected with the DW displacement

$$F_{(el)}=\frac{1}{2}\int dx\,dy[C_x(\nabla_xu)^2+C_y(\nabla_yu)^2+k^{-2}C_3(\nabla_y{}^2u)^2],\quad (13)$$

where C_x, C_y, and C_3 are the effective elastic moduli, explicit expressions for which are given in Refs. 3 and 28. Neglecting the dispersion of the elastic moduli C_i, we obtain for the elastic displacements far from nuclei of the defects produced by a system of magnetic dislocations with Burgers vectors $\mathbf{B}_i\parallel\pm\mathbf{e}_x$ at the points $\{r_{\perp_i}{}^{(d)}\}$ and by the system of disclinations with Frank vectors $\mathbf{\Omega}_j\parallel\pm\mathbf{e}_z$ at the points $\{r_{\perp_j}{}^{(D)}\}$ the equation

$$\Big(C_x\frac{\partial^2}{\partial x^2}+C_y\frac{\partial^2}{\partial y^2}\Big)\frac{\partial u}{\partial x}$$
$$=C_y\Big[2\pi\sum_j\Omega_j\delta(\mathbf{r}_\perp-\mathbf{r}_{\perp j}^{(D)})+\sum_iB_i\frac{\partial\delta(\mathbf{r}_\perp-\mathbf{r}_{\perp i}^{(d)})}{\partial y}\Big].\ (14)$$

In the case of a single disclination at the point $\mathbf{r}_{\perp_j}^{(D)}=0$ the solution of this equation is

$$u^{(D)}=\Omega\Big\{y\,\text{arctg}\Big[\Big(\frac{C_x}{C_y}\Big)^{1/2}\frac{y}{x}\Big]-\Big(\frac{C_y}{C_x}\Big)x\ln\frac{|\tilde{\mathbf{r}}_\perp|}{R_x}\Big\},\quad (15)$$

where $|\tilde{\mathbf{r}}_\perp|=(x^2+C_xy^2/C_y)^{1/2}$, and R_x is the transverse dimension of the film along the x axis. The boundary condition $u^{(D)}(x=R_x)=0$ was used in the derivation of Eq. (15).

Substituting (15) in (13) we find that the energy of a single disclination in a stripe DS of a two-axis film is

$$E^{(D)}=\frac{2\pi^3\Omega^2}{3}(C_xC_y)^{1/2}\left(1+\frac{3}{8\pi^2}\right)\left(R_y^2+\frac{C_yR_x^2}{C_x}\right)+E_D, \quad (16)$$

i.e., in contrast to the case $\beta_p=0$, the energy of a single disclination is proportional to the surface area of the film. The energy of the disclination system is finite if the following conditions are met (cf. the case of a film that isotropic in the basal plane):

$$\sum_i \Omega_i=0, \quad \sum_i [\Omega_i \mathbf{r}_{\perp i}^{(D)}]=0. \quad (17)$$

In fact, substituting (13) and taking (14) and (17) into account we obtain

$$E^{(D)}=C_y\sum_{i\neq j}(\Omega_i\Omega_j)(x_i^{(D)}-x_j^{(D)})$$
$$\times\left\{\left(\frac{C_y}{C_x}\right)^{1/2}(x_i^{(D)}-x_j^{(D)})\ln\frac{|\tilde{\mathbf{r}}_{\perp i}^{(D)}-r_{\perp j}^{(D)}|}{d}\right.$$
$$\left.-(y_i^{(D)}-y_j^{(D)})\operatorname{arctg}\left[\left(\frac{C_x}{C_y}\right)^{1/2}\frac{y_i^{(D)}-y_j^{(D)}}{x_i^{(D)}-x_j^{(D)}}\right]\right\}+\sum_i E_{Di}. \quad (18)$$

The energy of a system of magnetic dislocation, in a stripe DS is finite if the sum of their Burgers vectors vanishes. In this case

$$E^{(d)}=(C_xC_y)^{1/2}(4\pi)^{-1}\sum_{i\neq j}B_iB_j\ln\frac{|\mathbf{r}_{\perp i}^{(d)}-\mathbf{r}_{\perp j}^{(d)}|}{d}+\sum_i E_{di}, \quad (19)$$

where E_{di} is the energy of the core of the ith dislocation. In films without anisotropy in the developed plane ($\beta_p=0$) the energy of the system of magnetic dislocations is finite for all values of the sum of the Burgers vectors.

The results of the present section can be readily generalized to include an orientational PT induced by a magnetic field $\mathbf{H}_\perp$ applied parallel to the developed surface of the film, and also a "developed" DS (far from the PT lines) by simple redesignation of the parameters and of the corresponding variables [see (3.28)].

1.3. WKB analysis of magnetization distribution in reflexive DS

We represent the inhomogeneous part of the solution of (6) for a stripe DS with smooth variation of the local transverse wave vector $\mathbf{k}(\mathbf{r}_\perp)$, i.e., at $\eta^2\equiv d/L\ll 1$ (L is the characteristic spatial scale of the variation of $\mathbf{k}$ in the sample plane) in the form

$$\tilde{m}_z(\mathbf{r},t)=\left[m_z^{(0)}(\tilde{\Phi},\tilde{x},\tilde{y},\tilde{t})\right.$$
$$\left.+\sum_n \eta^{2n}m_z^{(n)}(\tilde{\Phi},\tilde{x},\tilde{y},\tilde{t})+\text{c.c.}\right]\cos(\pi z/l_z), \quad (20)$$

where $\Phi(x,y,t)=(1/\eta^2)\tilde{\Phi}(\tilde{x},\tilde{y},\tilde{t})$ is the "fast" phase variable, $\tilde{x}=\eta^2x$, $\tilde{y}=\eta^2y$, $\tilde{t}=\eta^4t$ are the slow variables, and $\mathbf{k}(\tilde{x},\tilde{y},\tilde{t})=\mathbf{e}_x\nabla_x\Phi+\mathbf{e}_y\nabla_y\Phi=\mathbf{e}_x\nabla_{\tilde{x}}\tilde{\Phi}+\mathbf{e}_y\nabla_{\tilde{y}}\tilde{\Phi}$.

Substituting (20) in (6) and equating to zero the coefficients of like powers of η^{2n}, we obtain a set of equations for $m_z^{(n)}$. In the zeroth approximation,

$$m_z^{(0)}=Ae^{i\Phi}, \quad \Phi=(\mathbf{k},\mathbf{r}_\perp), \quad (21)$$

where the parameters A and $\mathbf{k}$, related by (7b), are no longer constants but functions of the slow variables $\tilde{x}$, $\tilde{y}$, and $\tilde{t}$.

The remaining coefficients of the asymptotic expansion (20) are calculated from the equations

$$\hat{L}_0 m_z^{(n)}=f^{(n)}, \quad (22)$$

Where $\hat{L}_0$ is the operator obtained after linearizing the nonlinear differential equation (6) with respect to Φ in the vicinity of the solution $m_z=m_z^{(0)}$, and $f^{(n)}$ is a function of the slow variations of $\mathbf{k}$ and A, with

$$\hat{L}_0 m_z^{(n)}=\left\{\mu_\perp k^2\frac{\partial^2}{\partial\Phi^2}\left[\alpha k^2\frac{\partial^2}{\partial\Phi^2}+\tilde{\xi}\right.\right.$$
$$\left.\left.-{}^9/_2\delta m_z^{(0)}m_z^{(0)*}\right]+\frac{4\pi^3}{l_z^2}\right\}m_z^{(n)}$$
$$-{}^9/_4\delta\mu_\perp k^2\frac{\partial^2}{\partial\Phi^2}((m_z^{(0)})^2m_z^{(n)*}). \quad (23)$$

It is easy to verify that the functions $f^{(n)}$ can be represented in the form $\tilde{f}^{(n)}e^{i\Phi}$. Since we are interested only in solutions of (22) which are bounded with respect to Φ and have a period 2π, exclusion of the secular terms in $f^{(n)}$ calls for satisfaction of the relation

$$\operatorname{Im}\tilde{f}^{(n)}=0, \quad (24)$$

which describes the slow variation of the phase Φ. At $A^2\gg\eta^2$ the solution of (22) with allowance for (24) can be written in the form

$$m_z^{(n)}\propto(1/A^2)\operatorname{Re}\tilde{f}^{(n)}\exp(i\Phi), \quad (25)$$

i.e., we have here a simple renormalization of the parameter A in (21), and all the terms of (20) can be represented as the renormalized parameter A multiplied by $\exp(i\Phi)$. To exclude secular terms from (22) in the limit of small A, i.e., for $A^2\sim\eta^2$ and as $\tilde{\xi}\to\xi_c$, we expand the eikonal equation (7b) in the asymptotic series

$$\tilde{\xi}-(9\delta/4)|A|^2=\sum_{n=0}^{\infty}\eta^{2n}\xi^{(2n)}, \quad (26)$$

and the derivative $\partial\tilde{\Phi}/\partial\tilde{t}$ in the series

$$\partial\tilde{\Phi}/\partial\tilde{t}=\sum_{n=0}^{\infty}\eta^{2n}\partial\tilde{\Phi}^{(2n)}/\partial\tilde{t}, \quad (27)$$

where the coefficients $\xi^{(2n)}$ are determined from the condition $\operatorname{Re}\tilde{f}^{(n)}=0$, and the coefficients $\partial\tilde{\Phi}^{(2n)}/\partial\tilde{t}$ from the condition (24). In our case $m_z^{(n)}=0$, and the renormalized value of the coefficient A is calculated from Eq. (26).

We represent the function $f^{(2)}$ in the form

$$f^{(2)}=i\mu_\perp\left[\alpha(\hat{G}_1k^2+k^2\hat{G}_1)-\hat{G}_1\xi^{(0)}-\gamma k^2\frac{\partial\tilde{\Phi}^{(0)}}{\partial\tilde{t}}\right]Ae^{i\Phi}$$
$$+\mu\xi_2^{(2)}k^2Ae^{i\Phi}, \quad (28)$$

where

$$\hat{G}_1=2\mathbf{k}\nabla+(\nabla\mathbf{k})\frac{\partial}{\partial\Phi},$$

$$\xi^{(0)}=\tilde{\xi}-(9\delta/4)|A|^2\equiv\xi_c+\alpha k^{-2}(k^2-k_c^2)^2.$$

It follows from (28) that

$$\xi^{(2)}=0, \tag{29}$$

$$\gamma k^2 A(\partial\tilde{\Phi}/\partial\tilde{t}) = \alpha(\hat{G}_1 k^2 + k^2\hat{G}_1)A - \hat{G}_1(\xi^{(0)}A). \tag{30}$$

It is more convenient to analyze DS with slowly varying DW directions by using a new coordinate frame $\nu(\tilde{x},\tilde{y}) = \tilde{\Phi}$, $\sigma(\tilde{x},\tilde{y})$, whose unit vectors have the direction cosines ($k\cos\psi$, $-l\sin\psi$) and ($k\sin\psi$, $l\cos\psi$), respectively, while the Jacobian of the transformation from (ν,σ) to $(\tilde{x},\tilde{y})$ is equal to kl. The equation $\nu(\tilde{x},\tilde{y}) = \text{const}$ defines a constant-phase curve having a curvature $[K_\nu = [-k(\partial l/\partial\nu)]/l$, while the equation $\sigma(\tilde{x},\tilde{y}) = \text{constant}$ defines trajectories perpendicular to the DW with curvature $[K_\sigma = -l(\partial k/\partial\sigma)]/k$.

Equation (30) can be written in the canonical form

$$\tau_k \frac{\partial\Phi}{\partial t} = -\nabla[\mathbf{k}P(k)] = -\frac{\partial(kP(k)/l)}{\partial\nu}, \tag{31}$$

where $\tau_k = \gamma k^2 A^2$, $P(k) = [\xi_c + \alpha k^{-2}(k^2 - k_c^2)^2$
$\tau_k = \gamma k^2 A^2$,
∂k^2. In the derivation of (28)–(31) it was assumed that $A^2 \propto \eta^2$, corrections proportional to $O(\eta^4)$ were discarded in (6), and the following relations were used:

$$\nabla_x m_z(\Phi;\tilde{x},\tilde{y},\tilde{t}) = \left(k\frac{\partial}{\partial\Phi} + \eta^2\nabla_{\tilde{x}}\right) m_z(\Phi;\tilde{x},\tilde{y},\tilde{t});$$

$$\frac{\partial}{\partial t} m_z(\Phi;\tilde{x},\tilde{y},\tilde{t}) = \left(\eta^2\Phi_{\tilde{t}}\frac{\partial}{\partial\Phi} + \eta^4\frac{\partial}{\partial\tilde{t}}\right) m_z(\Phi;\tilde{x},\tilde{y},\tilde{t}).$$

Putting $\mathbf{k} = (k_1,k_2) = (k\cos\psi, k\sin\psi)$, we write (31) in the form

$$\tau_k\partial\tilde{\Phi}/\partial\tilde{t} + (P + (k_1/k)^2\, dP/dk)\,\tilde{\Phi}_{\tilde{x}\tilde{x}} + (2k_1k_2/k^2)(dP/dk)\,\tilde{\Phi}_{\tilde{x}\tilde{y}} + (P + (k_2/k)^2\, dP/dk)\,\tilde{\Phi}_{\tilde{y}\tilde{y}} = 0. \tag{32}$$

The quantities $D_\perp = -P/\tau_k$ and $D_\parallel = -(1/\tau_k)d(kP)/dk$ determine the DW diffusion coefficients. At $k_1 = k$ and $k_2 = 0$ (or at $k_1 = 0$ and $k_2 = k$) Eq. (32) describes the dynamics of an ideal stripe DS (cf. Ref. 28).

Equation (32) can be used to determine the stability limits of a stripe DS with small DW curvature. In particular, at $P > 0$ the DW can become unstable to sinusoidal distortions of the DW shape when variation of the external parameters (Temperature T or magnetic field $\mathbf{H}_\parallel$) tends to decrease the equilibrium period of $d_s(T,\mathbf{H}_\parallel)$; collapse can occur[6] if the external parameters vary in the opposite direction. In DS with multiple defects, for example in a lattice of spiral domains of finite length, the period can also be changed by twisting or untwisting of the spirals.

The static solution of Eq. (31) is

$$kP(k)l^{-1} = F_{st}(\sigma), \tag{33}$$

where F_{st} is an arbitrary function with a gradient directed along a tangent to the DW. For DS with focus-like magnetic singularities (for example, magnetic dislocations and disclinations) at a distance $O(1)$ from the singularity center in the initial variables, the variation of the DW direction can no longer be regarded as smooth, and the value of l increases in proportion to η^{-2}, and therefore $F_{st} \approx f_{st}\eta^2$, where $f_{st} = \text{const}$. Far from the defect center we have $l \sim O(1)$ and the following relation holds

$$kP(k) = f_{st}(\sigma)l\eta^2, \tag{34}$$

so that

$$k = k_0 + O(\eta^2), \tag{35}$$

where k_0 is determined from the condition $P(k_0) = 0$, with $k_0 \sim k_c$.

2. EXPERIMENT

We investigated quasiuniaxial iron-garnet films of varying composition, grown by liquid-phase epitaxy on a $Gd_3Ga_5O_{12}$ substrates. The films were placed in a static magnetic field $\mathbf{H} = H\mathbf{e}_z$ parallel to the normal $\mathbf{n}$ to the surface; a pulsed (or harmonic) variable magnetic field in the same direction,[7] with amplitude $\tilde{H}$, was produced by a flat 10-turn coil with inside diameter 1 mm. Films with different substrate orientations were used, but analysis of the results has shown that SD and CRD are formed only in films in which there is no noticeable anisotropy in the basal plane, i.e., having orientation (111) or (100).

In the initial stage of the experiments we studied the influence of an alternating magnetic field on an ordered stripe DS. Figure 1 shows the results for one of the investigated films [film No. 1 with orientation (111), DS annihilation field H_s and saturation magnetization $4\pi M$ at room temperature is, ≈ 64 Oe and 166 G, respectively, a thickness $l_z = 3$ and a figure of merit $Q_u = \beta_u/4\pi = 12.3$]. We used an alternating magnetic field in the form of unipolar pulses (pulse duration τ_p, front duration τ_f, and cutoff time τ_c equal to 6, 1, and 1 μs, respectively, and repetition period $T_p = 1$ ms, i.e., repetition frequency 1 kHz).

In the initial state, the method described in Ref. 3 was used to produce in the film an ordered stripe DS with low magnetic-dislocation density and with a period d close to the equilibrium value (Fig. 1a). Weak magnetic fields (of amplitude not exceeding ≈ 17 Oe) did not restructure the DS. Once the first critical value $\tilde{H}_1$ was reached, magnetic dislocations began to move and sinusoidal distortions were produced on the DW profile (by the mechanism described in Refs. 29 and 30), as well as small-angle long-period distortions (Fig. 1b; $H \approx 26$ Oe). This was followed by formation of chains of small-angle distortions and by appearance of isolated seeds of magnetic disclinations in the form of lateral stubs of the stripe domains (Fig. 1c). Mass multiplication of disclinations started at the second critical value $\tilde{H} = \tilde{H}_2 \approx 28$ Oe (Fig. 1d), led to randomization of the DW orientations and continued (Figs. 1e, f) all the way to the transition into an SD generation regime at a pulsed-field amplitude $\tilde{H} > \tilde{H}_3 \approx 34$ Oe (Fig. 1g). Formation of SD is observed in the energy range $\tilde{H}_3 \lesssim \tilde{H} \lesssim \tilde{H}_4 \approx 39$ Oe. As the upper limit is approached the SD become crowded out by BMD and by fragments of stripe domains (Fig. 1h), and at $\tilde{H} \gtrsim \tilde{H}_4 \approx 39$ Oe the DS becomes completely randomized (Fig. 1i).

Thus, as the amplitude of the pulsed magnetic field is increased, we have here the following chain of transition: latticed (ideal) order (stripe DS) $\to$ continual (complete) chaos $\to$ topological chaos with partial order (spirals) $\to$ continual chaos.[8] The first phase is naturally not realized if the starting point is a maze DS.

With decrease of $\tilde{H}$ (from the region $\tilde{H} > \tilde{H}_4$) the generation of the SD started at an amplitude practically equal to $\tilde{H}_4$ (with a hysteresis not exceeding 1 Oe); at $\tilde{H} < \tilde{H}_3$ the generation of new SD ceased, but the previously produced

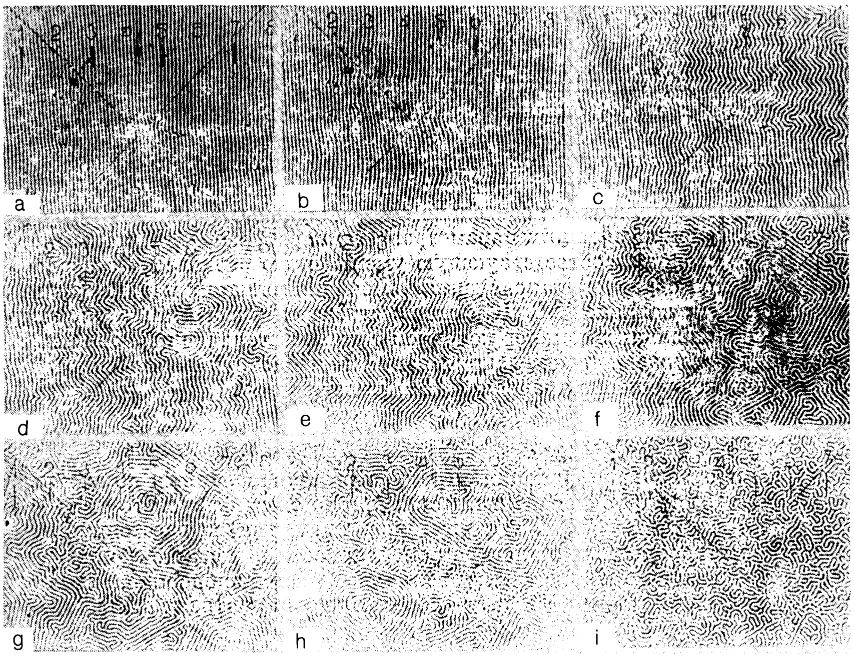

FIG. 1. Magnetic defects in ordered stripe DS of film No. 1 induced by a pulsed magnetic field H of intensity (Oe): a—17, b—26, c—28, d—30, e—31, f—33, g—34, h—39, i—41.

spirals "froze" and were preserved down to $\tilde{H} = 0$. The freezing of the spirals at low density of the latter was usually accompanied by the onset of sinusoidal distortions of the DW profile, and even by formation of lateral stubs (see the photographs on Fig. 1). This is evidence that the average period of the dynamic SD exceeds the period of the thermodynamic-equilibrium DS (other conditions being equal) (see Ref. 28).

SD generation exists in a narrow ($\sim 10\ \mu$s) range of pulse durations $\tau_{p1} \leqslant \tau_p \leqslant \tau_{p2}$ which depends quite strongly on the front duration τ_f and cutoff time τ_c, but is practically independent of the repetition period T_p (if $T_p \gtrsim 2\tau_{p1}$). The shortest permissible magnetic-field pulse duration τ_{p1} is determined apparently by the inertial properties of the DS and the defects (by the characteristic relaxation time). As $\tau_p \to \tau_{p2}$ the pulse-amplitude interval in which SD exists is shortened; with decrease of the front slope and cutoff the allowed range of τ_p variation can be approximately doubled.

The influence of the parameters τ_p, τ_f, and τ_c on the $\tilde{H}$ interval in which SD is formed are illustrated for film No. 1 at $T_p = 1$ ms in Figs. 2, 3, and 4, respectively. The fact that the pulse amplitude needed for SD formation increases with decrease of the front and (or) cutoff slope (see Figs. 2–4) agrees with the assumption that generation of SD in a system calls for a definite energy input during each period.

A steep front and (or) steep cutoff, as well as a long magnetic-field pulse duration, are factors favoring the transformation of the stripe domains into MBD; this transformation interferes with the SD formation, especially when the pulse amplitude is lowered from the region $H > H_4$. Note that no spiral domains are formed from an ordered (or amorphous) MBD lattice. SD and MBD are apparently pro-

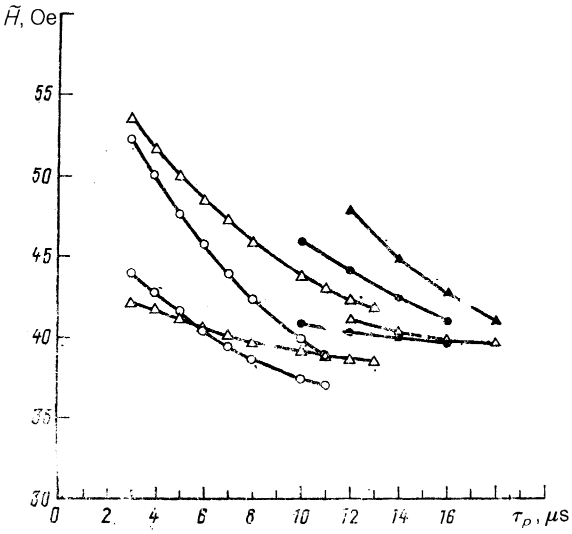

FIG. 2. Effect of magnetic-field pulse duration on the interval of SD formation in film No. 1 at $\tau_f = \tau_c = 3\ \mu$sec (○); 1.5 μsec (Δ), 5 μsec (●), and 6 μsec (▲).

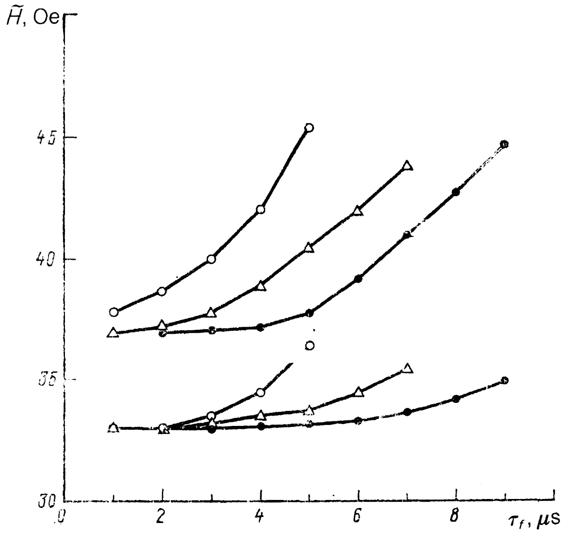

FIG. 3. Effect of magnetic-field pulse-front duration on the interval of SD formation in film No. 1 at $\tau_c = 1\ \mu$sec and $\tau_p = 6\ \mu$sec (○), 8 μsec (Δ), and 10 μsec (●).

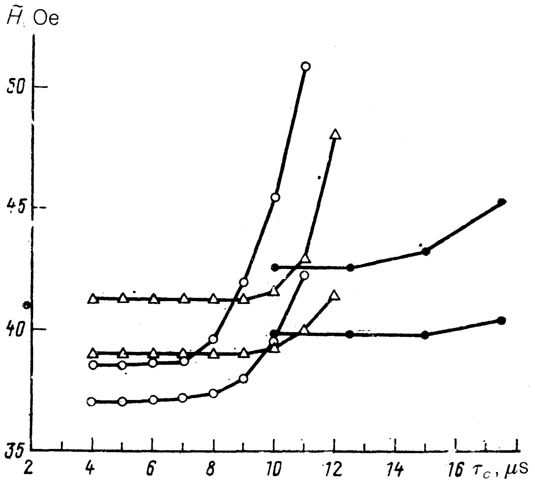

FIG. 4. Effect of magnetic-pulse cutoff duration on the interval of SD formation in Film No. 1 at $\tau_f = 1\,\mu$sec and $\tau_p = 12\,\mu$sec (○), $14\,\mu$sec (Δ), and $20\,\mu$sec (●).

duced if the density of the magnetic dislocations in the initial stripe DS does not exceed a certain critical value. Conversely, high density of seeds of magnetic disclinations with Frank vector $\mathbf{\Omega} = -(1/2)\mathbf{e}_z$, i.e., lateral stubs of stripe domains, are a factor favoring SD formation (more below). Moreover, these disclinations, which have in developed form *Y*-shaped domains, are necessary elements of DS with multiple SD separating neighboring spirals with $\mathbf{\Omega} = \mathbf{e}_z$ (see Fig. 1), as follows from conditions (17).

An important role in the formation of SD is played by lateral stubs of stripe (maze) domains produced in the initial DS during the initial stage of the action of a pulsed magnetic field. This is seen from the photographs of Fig. 5, which were obtained in the regime of manual starts of initial magnetic-field pulses and illustrate the change of the DS after application of a definite number of pulses.

The initial maze DS obtained by quasistatic demagnetization from a uniformly magnetized state contains relatively few free ends of stripe domains or lateral stubs (Fig. 5a). After application of the very first magnetic field-pulse the number of stubs increases abruptly; at the same time, the average period of the maze DS is insignificantly shortened (Fig. 5b). The succeeding pulses decrease monotonically the number of stubs, and the SD is simultaneously formed (Fig. 5, c–h). The dependence of the number N_0 of lateral stubs on the number N_p of magnetic-field pulses is shown for the two investigated films (Nos. 1 and 2)[9] in Fig. 6; the dashed lines correspond to the initial level of the stubs in both films (counted on an area $\approx 3500 d^2$ for film No. 1 and $\approx 6000 d^2$ for film 2, where d is the equilibrium period of the maze DS at $H = 0$). Evidently, a large number of pulses establishes in the DS a dynamic equilibrium in which the number of stubs remains practically constant; the maximum

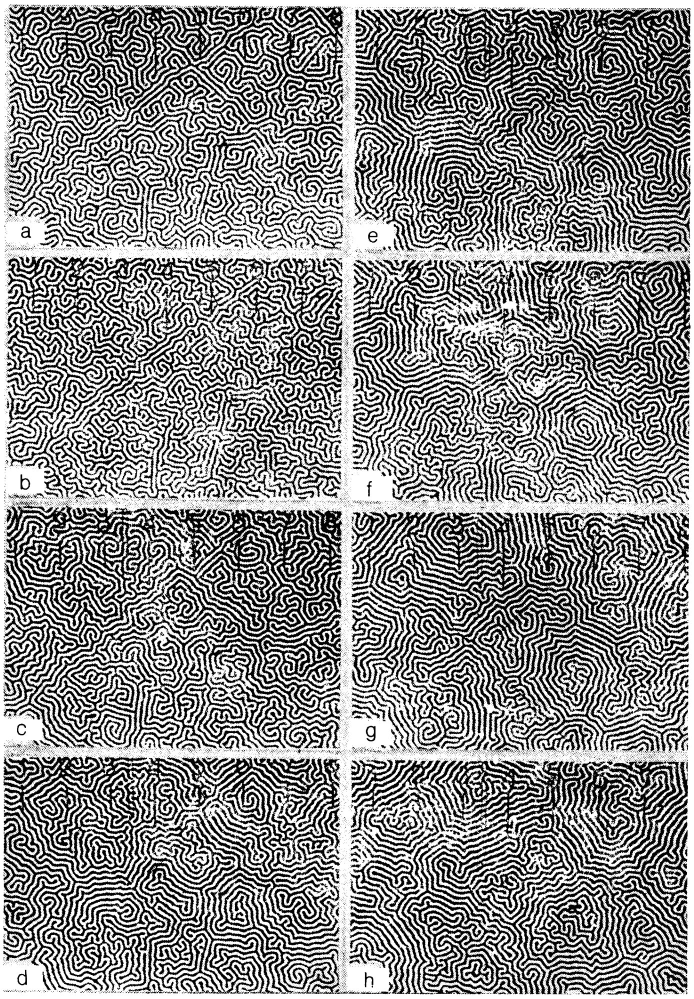

FIG. 5. Modification of form of DS film No. 2 by application of N_p magnetic-field pulses ($\tau_f = \tau_c = 0.5$ $\tau_p = 55\,\mu$sec; $H = 36$ Oe. The number N_p of pulses for photographs a–h is 0, 10, 50, 100, 200, 500, and 1000.

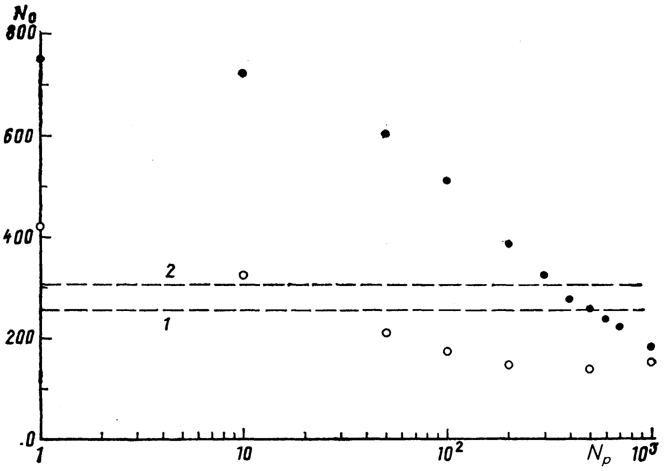

FIG. 6. Dependence of the number N_0 of lateral stubs of stripe domains on the number N_p of magnetic-field pulses for films No. 1 (○) and 2 (●).

attainable SD diameter also "freezes" in this case on a certain level that depends on the waveforms and durations of the magnetic-field pulses.

The significant role of lateral stubs in the formation of SD is due to their higher mobility compared with stripe domains. Each magnetic-field pulse draws the stubs rapidly into the walls of the stripe domains, ensuring thereby a "free" space for the twisting of the spirals.

Dynamic generation of defects of type SD and CRD was observed also in the stripe and maze DS in the films investigated by us upon application of a harmonic alternating magnetic field or of a meander field. Just as in the experiments of Refs. 5–10, the CRD were formed in a low-frequency alternating magnetic field ($f \approx 10$ Hz–1 kHz); at higher frequencies the dominant effect is SD formation, the number of spiral arms tends to increase when the frequency is raised.[10] The alternating magnetic field amplitude interval

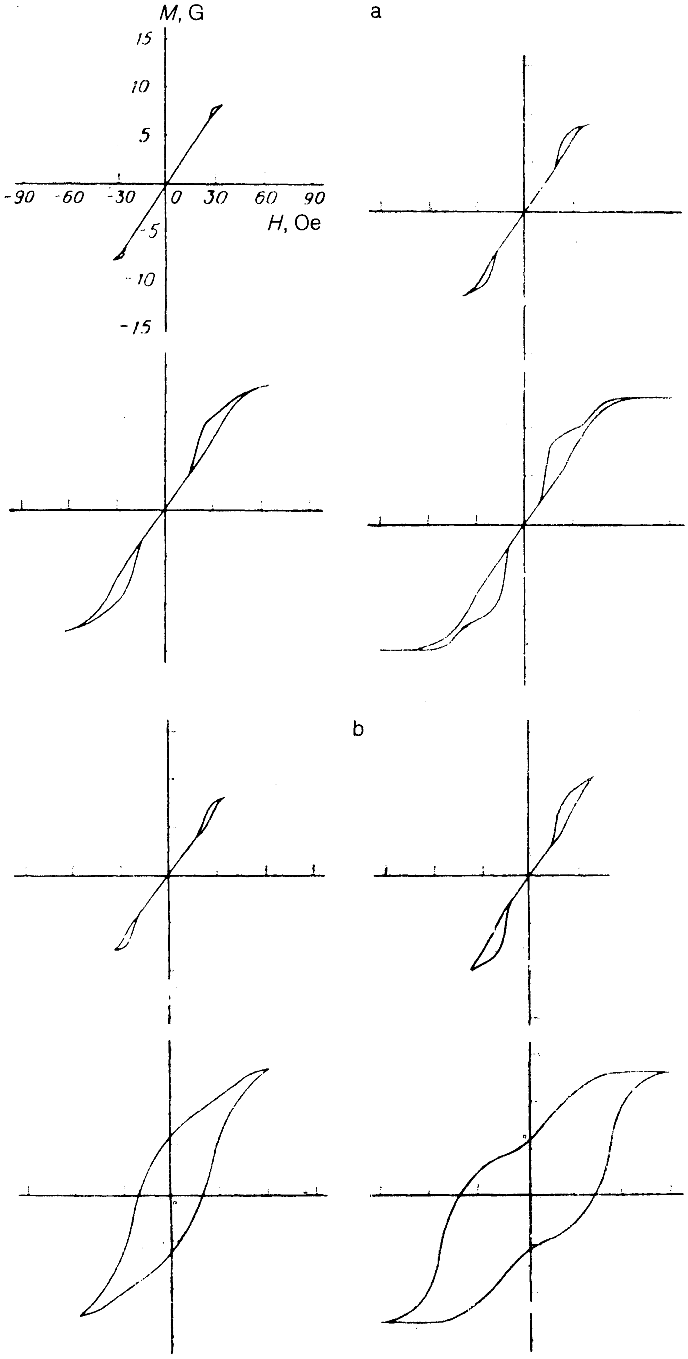

FIG. 7. Dynamic hysteresis loops of film No. 1 at different amplitudes of an harmonic magnetic field of frequency $f = 100$ Hz (a) and 10 kHz (b).

in which CRD and SD are formed becomes monotonically narrower with increase of frequency (in film No. 1, for example, from 9 Oe at $f = 10$ Hz to 3 Oe at $F = 120$ kHz). CRD were generated only in films with block structure;[11)] spirals, on the other hand, were formed in practically all the investigated films without noticeable anisotropy in the basal plane. Favoring the existing of developed (multiturn) SD are the low defect density, the small period of the DS, and the high value of Q_u.

A comparative analysis of the results of experiments on many films of varying composition and with different parameters has shown also that SD are well formed only in samples whose static remagnetization loop has (at the working temperature) a practically noncoercive linear section bordered (in fields close to saturation) with two small triangular hysteresis loops.

A similar (but not identical) form is possessed in such films also by the dynamic hysteresis loops at sufficiently low frequencies and amplitudes $\tilde{H} \leqslant H_s$. The character of the dynamic-hysteresis-loop modification [12)] with change of alternating-field amplitude is illustrated for two fixed frequencies ($f = 100$ Hz and 10 kHz) in Figs. 7a and 7b, respectively. An onset of SD is observed only for an alternating (bipolar, harmonic, meander, or pulsed) magnetic field intensity in the interval $H_n \pm \delta H_n \leqslant \tilde{H} \leqslant H_s - \delta H_s$, where H_n is the static field of DS generation in the film, $0 < \delta H_n \ll H_n$ and $0 < \delta H_s \ll H_s$. It is necessary to exceed the field H_n for bipolar action, while for monopolar pulses the situation is reversed (this is indicated by the $\pm$ sign in the left-hand side of the inequality chain for the accessible H_s interval); the actual values of δH_n and δH_s are determined by the type and parameters of the employed action—by the frequency or duration of the pulses, and also (in the latter case) by the durations of the front and of the cutoff (see, e.g., Figs. 2–4).

Analysis of the form of the dynamic hysteresis loops shows also that the second necessary condition for SD (or CRD) formation by nonstationary magnetic fields is the absence of developed "bordering" hysteresis sections (as on the lower plots of Fig. 7a), and also of a noticeable dynamic broadening of the loops on the linear section (as on the lower plots of Fig. 7b and Fig. 8). If this condition is not met, i.e., if too much energy is pumped into the system in one period (or in one pulse), only disordered motion of the DW is observed, without formation of spirals. At higher frequencies the dynamic broadening of the hysteresis loops increases,[13)] as illustrated in Fig. 8. The cause of the hysteresis-loop broadening in iron-garnet films at $\tilde{H} < H_s$ is the approach to the relaxation (limiting) oscillation frequency f_c (an explicit expression for f_c was obtained only for small DW oscillation amplitudes; see, e.g., Ref. 33) or the excess above the limiting velocity of the DW steady-state motion;[24] another cause in the case $H > H_s$ is the slower seed formation.

The close connection between the forms of the hysteresis loops and the possibility of dynamic formation of SD and CRD is confirmed also by results on the temperature dependence of the dependence of the interval of the alternating magnetic field amplitudes in which the effect is observed. The results are shown in Fig. 9 for two investigated films (No. 1 and No. 2). The figure shows also the analogous dependences of the fields H_s and H_n. It can be seen that SD generation is observed within an hysteresis region corresponding to a first-order phase transition between a uniformly magnetized state and a maze DS.

The vanishing of the effect as the Curie temperature is approached is apparently due to the increase of the ratio β_p/β_u, i.e., to the increase of the relative contribution of the rhombic component to the total magnetic-anisotropy energy, as is typical for epitaxial iron-garnet films (see, e.g., Ref. 35). In film No. 1 the increase of the ratio β_p/β_u with rise of temperature was so strong that in a second-order phase tran-

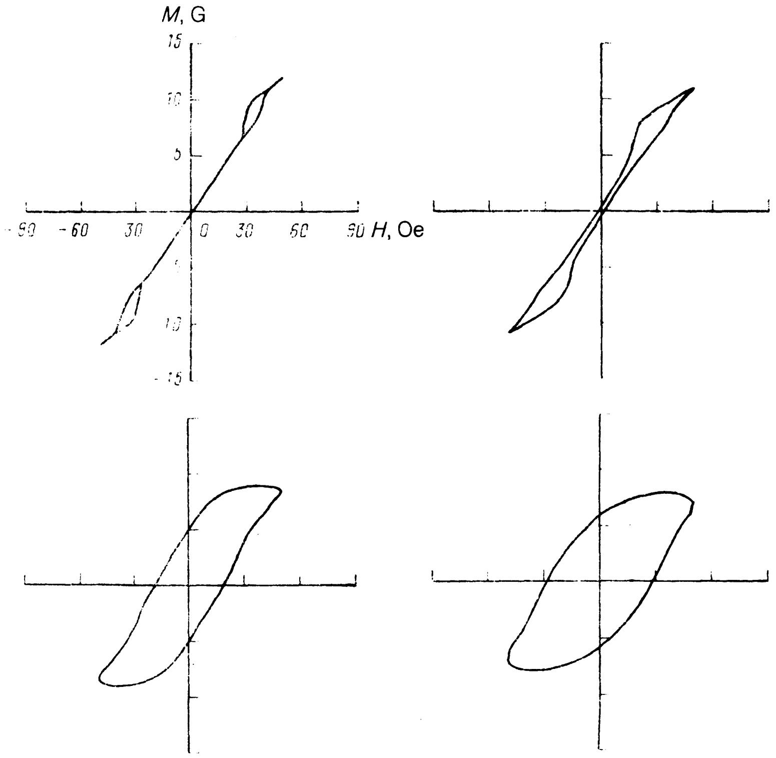

FIG. 8. Dynamic hysteresis loops of film No. 1 at various harmonic magnetic field frequencies f (100 Hz, 10 ( ), 100 (and 200 kHz) and of amplitude 50 Oe.

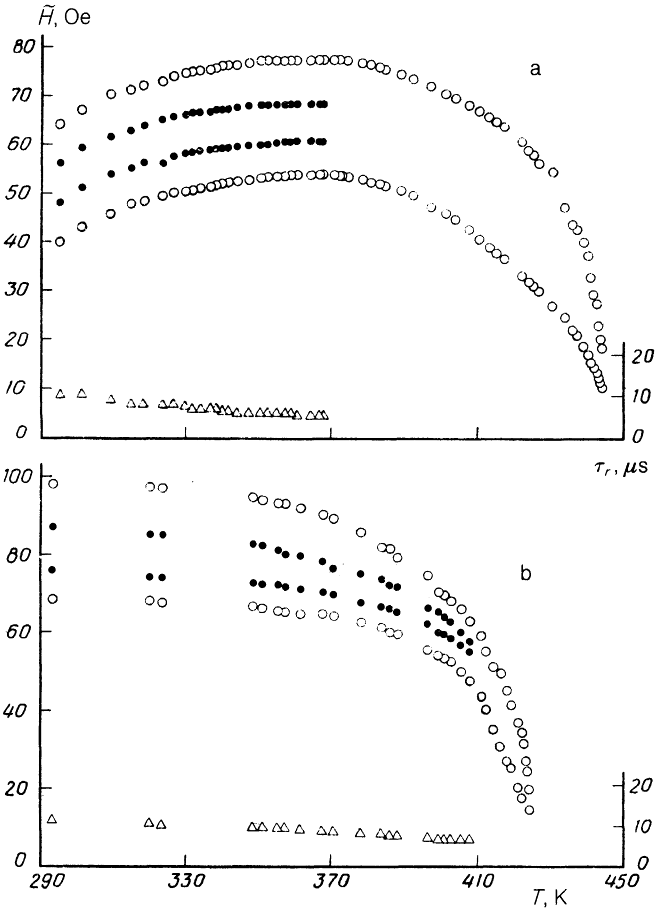

FIG. 9. Temperature dependences of the lifetimes of the SD (●), of the DS suppression fields (H_s) and nucleation fields (H_n) of the DS (○), and of the maximum possible pulse duration τ_p (Δ) in films No. 1 (a) and No. 2 (b) under action of a monopolar pulse with parameters $\tau_p = 3\,\mu$sec and $\tau_f = \tau_s = 0.5\,\mu$sec.

sition at the Curie point was generated not a maze DS, which existed in the film at $T < T_c$, but a regular stripe DS. In film No. 2 the temperature dependence of the ratio β_p/β_u was much weaker, so that SD formation was observed all the way to temperatures differing from T_c by only 25 K (cf. Figs. 9a and 9b).

Another and possibly more substantial cause of the vanishing of dynamic SD generation near the Curie temperature is that in the vicinity of T_c the first-order phase transition from the uniformly magnetized state into a nonuniform one acquires a character close to that of a second-order transition. This is accompanied by a strong narrowing of the hysteresis sections on the magnetization curve, excluding in turn the possibility of a substantial energy pumping into the system. Finally one cannot disregard the influence exerted on SD formation by a phenomenon such as thermal nucleation of Bloch points, which leads in turn to spontaneous annihilation of the Bloch lines[24] that play a substantial role in the formation of lateral stubs in stripe domains.

Figure 9 shows also the temperature dependences of the maximum allowed (from the standpoint of SD formation) pulse duration in both films (at $\tau_f = \tau_s = 0.5\,\mu$s). Evidently, when the temperature is raised it is necessary to use shorter pulses for SD formation. The reason is, apparently, that the probability of formation of defects such as magnetic dislocations, which hinder (at high density) the SD formation, increases monotonically as the Curie temperature T_c is approached (see Refs. 1 and 2). To decrease the number of magnetic dislocations produced during the time of action of a single pulse it is necessary to decrease the pulse duration as the temperature is raised.

Investigation of the static properties of SD and CRD has shown that the region of SD stability with respect to the magnetization field is approximately the same as the stability region of a maze DS; on the other hand, CRD collapse occurs in fields exceeding the MBD collapse field. Films with spiral domains are magnetized via "untwisting" the inner turns of the spirals, which remain Archimedean only at large distances from the cures; the spacing of the spirals increases monotonically as the cores are approached.

We note in conclusion that we have not touched upon here on questions, which call for further theoretical and experimental research, connected with the actual mechanism of dynamic formation (or annihilation) of various magnetic defects. An important role is played here apparently by conversions of the structures of twisted DW in the course of motion. These conversions lead under definite conditions to generation of horizontal and vertical Bloch lines (BL) (see, e.g., Ref. 24). This is attested to, in particular, by the fact that SD formation by a sequence of magnetic-field pulses is observed only if the pulse amplitude is large enough to produce multiple lateral stubs on the stripe domains (see photographs *a* and *b* in Fig. 5). The existence of such stubs offers indirect (but quite reliable) proof of the presence of vertical BL in the DW.

The appearance of a characteristic "comblike" DS after the action of a single magnetic-field pulse of sufficient amplitude was noted also in experiments on formation of an ordered hexagonal MBD lattice from a labyrinth DS.[36,37] A possible influence of generation and annihilation of BL on the ordering (or DW reorientation) of a maze DS following the action of a pulsed or alternating magnetic field with an intensity vector parallel to the developed film surface. Undoubtedly, BL in moving DW determine to a considerable degree also the magnitude and direction of the gyroscopic forces,[24] and this is manifested in the SD twisting processes.

[1] If the magnetic defects are introduced in orderly fashion there is no transition to chaos. Thus, if a periodic distribution of dislocation dipoles with linear density $(3^{1/2}/2)d^{-1}$ is produced in a striped DS with period d in each even (or odd) domain, an hexagonal MBD lattice is produced. The orientational correlation function for the position of the DW (see Ref. 2) can serve in the general case as a measure of the degree of randomization.

[2] The method of describing SD and CRD by using Burgers and Frank vectors was first used in Ref. 14.

[3] In the opinion of the authors of Ref. 9, the only difference between SD and self-induced waves is that collisions annihilate the latter and repel the former.

[4] The spiral structures of the "magnetic vortex" type produced when the magnetization of films is reversed by strong pulsed fields[17,18] are probably of different origin.

[5] The SD helicity was defined by the polarity of the magnetic-field pulses; this seems to point to the important role of gyroscopic forces in the helix-twisting process.[11]

[6] A striped DS with small DW curvature can be transformed under certain condition into an MBD lattice (see Refs. 3 and 28).

[7] Strictly speaking, this is true only for points on the coil's symmetry axis; in all other points there exist an ac magnetic-field component perpendicular to the normal **n**. Its influence, however, on the restructuring of the DS was weak, since formation of SD and CRD was observed in the entire observable film region (see, e.g., Fig. 1).

[8] One can trace here a clear analogy with the processes that occur in nematic liquid crystals under electrohydrodynamic instability;[31] in the

classification of the types of chaos we use the terminology proposed in Ref. 32.

9) Film No. 2 with composition $(TmBi)_3(FeGa)_5O_{12}$ had the following parameters: orientation -(111), $H_s = 98$ Oe, $M_0 = 12.9$ G, $l_z = 6\,\mu$m $Q_u = 8.2$.

10) Spirals with more than two arms are rarely observed in view of the high energy of the nuclei.

11) The block boundaries apparently facilitate the onset of annular seeds with oppositely directed (relative to the initial) magnetization vector.

12) The dynamic hysteresis loops were plotted by a magneto-optic method using a two-beam system, with the laser beam split by a Wollaston prism.

13) This effect is present in practically all magnets and was investigated in detail earlier (see, e.g. Ref. 33).

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