Dynamical transformations of the domain structure of a ferromagnet in alternating magnetic fields

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The variation of the period of the domain structure of a ferromagnet in alternating magnetic fields of large amplitude is investigated. The magnetic-susceptibility spectra and the amplitudes of the oscillations of the domain walls are measured, and their dependence on the variations of the number of domain walls is exhibited. The effect of constant magnetizing fields on the phenomenon is analyzed. It is assumed that the dynamical rearrangements of the domain structure are determined by the generation of nonlinear excitations at the walls under the action of the alternating fields.

The behavior of the spin system of magnetically ordered crystals in weak alternating fields, when the dynamics of the magnetic moments can be described by linear equations, is currently being studied in detail. The response of the magnetization to a harmonic external force has singularities at frequencies corresponding to intrinsic spin and magnetoelastic excitations, the spectra of which have been calculated for practically all classes of magnetic crystals and agree well with experiment.[1,2] Here the spectra of the proper excitations are found to be dependent on the presence of the domain structure in the magnet. On the one hand, the boundary conditions imposed by the presence of the domain walls lead to displacement of the spectra of the bulk spin waves in comparison with the dispersion curves for the single-domain crystal.[2] On the other hand, specific modes appear that are associated with oscillations of the magnetic moments at the walls themselves.[3] In particular, both theory and experiment display resonances in the displacement and in the flexural oscillations of the domain walls.[3,4]

In turn, the behavior of the domain structure has singularities when the frequency of the alternating field coincides with the frequency of the intrinsic modes. For example, at the frequencies of the natural FMR the domains change in size and rotate relative to the polarization of the microwave field.[5–8] At the frequencies of the domain–wall resonances the amplitude of the forced oscillations of the walls increases and flexural modes are excited.[9,4]

In the general case the dynamics of the magnetization is essentially nonlinear, and this nonlinearity manifests itself in an alternating field both in changes in the response of the magnetic moments inside the domains and in the behavior of the domain walls at large field amplitudes. In particular, spin waves are excited under the action of a microwave field parallel to the magnetization (longitudinal pumping), which is forbidden in the linear approximation,[10] and as the field amplitude increases self-oscillations of the power absorbed by the crystal arise.[11,12] The resonance frequencies of the oscillations of the walls begin to depend on the field amplitude,[13] and the form of the oscillations becomes nonharmonic,[14] while with increase of the field the forced oscillations of the walls become chaotic and the structure of the domain walls changes cyclically.[13] At the FMR frequencies in high-power fields the nonlinearity gives rise to the formations of domains; this has been observed in films of ferromagnetic garnets[7,8] and subsequently explained as a local magnetization switching induced by the high-frequency field.[15]

Recently a further nonlinear phenomenon has been detected in magnetic insulators—change of the period of the domain structure under the action of an alternating field at frequencies much lower than $f_{\rm FMR}$ (Refs. 16, 17). The possibility of changing the number of domain walls upon remagnetization of ferromagnets in an alternating field was postulated earlier (without an analysis of the reasons) by Pry and Bean[18] in order to explain the dependence of the power loss on the amplitude h_0 and frequency f of the field in metallic ferromagnets. Subsequently, the increase of the number of domains under the action of an alternating field was demonstrated by direct observation of the domain structure in Fe–Si crystals.[19–21] An analysis of the phenomenon using ideas from the theory of irreversible processes showed that the domain structure in metals are broken up by eddy currents excited by the oscillating domain walls.[20] With increase of the number N of walls the losses W_1 to eddy currents decrease, and so N tends to increase. The power $W_{\rm dw}$ expended in the creation of new domain walls hinders the increase of N. As a result, the domain-structure period that is established in the alternating field should be proportional to the amplitude of the field and to the square root of the frequency of the field, in accordance with the condition $\delta(W_1 + W_{\rm dw}) = 0$ for minimizing the entropy-production function. The experimentally obtained energy $\delta W_{\rm dw}$ necessary for the creation of one domain wall was found to be an order of magnitude greater than the surface-tension energy of the boundary, and this raises doubt as to the correctness of the calculations in Ref. 20. Nevertheless, the dependences $N(f, h_0)$ that have been observed in metals do agree qualitatively with the calculation. We note that the changes of the period of the domain structure in metals have been studied at low field frequencies, since as f increases the flexing (associated with the skin effect) of the walls through the thickness

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of the crystal becomes a determining factor in the behavior of the domain structure.[22]

It might be supposed that the phenomenon, discovered in insulators, of dynamical transformations of the domain-structure period[16,17] is determined by the same mechanism as the change of the number of domain walls in metals. Here it is necessary to take into account that, in an insulator, the dissipation of energy by oscillating domain walls is not due to Foucault currents but has a different origin.[23] Then the dissipative function, which is proportional in the first approximation to the square of the velocity of the domain walls, should, in accordance with Ref. 20, decrease as the number of walls increases ($W_1 \propto NV_{\rm dw}^2$, $V_{\rm dw} \propto 1/N$, and $W_1 \propto 1/N$), and this would determine the increase of N with f and h_0. However, it was found that the changes of the period of the domain structure in yttrium iron garnet are not described within the framework of the simple treatment of Ref. 20, but are essentially nonmonotonic functions of the frequency and amplitude of the field. Moreover, variations of N have been observed in a field perpendicular to the domain walls, which should not induce motion of the walls.[17] An analysis[5,6] of calculations of the change of the effective energy of domains and walls in an alternating field that ought to be able to predict the variation of the period of the domain structure showed that these calculations also do not describe the effect.

It has been postulated that the phenomenon is determined by the creation under the action of the alternating field, of nonlinear magnetic excitations that lead, on the one hand, to the generation of Bloch lines in the domain walls, and, on the other hand, to the formation and growth of new domains. In the present paper we report the results of further experimental study of dynamical rearrangements of the domain structure in yttrium iron garnet in a wide range of frequencies and amplitudes of the alternating magnetic field, and these results confirm the latter conjecture. The influence of magnetizing fields of different orientations on the change of the domain-structure period is investigated. Results are also given of a study of the influence of the variation of the number of walls on the magnetic-susceptibility spectra of yttrium iron garnet wafers and on the spectra of the domain-wall oscillations.

EXPERIMENTAL METHOD

We investigated $(11\bar{2})$ wafers, cut from yttrium iron garnet single crystals. The wafers were 50–100 μm thick, and contained the easy-magnetization axis $\langle 111 \rangle$ in the plane. The transverse dimension of the wafers were a few millimeters. Crystals of irregular shape were chosen, since in rectangular plates, at the frequencies f_{mn} of the intrinsic elastic resonances, a qualitative rearrangement of the domain structure occurs[24] and leads to strong changes in the number of domain walls in the vicinity of f_{mn}. The domain structure of the samples consisted mainly of domains abutting at 180°, with the magnetization vectors (and walls) lying along $\langle 111 \rangle$. The wafers were oriented with a slight inclination with respect to the light axis in a polarization microscope, and the domains in them were exhibited and analyzed by means of the Faraday effect. The alternating field was produced by solenoidal coils, which had been prepared by winding 50-μm wire onto rectangular plates whose thickness and width were twice the corresponding dimensions of the samples. The coils were supplied from an ac generator, and the field in them was determined by the current amplitude, which could be measured from the voltage across an inductionless resistor connected in series. The coils were calibrated in dc current by canceling their field with large Helmholtz coils. For the zero reading we used a long narrow sample of yttrium iron garnet, with one 180° domain wall, the presence of a field being determined from the position of this wall. Taking into account that the resonance frequencies (associated with the presence of stray capacitance) of the coils were substantially above the frequencies used in the experiment, we can assume that the dc calibration is sufficiently accurate for determination of the amplitude of the alternating field in the coils.

The changes in the number of domain walls in the wafers were determined by direct visual observation and by photography in continuous light or with pulsed-laser illumination. For observation of the domain structure in the middle of the coils a narrow gap was left in the winding. The sample was oriented relative to the field direction by selecting the angle between the image of the domain wall and the reference line (parallel to the axis of the coil) in the eyepiece of the microscope.

The magnetic-susceptibility spectra were determined by the standard induction technique using balanced secondary coils. The amplitude of the signal, in phase with the field and with a phase shift of $\pi/2$, was measured by means of selective synchrodetectors. Then, from values obtained for the susceptibility $\chi_{\rm b}$ of the body, the susceptibility $\chi_{\rm s}$ of the substance was calculated: $\chi_{\rm s} = \chi_{\rm b}/(1 - 4\pi k\chi_{\rm b})$. Here k is the demagnetizing factor, which was measured from the slope of the linear dependence of the displacement of the walls on the magnitude of the external field. In addition, by means of magneto-optical apparatus that makes it possible to determine changes in the intensity of the image of different parts of the sample, which are proportional to changes in the volumes of the domains of the different phases, the spectra of the oscillations of the domain walls were measured. Below we give experimental data obtained by means of the techniques described.

RESULTS AND DISCUSSION

The initial domain structure of the samples was a lattice of 180° domain walls. In addition, at the edges of the wafers were domains of closure of small volume, of the type considered in Ref. 25. The period of the 180° domain walls was substantially dependent on the method of obtaining the demagnetized state. In the course of the experiment we chose a method of demagnetization by a low-frequency alternating field of decreasing amplitude—a method which leads to an equilibrium static domain structure. It gives a result that can be reproduced well in the range of frequencies up to several tens of kHz. Here the period of the domain structure is found to be greater than that obtained when the sample is heated

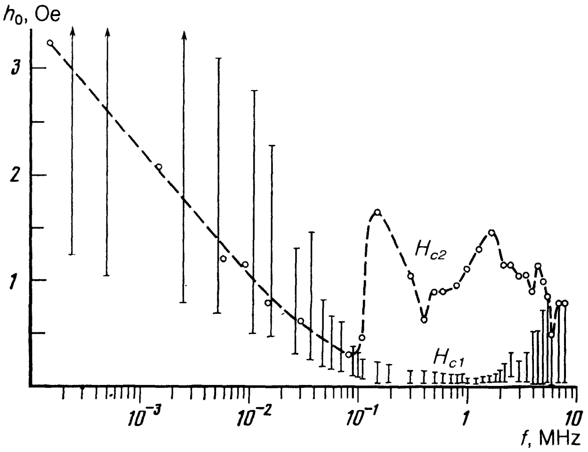

FIG. 1. Critical alternating-field amplitudes at which the nucleation of Bloch lines (H_{c1}) and new domains (H_{c2}) begins, as a function of the frequency of a field $\mathbf{h} \parallel$ EA (EA ≡ easy axis). The spread of H_{c1} corresponds to the variation of the Bloch-line-nucleation field through the crystal.

above the Curie point and then cooled.

A strong alternating field gives rise to dynamical rearrangements of the domain structure that are in accord with those discovered earlier.[16,17] The quantitative characteristics of the rearrangements are found to depend on the frequency and amplitude of the field, and on its orientation with respect to the domain walls. The structure of the domain walls is found to be most sensitive to the action of an alternating field: As the amplitude of the field increases the first changes occur in the behavior of the Bloch lines separating subdomains of opposite polarity in the domain walls.[26] In small fields, when the walls have not yet been set in motion, and also at low frequencies, when the domain walls oscillate in the field parallel to the easy axis, the Bloch lines execute oscillations, along the domain walls, about their static equilibrium positions. When the first critical amplitude H_{c1} is reached, generation and directed displacement of the Bloch lines in the walls begin, so that the image of the Bloch lines in continuous illumination is smeared out. This amplitude decreases with increasing frequency of the field, and for $f > 200$ kHz changes nonmonotonically while remaining small. The value of H_{c1} varies slightly through the crystal, this being due to the nonuniform distribution of point defects (i.e., to growth bands), which is practically always present in garnets grown from solution in the melt.[25] In Fig. 1 the spread of H_{c1} over the crystal is depicted by bar lines parallel to the ordinate axis. The quantity H_{c1} also depends on the orientation of the alternating field $\mathbf{h}$.

When the field amplitude reaches the second critical value H_{c2}, changes appear in the period of the domain structure, i.e., in the number N of domain walls in the sample. We note that here, in certain domain walls, the generation of Bloch lines may not yet have started, if the upper limit of the spread of H_{c1} lies above H_{c2}. Both H_{c1} and H_{c2} decrease at first with frequency (up to ~ 100 kHz), and then vary nonmonotonically (Fig. 1). It was established that quantity H_{c2} depends on the initial state of the domain structure. Obviously, this depends on how strongly the period of the initial domain structure differs from the period established at $h_0 > H_{c2}$. The dependence $H_{c2}(f)$ shown in Fig. 1 was obtained by increasing the amplitude of the field at each frequency for the same initial domain structure, which each time is established by demagnetization.

In fields close to H_{c2} the number of domains in the samples changes only slightly at first. However, further increase of the amplitude leads to substantial changes of N. New domains appear in the crystal suddenly on account of the growth of wedge-shaped domains with one or two edges of the lattice of 180° walls (more rarely, in the middle). The remaining domains are displaced in such a way that the period of the domain structure through the crystal is equalized and decreases. When N decreases, as a rule, the outer domains "emerge" from the crystal (and, more rarely, in the middle of the crystal). The process of the growth of new domains and the displacement of already existing walls was observed in conditions when the alternating field was applied in the wave-train regime with a sufficiently low-duty factor of the field trains. Here the change that occurs in the domain structure during a radio-frequency pulse of the field is preserved, on account of the coercivity, over the period of absence of the field. By selecting the pulse length and duty factor, we can extend the rearrangement process in time and thereby study its details. It should be noted that an alternating field in the pulse regime gives changes in the period of the structure that are quantitatively substantially different from those obtained in the continuous regime. This, evidently, is connected with the different harmonic composition of the field in these two cases, which, by virtue of the frequency dependence of the effect, should lead to the indicated differences. In this connection we note that the quantitative characteristics of the effect are also found to be different for different forms of the current in the ac coil—sinusoidal, pulsed, and sawtooth. However, the qualitative features of the phenomenon are the same.

In fields of moderate amplitude (less than H_{c2}) the domain structure in an alternating field is found to be stable (after the corresponding changes of N). A sharp, stable pattern of domains is observed, and only the image of the Bloch lines in the walls is smeared out; to given f and h_0 there corresponds a strictly determined domain-structure period.

Upon further increase of the field amplitude the domain structure becomes unstable. Domains begin to be generated continuously at one of the edges of the crystal and to be displaced along the normal to the easy axis in the direction of the opposite edge, where the outer domains "emerge" from the crystal. The velocity of this directed displacement of domains depends on the frequency and amplitude of the field. Here, in the conditions of instability, as in the case of dynamical stability of the domain structure, the number of domains that corresponds to the given frequency and amplitude of the field is preserved. This was established by photographing the domain structure under pulsed-laser illumination (with light-pulse duration ~ 20 nsec). In continuous light, on the other hand, the image of the domain structure is fully smeared out. When the alternating field is switched off, some of the domains collapse if the number of walls existing in the field is much greater than in the static equilibrium configu-

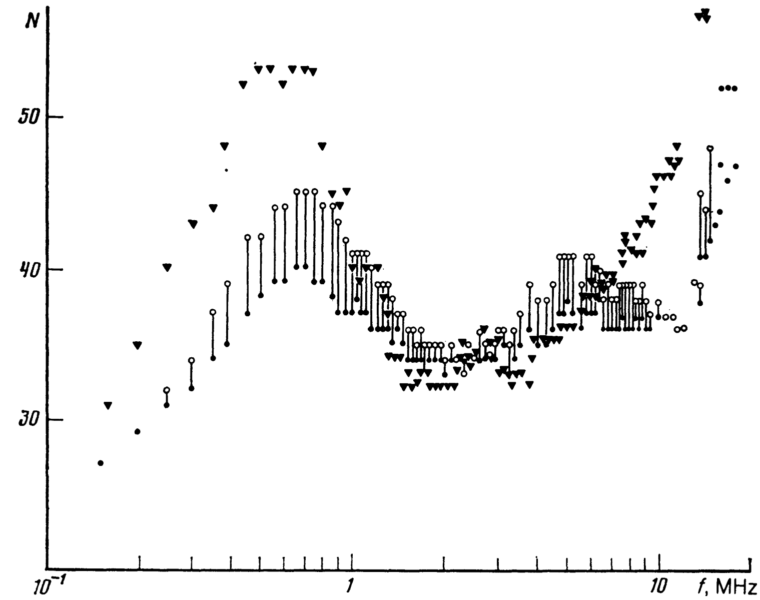

FIG. 2. Variation of the number of walls in the crystal with the frequency of an alternating field **h** ∥ EA. The field amplitude $h_0 = 2.15$ Oe: ○) points taken directly in the field, ●) points taken after the field is switched off. Field amplitude $h_0 = 3.1$ Oe: ▼) points taken in the field.

ration. Conversely, new domains appear in the crystal if the domain structure in the field has a larger period than in the static case. Nevertheless, when the field is switched off the dynamical domain structure is largely "frozen." This means that the difficult procedure of determining the number of boundaries existing during the instability by photographing the domain structure in pulsed illumination could be replaced by direct counting of N after **h** was switched off. As an illustration of the error involved in this method, the values of N obtained during the action of the field and after it was switched off are combined in Fig. 2.

In Figs. 2–5 we present typical dependences of the number of domain walls on the frequency of the alternating field (for $h_0 = \text{const}$) and on the amplitude of **h** (for $f = \text{const}$). Curves obtained in a field parallel and normal to the easy axis (EA) are given, since with these orientations we observed the strongest changes of the period of the domain structure. There is no qualitative difference in the patterns of the changes of the domain-structure period for different orientations of the field. However, for **h** ∥ EA we observe synchronous (with **h**) oscillations of the walls about their dynamical equilibrium positions, while for **h** ⊥ EA these oscillations are absent. Only for large amplitudes of the field **h** ⊥ EA are oscillations of the domain walls exhibited, these oscillations being associated with displacement of the domains of closure at the edges of the crystal. We note that the change of the number of domains in a field normal to the easy axis was not observed earlier in the work of other authors. In a field normal to the surface of the wafer it was not possible to reach amplitudes sufficient for rearrangement of the domain structure (only changes in the domain-wall structure that were associated with the generation of Bloch lines were exhibited).

The nonmonotonic behavior of the dependences $N(f)$

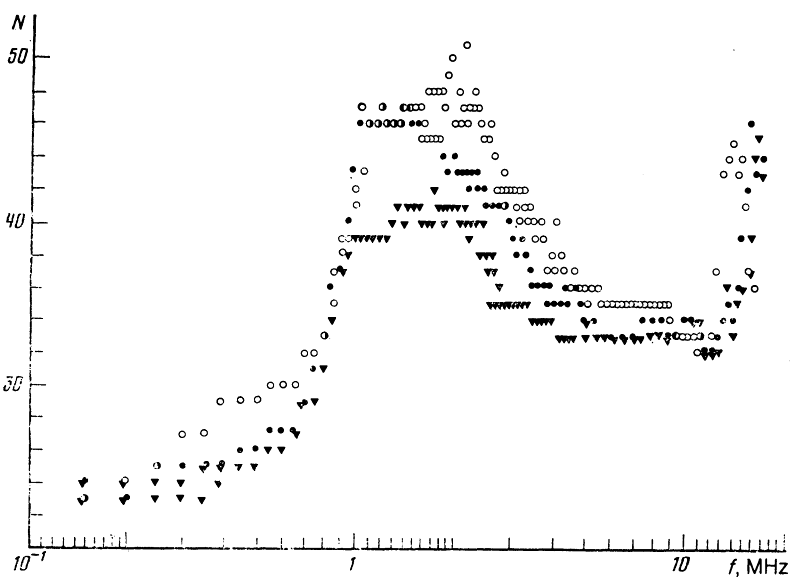

FIG. 3. Dependence of the number of domain walls in the crystal on the frequency of a field **h** ⊥ EA: ▼) $h_0 = 2.8$ Oe; ●) $h_0 = 3.1$ Oe; ○) $h_0 = 3.4$ Oe.

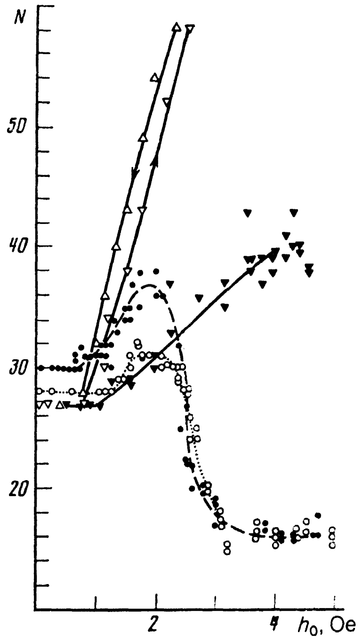

FIG. 4. Dependence of the number of walls on the amplitude of an alternating field **h** ∥ EA. For $f = 0.6$ MHz the points are taken in the field during the increase (▽) and decrease (△) of the field amplitude, and also after the field is switched off (▼), while for $f = 3$ MHz (○) and $f = 10$ MHz (●) the points are taken after the field is switched off.

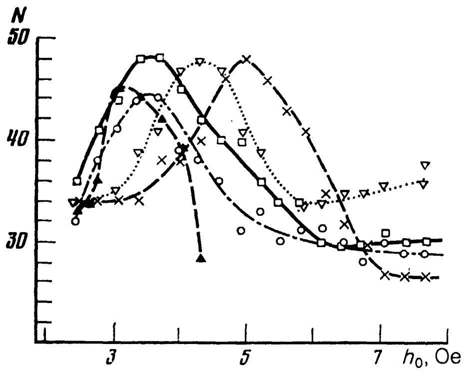

FIG. 5. Amplitude dependence of the number of walls in a field **h** ⊥ EA for $f = 1$ MHz (○), $f = 2$ MHz (□), $f = 4$ MHz (▽), $f = 10$ MHz (×), and $f = 15$ MHz (▲) (the points are taken after the field is switched off).

and $N(h_0)$, which differ from those measured in metallic ferromagnets,[20,21] is noteworthy. Here it turns out that the maxima of the frequency dependences for different orientations of the field occur at different values of f. It is necessary also to note the existence of a small hysteresis of the frequency and amplitude dependences. It is shown in Fig. 4 for $N(h_0)$ with $f = 0.6$ MHz; the hysteresis is displayed on the other plots, in order not to encumber the figures.

To elucidate the reasons for the dynamical changes of the domain-structure period we also studied the rearrangements of the domain structure under the action of constant fields H of different orientations. Below we give a brief description of the principal regularities revealed.

A field parallel to the easy axis leads to growth of the domains magnetized along H, at the expense of their neighbors, without change of the total number of walls. Then the domains magnetized against the field collapse in the middle of the crystal (at $H > 10$ Oe), and each pair of wedge-shaped domains formed decreases with increasing H. We note that the coercivity for the displacement of the walls in the samples investigated is $\lesssim 0.01$ Oe.

In a field perpendicular to the domain walls, at fairly large values $H > 4.5$ Oe, a rearrangement occurs from domains abutting at 180° and magnetized in the plane to a structure of 71° domains with magnetization along easy axes of the ⟨111⟩ type that have a component along the normal to the wafer and along the direction of the external field. At the surface these domains are closed by triangular prismatic domains magnetized parallel to the plane of the wafer. The regions occupied by 71° domains grow from the edges of the crystal to the middle of the crystal as the field increases. As in the case **H** ∥ EA, for **H** ⊥ EA the number of initial 180° domains remains unchanged up to considerable values of H, much greater than the alternating-field amplitudes at which the generation of domains begins.

Thus, the analysis of the behavior of the domain structure in a constant field shows that the variations of the period of the domain structure in an alternating field are an essentially dynamical effect. These variations can be due to several causes. First of all, as was shown in Refs. 5 and 6, in an alternating field the effective energy of the domains and walls should change, and this can lead to a change of N. Unfortunately, the theoretical analysis developed for this effect turns out to be inapplicable to our case. In the linear approximation[5] with the field oriented along and perpendicular to the easy axis the field should not affect the domain structure. It is necessary to note, however, that the linear calculation of Ref. 5, based on analysis of the time-averaged energy $\langle E \rangle_t$ of the magnet, is not justified. As was pointed out in Ref. 6, the dynamical state of the magnetization is determined not by $\langle E \rangle_t$ but by the effective potential energy E_{eff} obtained by direct averaging of the equations of motion of the magnetic moments. It is possible to calculate the quantity E_{eff} for $f > f_{\text{FMR}}$, when the variations of the magnetization can be divided into fast and slow variations.[6] Here it was found that $\langle E \rangle_t$ coincides with twice the value of E_{eff}. It is this equality which accounts for the success of the theory of Ref. 5 in explaining experiments[7,8] carried out at FMR frequencies. However, it would not be justified to use the results of Ref. 5 for $f \ll f_{\text{FMR}}$. A nonlinear calculation of the variation of the wall energy $E^{\text{dw}}_{\text{eff}}$, performed for $f > f_{\text{FMR}}$, gives the following result: In a field **h** ∥ EA the energy $E^{\text{dw}}_{\text{eff}} = 4(AK_{\text{eff}})^{1/2}$ for Bloch walls ($K_{\text{eff}} = K + \pi M^2 a^2$, in which $a = \gamma h_0/\omega$, where γ is the gyromagnetic ratio and h_0 and ω are the amplitude and frequency of the field) decreases as a function of the frequency of the field (and increases as a function of the amplitude), while the energy $E^{\text{dw}}_{\text{eff}}$ for Néel domain walls ($K_{\text{eff}} = K + 2\pi M^2 - \pi M^2 a^2$) increases with f (decreases with h_0). Correspondingly, the number of Bloch domain walls should increase with f (decrease with h_0), while the number of Néel domain walls should decrease with f (increase with h_0). In the case when **h** is perpendicular to the domain walls, $K_{eff} = K(1 - a^2)$ for Bloch domain walls and $K_{eff} = K + 2\pi M^2 - Ka^2/2$ for Néel domain walls, i.e., the number of both Néel and Bloch domain walls should decrease with f (increase with h_0). The FMR frequencies for yttrium iron garnet lie above the value $\gamma H_A/2\pi \cong 160$ MHz ($H_A = 4K/3M$), i.e., are an order of magnitude higher than the frequencies used in the experiment. Nevertheless, for frequencies $f < f_{FMR}$ we can also expect variations of E_{eff}^{dw} as a function of the frequency and amplitude of the field, although it is doubtful whether it is possible to explain the observed nonmonotonicity of $N(f)$ on the basis of the mechanism discussed.

In the framework of another approach, based on the premises of the theory of irreversible processes,[20] one can attempt to relate the maxima of $N(f)$ to the dispersion of the magnetic susceptibility. If at the corresponding frequencies there were peaks in the absorption χ'', the decrease of the period of the domain structure could be explained by the increase of the damping coefficient β appearing in the dissipative function $W_1 = (\beta V_{dw}^2/2)N$. We recall that W_1, which is regarded in Ref. 20 as the entropy-production function, determines the increase of N.

On the other hand, if in the frequency region of the maximum of $N(f)$ there is a resonance of the domain walls or Bloch lines (domain-wall resonances at $f \lesssim 1$ MHz have been observed in polycrystals of yttrium iron garnet,[27] and resonance oscillations of Bloch lines in 180° domain walls in yttrium iron garnet have been detected at $f \lesssim 0.5$ MHz in Ref. 28), this should also increase W_1. At the frequency of the domain-wall resonance there would be a maximum of V_{dw}. But at the frequencies of the Bloch-line resonances one may expect, on the one hand, the amplitude of the domain-wall oscillations to increase on account of gyroscopic forces, and, on the other hand, the damping coefficient β for the motion of the walls to increase as a result of losses at the Bloch lines. In all cases we can expect susceptibility anomalies near the frequencies at the maximum of $N(f)$. To check this conjecture we measured the susceptibility spectra $\chi(f)$ of the wafers, and also the spectra of the amplitudes $A(f)$ of the domain-wall oscillations. The measurements were performed at field amplitudes smaller than H_{c2}, when the number of walls in the crystal is not yet changing, since variations of N at $h_0 > H_{c2}$ lead to discontinuous changes of χ and A at $f > 10$ kHz, and this prevents one from displaying the dispersion of χ and A associated with the microscopic mechanisms. Examples of the spectra of $\chi(f)$ and $A(f)$ for different numbers of walls in the crystal are given in Figs. 6 and 7. The spectra have a typical relaxation character (the step in the dependence $A(f)$ near $f \sim 1$ kHz is connected with the fact that the measurements of the total amplitude of the domain-wall oscillations are carried out in the central part of the crystal, and for $f < 1$ kHz there are appreciable oscillations of the wedge-shaped domains that are situated at the ends of the crystal and partially screen the action of the external field). The increase of the susceptibility and of the total amplitude of the domain–wall oscillations with increase of the number of walls at $f > 10$–30 kHz are worthy of note. Here the changes of χ and A with N begin at lower frequencies with increase of the field amplitude. In the region $f \sim 1$–4 MHz the susceptibility is found to be proportional to the number of walls. As a function of N the relaxation frequency also increases.

An important point is that the dependences $\chi(f)$ and $A(f)$ are not observed to have any special features at the frequencies of the maxima displayed by $N(f)$ at large field amplitudes. There are also no anomalies associated with the Bloch-line resonances that were observed earlier in an analogous experimental situation but with smaller values of h_0 (Ref. 28). Obviously, the latter circumstance is connected with the generation of Bloch lines, which suppresses the resonances at the rather large field amplitudes that were used for the measurements of χ and A.

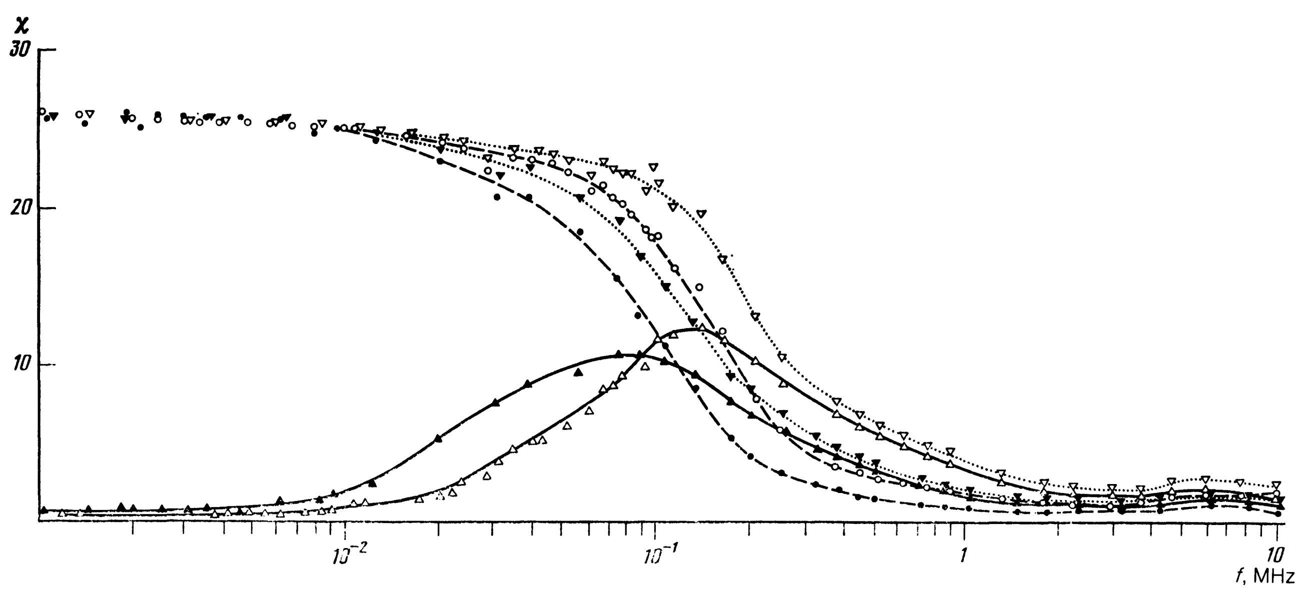

FIG. 6. Magnetic-susceptibility spectra of a wafer of yttrium iron garnet for two different numbers of domain walls (**h** ∥ EA, $h_0 = 0.4$ Oe): χ' (●), χ'' (▲), $|\chi|$ (▼) (all for $N = 4$); χ' (○), χ'' (△), $|\chi|$ (▽) (all for $N = 8$).

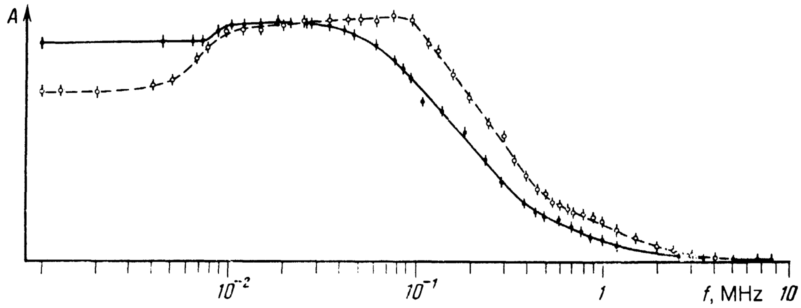

FIG. 7. Total amplitude of the domain-wall oscillations as a function of the frequency of the field (**h**||EA, $h_0 = 0.4$ Oe) for $N = 4$ (●) and $N = 8$ (○).

The observed increase of χ and A as functions of the number of domain walls at $f > 10$ kHz is interesting. It may be evidence in favor of a decrease of losses to the motion of the walls as their number increases in accordance with the dissipative mechanism described above. Here the displacement of the relaxation frequency, i.e., of the loss maximum, into the region of higher frequencies with increase of N points to the possibility of self-regulation of the period of the domain structure at $h_0 > H_{c2}$, when the increase in the number of boundaries raises $f_{\rm rel}$ and creates the conditions for a further increase of N at higher frequencies, and so on. However, the shift of $f_{\rm rel}$ should be bounded, since χ'' should decrease at high frequencies, and this will give rise to a decrease of N with increase of f. The arguments given could explain the presence of the first maximum in the dependence $N(f)$ for **h** || EA.

We note one further fact, which follows from comparison of $\chi(f)$ and $A(f)$: The amplitude of the oscillations of the walls decreases faster than the modulus $|\chi|$ of the susceptibility at high frequencies, reflecting the increase of the contribution to χ from processes involving the rotation of the magnetization at $f > 1$ MHz. Taking into account that $|\chi|$ here is proportional to N, we can assume that rotation processes in the domain walls, associated with the change of the domain–wall structure and, in particular, with the generation and motion of Bloch lines, are the determining processes. Here, the dissipation associated with the creation and motion of the lines can be the main loss mechanism. Thus, on the one hand, the Bloch lines can affect the changes of the number of walls by a dissipative mechanism (losses to the creation and motion of Bloch lines). On the other hand, they can determine the variations of N through the dependence of the effective energy of the domain walls on the density of Bloch lines, and also on the nonlinear perturbations of the wall structure that lead to the nucleation of the lines. In this case the frequencies of the maxima of $N(f)$ can be determined by the inverse generation times of the Bloch lines.

To confirm that the dynamical changes of the domain-structure period are connected with processes of generation and motion of Bloch lines in the domain walls we studied the influence of constant magnetizing fields on the phenomenon. First of all, we investigated the variations of N in the presence of a field H_e normal to the plane of the wafer. This field, which causes polarization of the walls, i.e., suppresses the Bloch lines, should reduce the effect, if the latter is determined by the presence of lines in the domain walls.

It was found that a constant field ~ 50 Oe, which in the absence of an alternating field establishes a uniform polarization of all the domain walls, does indeed decrease the variation of N for one of the two possible polarizations of $\mathbf{H}_e$. However, reversing the polarity of the constant field led to an unexpected enhancement of the effect: The number of walls in the alternating field increased when $\mathbf{H}_e$ was switched on. This effect of a vertical remagnetizing field is illustrated in Fig. 8, which shows dependences $N(f)$ without H_e and with $H_e = \pm 43$ Oe. Similar asymmetric action of $\mathbf{H}_e$ also occurs at lower values of H_e. The appreciable difference in the dependence $N(f)$ for opposite directions of $\mathbf{H}_e$ is observed up to fields ~ 120 Oe, at which qualitative rearrangements of the domain structure occur.

A constant field $\mathbf{H}_\perp$ in the plane of the wafer and normal to the domain wall also affects the dynamical changes of the period in an asymmetric manner. For both polarizations of $\mathbf{H}_\perp$ the variation of N decreases, but to different degrees (see Fig. 9). Up to fields $H \cong 6$ Oe, at which appreciable rearrangement of the domain structure from domains abutting at 180° to 71° domains begins (as described above), the differences of the curves of $N(f)$ for different polarities of $\mathbf{H}_\perp$ remain considerable.

Finally, a magnetizing field $\mathbf{H}_\parallel$ parallel to the easy axis, like $\mathbf{H}_\perp$, decreases the changes of N in an asymmetric manner (Fig. 10). However, the asymmetry is weaker than for $\mathbf{H}_\perp$, and in a field $H_\parallel \cong 10$ Oe the curves of $N(f)$ for the two polarizations of $\mathbf{H}_\parallel$ are practically the same. Evidently, $\mathbf{H}_\parallel$ directly suppresses processes of formation of new domains.

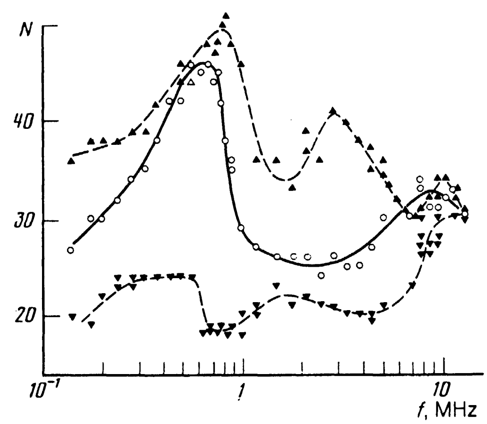

FIG. 8. Effect of a constant field, normal to the plane of the sample, on the changes of the number of domain walls in an alternating field (**h**||EA, $h_0 = 2.5$ Oe): $H_e = 0$ (○); $H_e = 43$ Oe (▲); $H_e = -43$ Oe (▼).

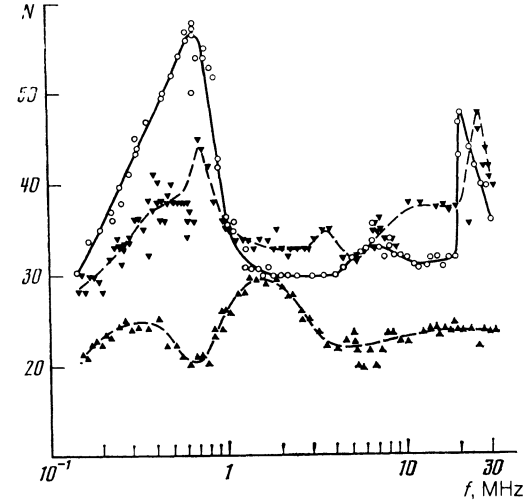

FIG. 9. Dynamical changes of the number of walls in the presence of a constant field in the plane of the wafer and normal to the walls; (**h**||EA, $h_0 = 2.2$ Oe): $H_\perp = 0$ (○); $H_\perp = 2.8$ Oe (▲); $H = -2.8$ Oe (▼).

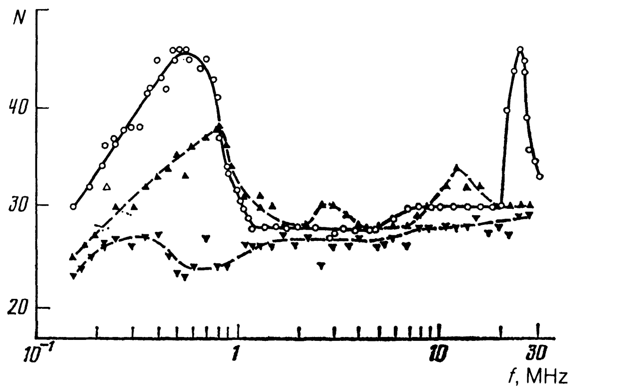

FIG. 10. Effect of a constant field, parallel to the easy axis, on the dynamical changes of the number of walls (**h**||EA, $h_0 = 2.3$ Oe): $H_\parallel = 0$ (○); $H_\parallel = 5.5$ Oe (▲); $H_\parallel = -5.5$ Oe (▼).

The results presented (above all, the enhancement of the dynamical changes of the domain-structure period in a field $\mathbf{H}_e$ that suppresses Bloch lines in the static situation) indicate that the variations of N in an alternating field are determined not by changes of the density of Bloch lines but directly by features of the process of generation (and subsequent annihilation) of Bloch lines—a process connected with nonlinear excitations of the structure of the walls. Here the asymmetry of the influence of magnetizing fields can be attributed to the nonduality of the magnetic excitations, an example of which is given by the unidirectionality of the motion of Bloch lines in domain walls under the action of a uniform alternating field,[29] and also by the directed motion (described in the present paper) of domains in **h**. The possibility of nondual phenomena in a magnet, even in the case of linear normal modes, is demonstrated by the well known examples of surface magnetostatic waves[30] and spin waves in domain walls.[31]

It appears that the changes of the domain-structure period in an alternating field correspond to the establishment of dynamical stationary states of the magnetic structure of the crystal under the action of a sufficiently large alternating external force. The magnetic moments in the domain walls are found to be the most sensitive to the alternating field. Nonlinear perturbations of the structure of the domain walls, as the experiment shows, begin at field amplitudes much smaller than those necessary for a change in the number of domains. Therefore, it is precisely in the walls that stationary nonlinear oscillatory processes should be established first. These can be self-excited waves of large amplitude, of the type obtained in computer modeling of the behavior of a chain of spins in a microwave field.[12] The establishment of self-wave processes, which, for a sufficiently large field amplitude, should be manifested in the form of a stationary process of nucleation of Bloch lines, evidently determines the dynamical changes of the domain-structure period as a result of losses to the generation of Bloch lines and as a result of changes of the effective energy of the domain walls (similar to the changes of $E_{\rm eff}$ of one-dimensional boundaries when $f > f_{\rm FMR}$), as was discussed above. We note that self-oscillations in a three-dimensional system of spins are observed in the form of periodic generation of domains at large field amplitudes. The results of a study of this process will be presented in a subsequent publication.

This scenario of nonlinear processes by which a dynamical structure is established do not have a theoretical description applying directly to our experimental situation. However, in support of the likelihood of the proposed mechanism we may note that there are a large number of theoretical and experimental investigations that demonstrate a universal tendency to the formation of spatial and temporal structures (and, in particular, display periodic generation of solitons) in nonlinear systems (including magnets) under the action of harmonic external forces of large amplitude[12,32,33] and under the action of light.[34]

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