Experimental observation of a new mechanism of domain-wall motion in strong magnetic fields

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(Submitted 12 February 1982; resubmitted 9 October 1982)
Zh. Eksp. Teor. Fiz. **84**, 1006–1022 (March 1983)

The dynamics of domain structures in epitaxial iron-garnet films is investigated experimentally in pulsed magnetic fields $H_{\rm pul}$ that are comparable with the effective uniaxial anistropy field H_k^*. An experimental setup was developed that permits study of the periods of nonrepetitive rapid processes in thin magnetic films in pulsed fields up to 4000 Oe at a high spatial resolution $\sim 0.3\,\mu$m and a high time resolution ~ 8 nsec in real time. The presence is observed of critical external magnetic-fields intensities that demarcate the regions where iron-garnet films can reverse magnetization on account of domain-wall (DW) motion and on account of inhomogeneous rotation of the magnetization vectors. It is shown that in strong pulsed gradient fields $H_{\rm pul} > H_k^*$ the sample magnetization is reversed because of the motion of the flopping magnetic-moment wave. In weak pulsed gradient fields $H_{\rm pul} > H_k^*$ the inhomogeneous rotation of the magnetization vectors has a clearly pronounced "turbulent" character. A new mechanism of DW motion in strong pulsed magnetic fields is observed in experiment. Its gist is that in $H_{\rm pul}$ stronger than a certain critical field $H^*_{\rm pul}$ local sections of a moving DW generate "magnetic perturbations" that precede the DW and are detached from the latter. The DW velocities, in the entire range of the fields in which the DW can exist, do not exceed their limiting value in this case. In the course of time the magnetic perturbations are transformed into microdomains that expand subsequently and generate around themselves these perturbations, merge with the initial domain, etc. Within the frameworks of the existing theories the experimentally observed magnetic perturbations are apparently magnetic solitons. It is shown that the use of a procedure different from that described in the present paper can lead to an erroneous treatment of the experimental results.

PACS numbers: 75.70.Kw, 75.60.Ch, 75.50.Gg

1. INTRODUCTION

Interest in nonlinear dynamics of domain walls (DW) in a uniaxial highly anisotropic ferro- and ferrimagnets has increased greatly in recent years. The dynamics of DW and of magnetic domains is the subject of a large number of experimentl and theoretical studies.

Theories. Walker[1] and independently Akhiezer and Borovik[2] have determined the maximum velocity of DW in a ferromagnet with anisotropy of the easy axis type, in magnetic field not exceeding the Walker critical field H_W

$$V_-=2\gamma\frac{(AK_u)^{1/2}}{M_s}[(1+\varepsilon)^{1/2}-1]\to 2\pi\gamma M_s\left(\frac{A}{K_u}\right)^{1/2}=v_W, \tag{1}$$

where γ is the gyromagnetic ratio, A is the exchange-interaction constant, K_u is the uniaxial anisotropic constant, M_s is the saturation magnetization, and $\varepsilon = 2\pi M_s^2 K_u^{-1}$. In magnetic fields $H > H_W$ the motion of DW is not stationary and exact solutions of the equations of motion of DW for this region are not known at present. An analysis carried out in Ref. 3 has shown that in such fields the average DW velocity v_1 is defined as $v_1 = v_W/2\pi$. The equation for the limiting velocity of the steady-state motion of DW in thin magnetic films was obtained by Hagedorn[4] and Slonczewski[5]:

$$v_p=24\gamma A K_u^{-1/2} h^{-1}. \tag{2}$$

In magnetic fields corresponding to the region of nonstationary motion of DW, the average velocities of the domain wall were determined by different methods; $v_2 \approx 0.55 v_p$ according to Ref. 4 and $v_3 = 0.3 v_p$ in Ref. 5. A generalization of a large number of experimental results, carried out by de Leeuw,[3] has shown that the DW velocity in the saturation regime is best described by the empirical formula $v_4 = v_W/5$.

An analysis of the dynamics of fast solitary magnetic-moment waves (magnetic solitons), carried out in Ref. 6, has made it possible to determine the upper limit of the propagation velocity of such magnetic perturbations:

$$V_+=2\gamma\frac{(AK_u)^{1/2}}{M_s}[(1+\varepsilon)^{1/2}+1]. \tag{3}$$

We note that V_+ is the minimum phase velocity of the spin waves. An analysis in Refs. 6 and 7 shows that in the velocity interval $V_- < v < V_+$ there exist only solutions of the solitary wave or magnetic soliton type. $A^t\, v \to V_+$, the amplitude of the soliton is small, and the localization region is large, whereas at $v \to V_-$ the soliton is reminiscent of a solitary moving domain having almost homogeneous magnetization and separated from the remainder of the crystal by two DW (Ref. 8).

In real cases the DW motion is under the influence of an external magnetic field, and the character of this motion is determined by dissipative processes in the system. It is well known that the theories in which the energy dissipation is

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taken into account phenomenologically, by introducing the damping parameter α, describe poorly the motion of DW in strong magnetic fields. Therefore methods for the investigation of the dynamics of DW, based on allowance for definite microscopic processes that lead to energy dissiption, are being diligently investigated at present. The DW velocity is determined from the condition that the change of the Zeeman energy be equal to the change of the energy dissipated by the quasiparticles (by phonons,[12] magnons[8,10,11] and spin waves.[9] To explain the "superlimiting" motion observed in orthoferrites by Chetkin, Akhutkina, and Shalygin,[13] Bar'yakhtar, Evanov, and Sukstanskiĭ[11] proposed a model of soliton mechanism of imitating such a motion.

It must be noted that all the presently existing theories of the motion of DW and of magnetic-moment waves have been developed under the assumption that the external magnetic field is weaker than the effective uniaxial-anisotropy field. There are no direct experimental data that confirm the existence of the theoretically predicted[8-12] mechanims of dissipation of the Zeeman energy of a ferromagnet.

Experimental methods of investigating the dynamics of domain structures. Materials with magnetic bubble domains (films of iron garnets (IG), orthoferrites, etc.) have high optical transparency in the visible and near infrared, and a sufficiently large specific Faraday rotation. Because of this, practically all the experimental methods are based on the Faraday effect.

For an experimental investigation of the dynamics of magnetic domains, extensive use is made at present of bubble-domain-collapse, photoelectric, stroboscopic, and indirect methods, such as radiofrequency and analytic. The main shortcoming of these methods is the temporal and spatial averaging of the results.

To investigate non-repeating high-speed dynamic processes in materials with bubble domains one uses frequently the method of single-flash high-speed photography.[14] We note that this procedure does not make it possible to determine the dynamic characteristics of the investigated samples in a large class of experiments, where the process of conversion of the domain structures in each pulse of the magnetic field has its own peculiarities. To investigate such processes one uses the methods of repeated illumination,[15,16] frame-by-frame photography,[17,18] and chronography.[16,17] Each of these experimental setups, operating in real time,[15-18] has its advantages and shortcomings, but meither makes it possible to investigate the dynamics of submicron domains. A substantial shortcoming of the installations of Refs. 15, 17, and 18 is the absence of small (of the order of several nanoseconds) and smooth delays between the frames and the illumination flashes.

Experimental results. We shall dwell briefly only on those experiments which have a direct bearing on the research reported in the present paper. The limitation on DW velocity was first observed in experient by the collapse method in Ref. 19. This was followed by many experiments in which it was shown that the DW velocity is subject to saturation. At the same time, there are many data[13,20,21] that point to the absence of a limiting DW velocity. Thus, it can be seen that it is not clear to this day whether the DW have a maximum velocity.

Zimmer *et al*,[22] in a high-speed-photography investigation of the dynamics of magnetic bubble domains, observed a broadening of the moving DW. The broadened DW observed in these and similar experiments[21,23-25] was called a diffuse domain wall. It was shown[21-25] that each intensity of the magnetic field pulse corresponds to a definite width of the diffuse wall and that irregular distortions of this wall are observed along the perimeter of the bubble. To explain the nature of the diffuse boundary it was suggested in Refs. 23-25 that such a wall is simply an inclined DW. Favoring this assumption, in the opinion of the authors of Ref. 23, are the results of an experimental investigation of a diffuse wall with the aid of the Kerr effect. The model of inclined DW was used in Ref. 26 to develop a theory of a diffuse wall.

2. EXPERIMENTAL PROCEDURE

To visually distinguish the domain structure we used in the present study the magneto-optic Faraday effect. As a rule, in the initial situation the sample was in a constant magnetic field having an intensity and a spatial distribution necessary for the chosen experiment. A magnetic field pulse H_{pul} then upsets the equilibrium state of the domain structure. The dynamic transition of the system from one stable state to another was investigated with the aid of pulsed illumination of the sample at various instants of time τ after the application of H_{pul}. We note that to realize an optimal temporal and spatial resolution it is necessary to use a light source that generates pulses of duration $\leqslant 10$ nsec at a wavelength $\lambda \sim 0.5\ \mu$m (at a shorter wavelength the absorption in the IG films increases strongly, and at a longer wavelength the Faraday rotation decreases).[27]

We consider in general form the operation of the developed assembly of the research apparatus intended for the

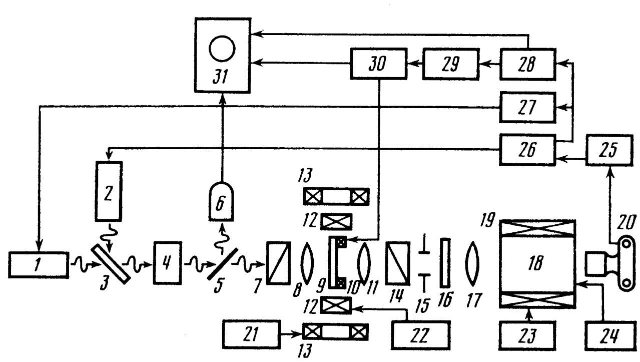

FIG. 1. Block diagram of facility for the investigation, in real time, of the dynamics of the domain structures in transparent magnetic materials: 1,2–LGI-21 lasers, 3–semitransparent mirror, 4–cell with dye, 5–beam-splitting plate, 6–avalanche photodiode, 7–polarizer, 8, 11–objectives, 9–sample, 10–pulse coil, 12–bias-field coils, 13–coils for field in the plane of the sample, 14–analyzer, 15–diaphragm, 16–benchmark, 17–lens, 18–UM-93 image converter, 19–focusing coil of image converter, 20–photographic camera, 21–23–stabilized power supplies, 24–stabilized high-voltage rectifier, 25–synchronization block, 26, 27–G5-54 generators, 28–G5-15 generator, 29–current-pulse shaping block, 30–circuit for changing the directions and measuring the amplitudes of the current pulses, 31–S1-75 oscilloscope.

study of nonrepeating dynamic processses in thin magnetic films. It consists of an illumination block, a system for producing magnetic fields of varying configurations, an optical system and a recording block, and a control and monitoring block. A block diagram of the setup is shown in Fig. 1.

Illumination block. The pulsed light sources employed were standard LGI-21 nitrogen lasers (*1*,*2*), which are triggered at the required instants of time τ_1 and τ_2 reckoned from the start of the action of the magnetic field pulse $H_{\rm pul}$ from the generators G5-54 (26, 27). The pulses of lasers *1* and *2* are guided to the optical axis of the experimental setup by the semitransparent mirror *3*. The laser emission ($\lambda \approx 0.33$ μm) is converted in with rhodamine-6Zh dye-solution optical cell *4* into $\lambda \approx 0.58\,\mu$m radiation. To record the waveform and the relative position of the illumination pulses, an cascade photodiode is used, which records the light pulses from the beam-splitting plate *5*. The electric signal from the photodiode is fed to a unviersal oscilloscope S1-75 (*31*). The illumination pulse duration at half maximum is ~ 8 nsec, and the stability of the pulse triggering is ~ 2 nsec. The energy of the light pulses ($\sim 10^{-5}$ J) turned out to be sufficient for the investigation of the dynamics of magnetic domains in DW films having thicknesses up to $\sim 0.3\,\mu$m.

Optical part of the installation. The radiation from the pulsed lasers *1* and *2* passes through a polarizer *7* and is focused by a polarization objective *8* on the investigated sample. The optical system *11*, *14–16* is based on a polarization microscope MIN-4. The image of the domain structure is projected by objective *10* through analyzer *14* and diaphragm *15* onto a bench mark *16*, whose orientation and position remain unchanged in the experiments. The polarizer *7* and the analyzer *14* are Ahrens prisms. The lens *17* projects the image of the domain structure, together with the image of the bench mark on the photocathode of an electron-optical image converter *18*. To obtain high spatial resolution in the experiments wide-aperture polarization objectives *8* and *11* are used, which have been specially selected for their resolving power and for polarization properties. Investigations of the instrumental function of the optical system of the apparatus have shown that in accordance with the Rayleigh criterion the resolution of the apparatus is $\sim 0.3\,\mu$m. We note that realization of all the limiting possibilities of the optical microscopy at the illumination wavelengh $\lambda \approx 0.58$ μm employed by us make it possible apparently to improve the spatial resolution to $\sim 0.15\,\mu$m.

Recording block. This block was based on a UM-93 image converter *18* with multislit photocathode having a spatial resolution ~ 25 lines/mm and a photocurrent gain $\sim 10^5$. It was fed from a high-voltage rectifier *24*. The electron beam was focused into the image converter by magnetic coils *19* fed from a VS-26 rectifier (23). The image on the exit screen of the image converter was recorded by camera *20*.

Control block. The pulsed electronic circuitry in the apparatus was triggered by a synchronizer *25*. The synchronization pulses are fed to the input of the triggering generators *26–28*. The generator G5-15 (*28*) triggers the shaping circuit *29* for the current pulses that produce the magnetic fields of required intensity and configuration. The current pulses with amplitudes up to 15 A, maximum duration 10 μsec, and rise time $\tau_f \lesssim 20$ nsec are shaped with a limiter-amplifier using GMI-6 tubes, and those with amplitude up to 100 A and duration $\sim 1\,\mu$sec are shaped by a generator based on a TGI1-100/8 thyratron ($\tau_f \approx 35$ nsec). The current pulses flow from the output of the shaper *29* to the measurements and direction-switching circuits *30*, after which they are fed at the required polarity to coil *10* for the experiments and to oscilloscope *31* for monitoring.

Magnetic part of the setup. The constant bias field H_b is produced by two Helmholtz coils *12*, and the sample in a special holder is placed in the gap between them. The coils are fed from a stabilized power pack B5-7 (*22*). The constant field $H_{\rm pl}$ in the smple plane is produced by an orthogonal pair of coils *13*, which are fed from two stabilized sources VS-26 and B5-21 (*21*). The magnetic system makes it possible to shape a field H_b with intensity up to 600 Oe and a field $H_{\rm pl}$ with intensity up to 220 Oe. The pulsed magnetic field $H_{\rm pul}$ was produced by flat single-layer coils with inside diameter $d \sim 1.5$ mm and with not more than 10 turns of wire of 30–120 μm diameter. In the experiments, $H_{\rm pul}$ ranged from 0 to 4000 Oe.

A feature of the experiments described below on the investigation of the dynamic processes that take place in the case of pulsed magnetization reversal of the IG films is that allowance is made for the axial symmetry and for the gradient character of the magnetic field produced by the flat single-layer coil. In the initial state, the sample was located in the constant bias field H_b. When the dyamics of the magnetic domains was investigated, H_b was somewhat weaker than the bubble collapse field H_0. This was followed by an application of the pulsed field $H_{\rm pul}$ antiparallel to H_b, and at various instants of time τ reckoned from the center of the leading front $H_{\rm pul}$ the dynamic domain configurations were recorded. Their characteristic form and the temporal diagrams of the magnetic-field and illumination pulses for operating regimes with single-pulse and two-pulse illumination are shown in Figs. 2 and 3.

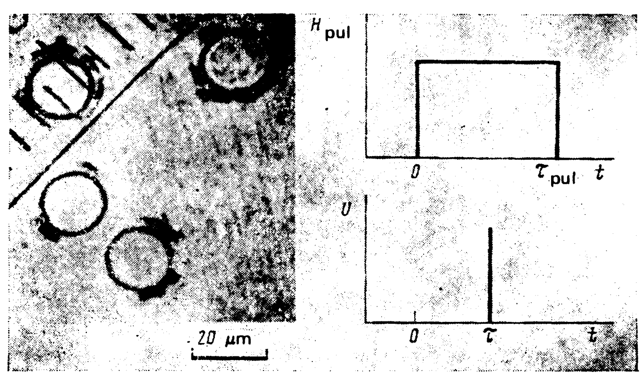

FIG. 2. Photographs of magnetic bubbles in radial expansion (left) and temporal diagrams of the pulses of the magnetic field and of the illumination (right). The polarizers are fully crossed, $H_b = 100$ Oe, $I_{\rm pul} = 250$ Oe; $\tau = 450$ nsec; $\tau_{\rm pul} = 900$ nsec.

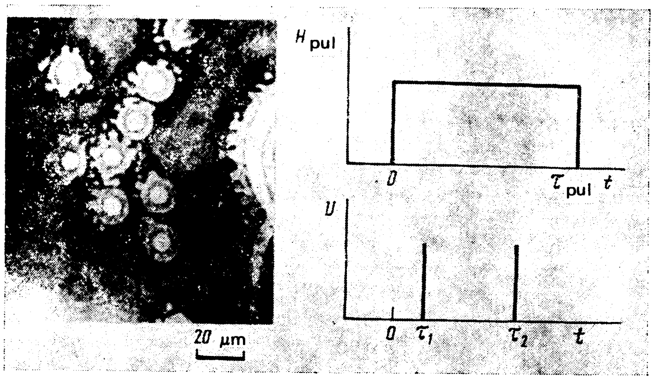

FIG. 3. dynamic domain configurations observed int he expansion of domains in experiments with two-pulse illumination. the time diagrams of the magnetic-field and illumination pulses are shown. $H_b = 94$ Oe, $H_{\rm pil} = 600$ Oe, $\tau_1 = 100$ nsec; $\tau_2 = 400$ nsec; $\tau_{\rm pul} = 600$ nsec.

The samples were IG films grown by liquid-phase epitaxy on the (111) plane of $GD_3Ga_5O_{12}$ substrates. In the experiments we used samples of various compositions, e.g., $(YGdYbBi_3)\cdot(FeAl)_5O_{12}$, $(BiTm)_3(FeGa)_5O_{12}$, $(YSmLuCa)_3(FeGe)_5O_{12}$ etc. We present here the results for two samples of composition $(BiTm)_3(FeGa)_5O_{12}$, of thickness $h \approx 10\ \mu$m thick, bubble collapse field $H_0 \approx 107$ Oe, saturation magnetization $4\pi M_s \approx 144$ Oe, uniaxial anisotropy field $H_a \approx 950$ Oe, and stripe-domain period $P_0 \approx 8.7$ m.

3. EXPERIMENTAL RESULTS AND THEIR DISCUSSION

The process that takes place in pulsed magnetization reversal in single-crystal magnets, particularly in IG films, have been investigated up to now in pulsed magnetic fields $H_{\rm pul}$ that are substantially weaker than the uniaxial-anisotropy field H_k^*. In the present paper we give the results of the first experimental investigation of the dynamics of domain structures in DW films in pulsed fields from 0 to 4000 Oe.

We assume hereafter that H_k^* is defined by the expression

$$H_k^* = H_a - 4\pi M_s, \tag{4}$$

where $H_a = 2K_u/M_s$ is the uniaxial anisotropy field. We note that this definition of H_k^* is valid only in first-order approximation. In particular, the expression for H_k^* takes no account whatever of the sample crystallographic anisotropy which, as will be shown below, exerts a substantial influence on the pulsed magnetization reversal of the IG films.

It is well known that at $H_{\rm pul} < H_k^*$. the sample magnetization reversal is due to the DW motion, as well as to the nucleation and growth of centers with oppositely directed (relative to the initial) magnetizations. If, however, $H_{\rm pul} > H_k^*$, the initial magnetic phase becomes absolutely unstable after application of a pulsed field and an inhomogeneous rotation of hte magnetization vectors takes place.[28] By homogeneous rotation is meant a process in which, at any point of the sample, the magnetization vectors rotate at equal velocities and make at any instant of time the same angle with their initial position. Strictly speaking, owing to the presence of defects in the films, to magnetic anisotropy, to the inhomogeneity of the external magnetic fields, etc. the possibility of realization of uniform rotation in real thin magnetic films is quite doubtful. Therefore, if a magnetic-moment rotation that does not agree with the definition of uniform rotation is observed when the magnetic vectors are rotated, it is usually stated that non-uniform rotation takes place.

Pulsed magnetization reversal of DW films on account of inhomogeneous rotation of the magnetization vector

We consider the dynamic processes that take place under pulsed magnetization reversal of IG films in fields $H_{\rm pul}$ comparable with H_k^*. It is shown in Ref. 29 that if the magnetic field near the turns of the pulse coil acting on the sample is $\Delta H(r \sim R) = H_{\rm pul}(r \sim R) - H_b > H_k^*$, where r is the distance from the center of the coil and R is the internal radius of the coil, the reversal of the magnetization of the sample via in homogeneous rotation of the magnetization vector begins in this region. Since the pulsed magnetic field produced by a flat coil has an axisymmetric and gradient character, it follows that, this process, starting near the turns of the coil, where $\Delta H(r \sim R)$ is a maximum, extends rapidly to the region of weaker fields $\Delta H(r \to 0)$, exciting a flopping magnetic-moment wave that moves from the edges of the coils towards it center. In fields $\Delta H(r = 0) > H_k^*$ the magnetization reversal due to the motion of the flopping wave takes place over the entire sample area subtended by the coil. We note that in fields $H_{\rm pul} > H_k^*$ the growth of nuclei with reversed (relative to H_b) magnetization directions were not observed, since the magnetization reversal due to non-uniform rotation of the magnetization vectors is essentially much faster than the growth of the nucleation points. From the plots of the dependence of the path traversed by the flopping magnetic-moment wave on the time we determined the wave velocity v_{fw} for different values of $\Delta H(r = 0)$. The calculations have shown that the minimum phase velocity of the spin waves V_+ (3) for the investigated sampe is $V_+ \approx 3 \times 10^3$ m/sec and agrees approximately with the minimum velocity $v_{fw} \approx 2 \times 10^3$ m/sec. It was shown that V_+ is by far the maximum velocity of the flopping wave and that in the magnetic field region $\Delta H(r = 0) \sim 4000$ Oe the wave moves with velocity exceeding V_+ by more than an order of magnitude.

Similar experiments for a number of IG films with different compositions and parameters have shown that the described sample magnetization reversal mechanism via motion of a flopping wave has a general character. We note that theoretically the magnetization reversal of single-crystal films on account of the motion of this wave has not been investigated at all, but it can be assumed that its nature is similar to that of a shock wave. Thus, we have demonstrated experimentally that pulsed magnetization reversal of single-crystals IG films via motion of DW is possible only in the range of pulsed magnetic fields $H_{\rm pul}$ satisfying the condition $\Delta H(r) \lesssim H_k^*$.

We consider now the magnetization reversal of IG films in pulsed fields $H_{\rm pul}(r = 0)$ such that the effective acting field $\Delta H(r = 0)$ is somewhat weaker than H_k^*. In this case, after application of $H_{\rm pul}$ in the central part of the coil, where

$\Delta H(r) < H_k^*$, the sample magnetization reversal proceeds on account of formation of nucleation centers with oppositely directed (relative to H_b) magnetization, and on account of the DW motion, while near the coil turns, where $\Delta H(r) > H_k^*$,the magnetization reversal is due to the motion of the flopping wave.[30,31] At definite values of H_b and $H_{\rm pul}$, a strictly oriented triangular region is produced in the center of the coil, and in this region the magnetization is reversed by the motion of the DW. For convenience, this region was called a triangular magnetic domain.[29–31] It was observed in experiments that there exists a certain field range $\Delta H(r=0) < H_k^*$ in which, independently of the orientation of H_b and $H_{\rm pul}$ there is always observed a triangular domain. If $H_b < H_0$ in the initial state, the triangular domain is compressed during the action of the field pulse $H_{\rm pul}$ and one observes inside this domain reversal of the sample manetization on account of the motion of the DW. If, however, $H_b > H_0$, contraction of the triangular domain takes place and nucleation centers grown on the defects inside this domain. The orientation of this domain is connected with the direction of the crystallographic axis as well as with the direction of the rhombic component of the induced anisotropy j_p. An analysis of the directions of the bisectors of the angles of the triangular domains has shown that a decisive influence on their orientation is exerted by the rhombic anisotropy, inasmuch as such a domain is elongated along j_p and the bisector of the smallest angle practically coincides with the direction of j_p. Under definite conditions (as a rule, at $H_b > H_0$) a layer-by-layer magnetization reversal of the sample is observed on account of the non-uniform rotation, and the film layers, which differ in their properties, become visually distinguishable. After a certain time $\tau = 150$–300 nsec, which depends on $\Delta H(r=0)$, the layer-by-layer magnetization reversal terminates in the entire area subtended by the coil, and a triangular domain that passes through the entire thickness of the film is produced. Thereafter the magnetization reversal is due to the motion of its boundary at a fixed orientation.

Let us consider some singularities of the process of formation of the triangular domain (Fig. 4) and of the process of magnetization reversal of the sample on account of non-uniform rotation of the magnetization vectors. The experiments were performed with fully crossed polarizers, so that it was possible to observe visually the DW. A triangular domain is produced very rapidly in one or several layers, in which the flopping-wave velocity is a maximum (see Figs. 4a, b). It appears that these layers have the lowest effective uniaxial anisotropy fields. After its formation, the triangular domain that does not pass through the entire sample contracts, and outside it, in the layers that have not yet reversed magnetization, the process of non-uniform rotation sets in (see Figs. 4a–d). It is clearly seen that this process, which takes place over the entire sample area with non-reversed magnetization, has a "turbulent" character. The turbulent domain structure is characterized by perfectly defined dimensions of isolated domains that do not pass through. In this experiment (Fig. 4) the pulse field was strong enough and no triangular domain passed through the entire thickness of the film during the time of action of $H_{\rm pul}$. By the end of the action of the field pulse (see Fig. 4h) there remains only a cluster of domains in a region close to triangular in shape. After the end of the action of $H_{\rm pul}$ (Fig. 4,j–m), a rapid growth of these domains is observed.

Dynamics of domain walls in strong magnetic fields

Just as before, the experiments were performed with the polarizers accurately crossed. Some experimental results concerning the dynamics of DW in strong fields are given in Ref. 32.

Figure 5A (a) shows the initial domain structure. In fields $H_{\rm pul} < 200$ Oe (Fig. 5A) we observed the petal-like dis-

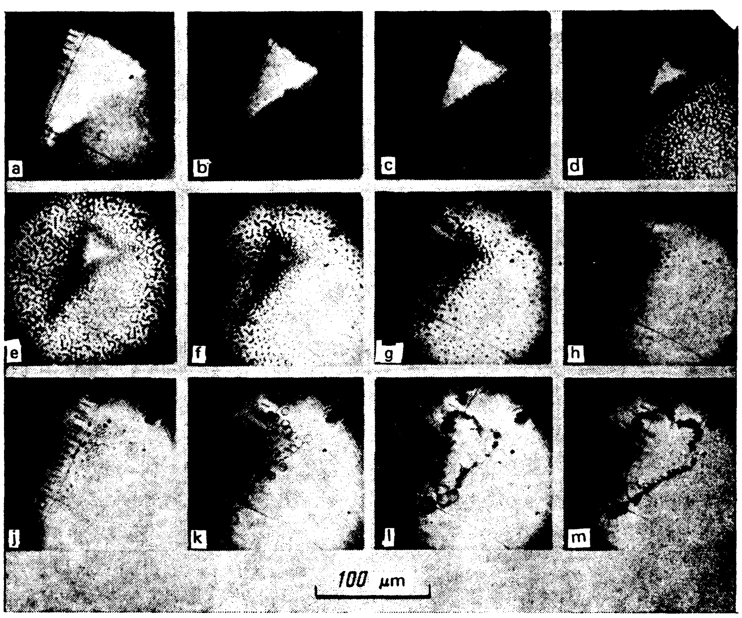

FIG. 4. Process of formation of a triangular magnetic domain and dynamics of DW after the termination of the field pulse. $H_b = 160$ Oe, $H_{\rm pul} = 910$ Oe, $\tau_{\rm pul} = \mu$sec, $\tau(\mu$sec): a — 0.08; b — 0.14; c — 0.18; d — 0.25; e — 0.3; f — 0.35; g — 0.4; h — 0.55; u — 0.75; k — 0.95; l — 1.15; m — 1.35.

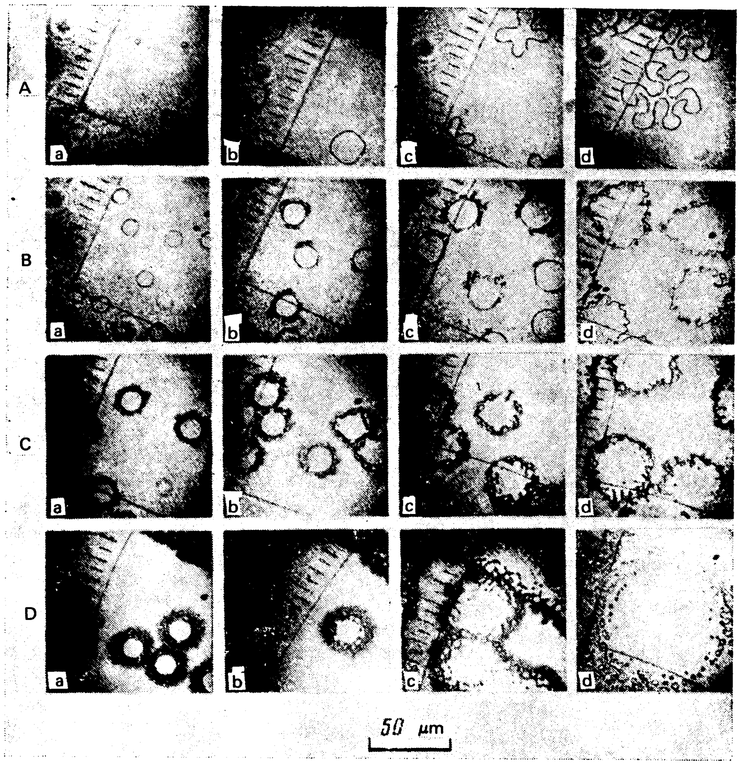

FIG. 5. Dynamics of magnetic bubble domains in strong pulsed magnetic field. $A - H_b = 105$ Oe $H_{pul} = 80$ Oe, $\tau_{pul} = 3\,\mu$sec, $\tau(\leqslant$sec$)$: $a - 0, b - 1.0, c - 1.5, d - 2.5$; $B - H_b = 100$ Oe, $H_{pul} = 240$ Oe, $\tau_{pul} = 1.0\,\mu$sec, $\tau(\mu$sec$)$: $a - 0.3, b - 0.45, c - 0.7, d - 1.0$; $C - H_b = 103$ Oe, $H_{pul} = 330$ Oe, $\tau_{pul} = 1.0\,\mu$sec, $\tau(\mu$sec$)$: $a - 0.4, b - 0.5, c - 0.6, d - 0.8$; $D - H_b = 90$ Oe, $H_{pul} = 680$ Oe, $\tau_{pul} = 1.0\,\mu$sec, $\tau(\mu$sec$)$: $a - 0.25, b - 0.3, c - 0.5, d - 1.1$.

tortions, investigated in detail earlier,[33,34] of the shape of the bubble. Accurate to the realized spatial resolution $\sim 0.3\,\mu$m, it can be stated that the DW is not distorted. However, if the pulsed field exceeds a certain critical value of $H^*_{pul} \approx 210$ Oe, the dynamics of the DW is radically altered (Figs. 5, B, C, D). In fields H_{pul} slightly exceeding H^*_{pul} the bubble domain expands during the first ~ 300 nsec without change in shape and thickness of the DW (Fig. 5B). At $\tau > 300$ nsec, there appear near the sections of the boundary of the domain localized "magnetic perturbations" of the medium, which anticipate the moving DW. It must be noted that, within the limits of the experimental accuracy, the DW of the bubble domain is not distorted, and the perturbations that precede the DW are located at a distance 2.5–3 μm from it (Fig. 2). If in the initial state the domain is exactly at the center of the pulse coil, then the perturbations are generated randomly over the perimeter of the domain. Even an insignificant ($\sim 40\,\mu$m at a coil inside diameter ~ 1.3 mm) deviation from its center causes the DW to begin to generate perturbations in the direction of the displacement from the center of the coil. This confirms the extreme sensitivity of the DW of a bubble domain to the intensity and orientation of the external pulsed fields.

In the course of time the perturbations that precede the DW are usually transformed into microscopic bubbles (Figs. 3 and 5). These microdomains are produced randomly over the perimeter of the initial bubble, but as a rule at a distance $\geqslant 3\,\mu$m from one another and from the DW. Subsequently these microdomains, generating around themselves new perturbations, expand and ultimately merge with the initial domain. The shape of the initial bubble domain is in this case strongly altered (see Figs. 5B, C. D). There exists one more critical value of the field $H^{**}_{pul} \sim 300$ Oe, above which the domains generate perturbations practically uniformly over the perimeter (Fig. 5D). It can be seen from Fig. 5 that the perturbations precede the DW earlier and earlier with increasing H_{pul}.

As noted above, if $\Delta H\,(r = 0) < H^*_k$ at the center of the coil, a triangular domain is produced there. From the series of photographs in Fig. 5D it follows that its boundary (one corner of the domain is seen) and the DW of a bubble domain are perfectly identical in structure (Fig. 5D(c)). We note that after turning off H_{pul} for a time comparable with the duration of the trailing edge of the field pulse (~ 50 nsec), the perturbtions that precede the DW disappear completely (Fig. 5D(d)). In maximum pulsed fields ($\Delta H\,(r = 0) \approx H^*_k$), the generation of local perturbations that precede the DW as they move backwards begins only at $\sim 1\,\mu$sec after the end of the pulse (Fig. 4, j–m). It can thus be seen that the pulse has substantially different dynamics in the presence of the pulsed magnetic field and after the field is turned off. The fact that when the DW moves backwards the generation of the perturbation begins only after a time much longer than in the case of forward motion (in the presence of H_{pul}) is apparently due to the inertia of the DW. The restructuring of the DW when the motion is reversed consumes a certain time. One cannot exclude the possibility that a substantial role is played here by the ratio of the durations of the leading and trailing edges of the field pulse.

It can be seen from Fig. 5 that for each value of the time τ there exists a limiting distance Δ from the perturbations to the DW that generate them and that with Δ increases substantially increasing H_{pul}. For the investigated sample, in the strongest pulsed fields, Δ did not exceed $\sim 11\,\mu$m. An analysis of the experimental data, similar to those shown in Fig. 5, has shown that as a rule in sufficiently weak H_{pul} the

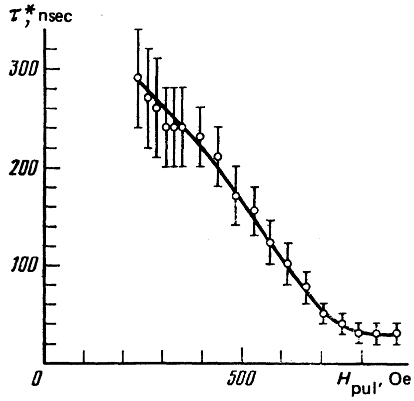

FIG. 6. Dependence of the minimum delay time of formation of the first magnetic perturbations on the intensity of the pulsed magnetic field H_{pul}.

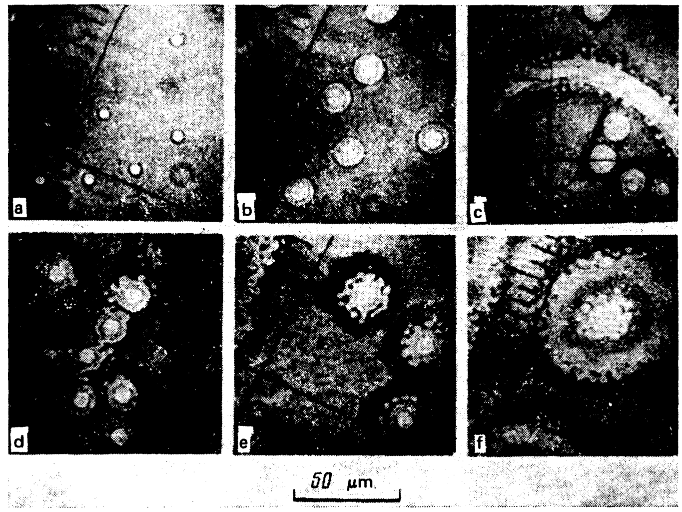

FIG. 7. Dynamic domain configurations observed in two-pulse illumination of a sample during the time of action of a magnetic-field pulse. The polaroids are slightly uncrossed, $\tau_{pul} = 1\ \mu$sec. *a*–Typical initial domain configuration, $H_b = 94$ Oe; $b - H_b = 90$ Oe, $H_{pul} = + + 0$ Oe, $\tau_1 = 0.1$, μsec, $\tau_2 = 0.4\ \mu$sec, $c - H_b = 90$ Oe, $H_{pul} = 290$ Oe, $\tau_1 = 0.1\ \mu$sec, $\tau_2 = 0.4, \mu$sec; $d - H_b = 94$ Oe, $H_{pul} = 590$ Oe, $\tau_1 = 0.1\ \mu$sec, $\tau_2 = \mu$sec; $e - H_b = 94$ Oe, $H_{pul} = 660$ Oe, $\tau_1 = 0.1\ \mu$sec, $\tau_2 = 0.4\ \mu$sec; $f = H_b = 94$ Oe, $H_{pul} = 660$ Oe, $\tau_1 = 0.4\ \mu$sec, $\tau_2 = 0.9\ \mu$sec.

perturbations are ejected to a distance of the order of 2.5–3 μm. In stronger fields, continuous generation of perturbations by the domain wall is observed. In this case it is of interest to determine the velocity v_{per} of propagation of the magnetic perturbations. It follows from experiment that, e.g., at H_{pul} values 330 and 680 Oe this velocity is respectively ~ 30 and ~ 50 m/sec, ie., with increasing H_{pul} the perturbation propagation velocity increases substantially.

For each value of $H_{pul} > H^*_{pul}$ there exists a critical delay time of the formation of the first perturbations. The dependence of the minimum delay time τ^* on H_{pul} is shown in Fig. 6. We note that for different domains (and different sections of DW of one and the same bubble) this time can differ substantially, apparently because of local changes of the DW structure in the course of the motion, and as a result of microdefects. It can be assumed that the observed dependence of τ^* on H_{pul} is determined by the fact that at the first instants of time after the start of the action of H_{pul} the DW are "accelerated" to the maximum velocity, the structure undergoes dynamic distortion, and in this case the wall "stores," so to speak, the energy until it reaches a certain critical value. Only then does the emission of perturbations begin. Since the local changes of the DW structure are quite sensitive to the microdefects, the experimentally observed scatter of the values of τ^* (see Fig. 6) in relatively weak pulsed fields ($H_{pul} \gtrsim H^*_{pul}$) becomes understandable. With increasing H_{pul}, the delay time decreases sharply, and the scatter of the experimental data becomes smaller. Within the framework of the suggestions advanced above, this can be explained by the fact that the time of the DW acceleration to the limiting velocity (the time of accumulation of energy) decreases with increasing H_{pul}. In this case, the influence of the DW interaction with the microinhomogeneities of the crystal on the instant of perturbation emission decreases, and it is this which leads to a lowering of the scatter of the experimental values of τ^*. Stabilization of the instant of the emission of the first perturbations at the level ~ 300 nsec for $H_{pul} > 700$ Oe is apparently connected only with the duration of the leading front of H_{pul} (~ 20 nsec), and with the characteristic times of the relaxation processes in the investigated film.

More complete information on nonrepeating dynamic processes of domain-structure conversion was obtained in experients with two-pulse illumination (Figs. 3, 7, 8). It follows from Figs. 3 and 7 that the perturbation-generation mechanism described above with a bubble domain as the example is perfectly valid for stripe and triangular domains. At fixed delays of the illumination pulses relative to the start of H_{pul}, $\tau_1 = 100$ nsec and $\tau_2 = 400$ nsec, we determined the average wall velocity $v = S/\tau_0$ from the distance S covered by the DW within the time $\tau_0 = \tau_2 - \tau_1$. The results are marked by points on Fig. 9. At a given time of averaging over all the pulsed fields possible for the given sample, saturation of the DW velocity v_0 is observed at a level ~ 12.5 m/sec. Experiments with two-pulse illumination (Figs. 7f and 8) have shown that the velocities of the walls of triangular, stripe and bubble domains are identical. We emphasize that the real velocity of the DW can be reliably determined if by the instant τ_2 the bubble did not lose completely its initial circular shape. It follows from Figs. 3, 5, and 7 that if we fix

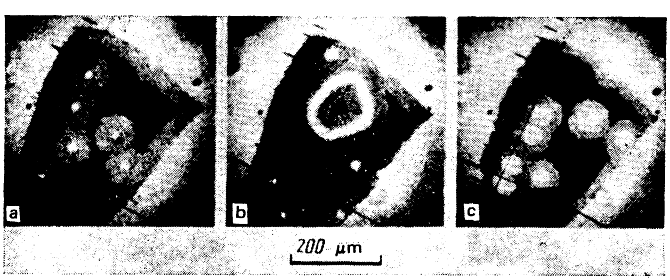

FIG. 8. Typical dynamic domain configurations obtained in experiments with two-pulse illunination. $H_b = 91$ Oe, $H_{pul} = 610$ Oe, $\tau_{pul} = 1.5\ \mu$sec. $a - \tau_1 = 0.3\ \mu$sec, $\tau_2 = 1.4\ \mu$sec; $b - \tau_1 = 0.4\ \mu$sec, $\tau_2 = 1.4\ \mu$sec; $c - \tau_1 = 0.7\ \mu$sec, $\tau_2 = 1.4\ \mu$sec.

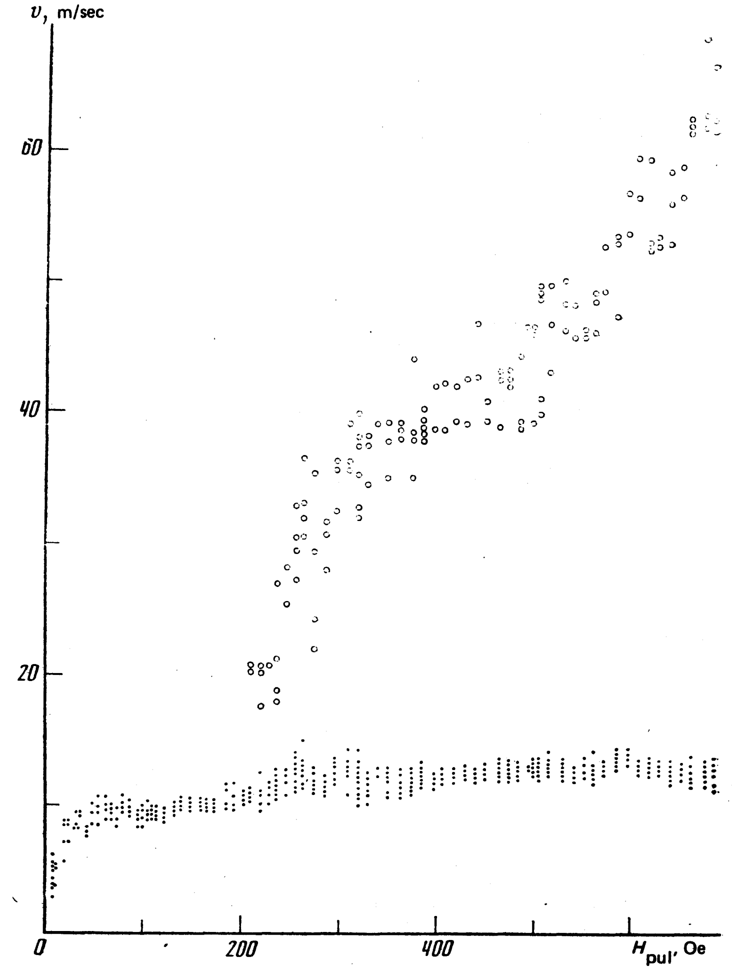

FIG. 9. Dependence of DW velocity on the intensity of the pulsed magnetic field H_{pul}: 0- real DW velocity; 0–"apparent" DW velocity.

at the instant of time τ_2 not the true position of the DW of the bubble that passes through the entire thickness of the film, but the perturbation and the microdomains farthest from the DW, then, using the described procedure for the determining the velocities at $H_{pul} \gtrsim H^*_{pul}$, we see that it increases abruptly, even though in this case the domain wall moves with velocity v_0. It follows from this figure that in sufficiently strong magnetic field, despite the fact that domain walls that penetrate through the entire thickness move at the saturation velocity v_0, the boundary between two magnetic phases moves with substantially larger velocity. Thus, the experimentally observed mechanism of generation of perturbations and microdomains by a moving DW leads to a considerable increase of the velocity of the interface of two phases. Using the procedure described above for determining the velocities and recording at the instant of time τ_2 the perturbations farthest from the DW, we have determined a certain "apparent" velocity that exceeds substantially the real DW velocity. The values of the apparent DW velocities obtained in this manner are marked by light circles on Fig. 9.

The calculations have shown that for the investigated samples the theoretical DW velocities in the saturation regime amount to $v_1 = v_w/2\pi \approx 17.5$ m/sec; $v_2 \approx 0.55 v_p \approx 12.5$ m/sec; $v_3 \approx 0.3\ v_p \approx 7$ m/sec $v_4 = v_w/5 \approx 22$ m/sec. The experimentally determined DW velocity v_0 in the saturation regime agrees with the theoretical value v_2 calculated by a formula given in Ref. 4. It is impossible, however, to conclude from this that this theory is perfectly valid for the description of the motion of DW in strong magnetic fields. This agreeent may be simply accidental, since a number of parameters of the investigated samples are determined with a rather large error. In the calculations, the exchange constant A was assumed equal to the exchange-interaction constant for $Y_3Fe_5O_{12}$, while γ was assumed equal to the gyromagnetic ratio of the free electron.

In an earlier study[25] as well as in a number of foreign papers,[21–24] observation of a so-called diffuse DW was reported. The experiments described above show that the diffuse broadening of the DW is apparently only illusory and is connected only with the low spatial resolution and the weak contrast of the images in Refs. 21–25. An analysis of the references cited above and a comparison of their results with our experimental data shows that the authors of Refs. 21–25 dealt apparently with the effect of generation of magnetic perturbations by the DW, which they could not observe because of the low spatial resolution of the apparatus. Because of this, the model of inclined DW proposed in Refs. 23–25 and the theory of motion of such a wall, developed in Ref. 26, are in our opinion in error.

A comparison of the experimentally observed generation of precursor perturbations by DW with the soliton mechanism proposed by Bar'yakhtar *et al.*[11] of imitation of the "superlimiting" motion of DW shows that within the framework of Ref. 11 the perturbations are apparently none other than magnetic solitons. Favoring this assumption are also the following facts: the propagation velocities of the perturbations exceed substantially the rate of saturation of the DW; no interaction was observed in the experients between the perturbations (see, e.g., Fig. 3, 5Da, and 7d and 7e). Magnetic perturbations so to speak do not "feel" one another and coalesce; no repulsion between them is observed. These experimental data agree qualitatively with the model representations and with the theories developed in Refs. 6–8 and 11.

However, one must not exclude completely other possibilities. In particular, a definite influence on the motion of DW in strong pulsed fields may be exerted by the layered character of the investigated samples. Nevertheless, the experimentally observed distinct detachment of the perturbations from the DW that generate them emphasizes that the observed mechanism of DW motion cannot be attributed to a simple difference between the velocities of the domain walls in different layers. It is not excluded that the experimentally observed singularities of the DW dynamics can be due to the mechanisms of dissipation of the Zeeman energy of the investigated sample, described in Refs. 8–12.

We note in conclusion that an investigation of the dynamics of domain structures by various indirect methods, as well as by the method of high-speed photography but with low spatial resolution and weak contrast of the image, can lead to an erroneous interpretation of the experimental results, owing to the existence of the already described generation of perturbations and microdomains by a moving DW. In particular, the substantial increase of the DW velocity in strong magnetic fields, observed by the authors of Refs. 13, 20, and 21, apparently due to generation of perturbations, is illusory and does not reflect the real velocity of the domain walls.

4. CONCLUSION

The main results of our study reduce to the following. A radiophysical research facility was developed to investigate with high spatial resolution ($\sim 0.3\ \mu$m) and time resolution (~ 8 nsec), in real time, nonrepeating high-speed dynamic processes in thin magnetic films in a pulsed-field range up to 4000 Oe. The develoed facility makes it possible to investigate the dynamics of weak-contrast magnetic domains of submicron size. It use made permits observation of a number of fundamentally new physical phenomena in polycrystalline IG films.

It was observed that there exist certain critical values of the external magnetic field intensity, close to the effective uniaxial-anisotropy field H_k^*, which demarcate the regions of existence of processes of reversal of the magnetization of IG films on account of motion of the DW and account of inhomogeneous rotation of the magnetization vectors. In strong pulsed gradient fields $H_{\rm pul} > H_k^*$, the inhomogeneous rotation of the magnetization vectors is effected by the motion of the magnetic-moment flopping wave. The velocity of this wave can exceed by more than an order of magnitude the minimum velocity of spin waves in the investigated samples. In weak-gradient pulsed fields $H_{\rm pul} > H_k^*$ the process of inhomogeneous rotation of the magnetization vector has a clearly pronounced "turbulent" character. The turbulent domain structure is characterized here by the fully defined dimensions of the isolated domains that do not pass through.

A new mechanism of DW motion in strong pulsed magnetic field was observed in experiment. When a certain critical intensity of the external pulsed field is exceeded, the local sections of the moving DW generate isolated magnetic perturbations that precede the DW. In the course of time, such perturbations are transformed as a rule into microdomains. Subsequently these microdomains broaden, generate around themselves new perturbations, and merge with the initial domain. The velocity of the DW does not exceed its limiting value v_0 in the entire range of fields of their existence. Since the propagation velocity of the perturbations exceeds the limiting velocity v_0 of the DW, the velocity of the interface between the magnetic phases can exceed v_0 significantly (effect of apparent superlimiting motion).

Within the framework of the existing theories[6–8,13] the perturbations generated by DW in the course of superlimiting motion are apparently magnetic solitons.

It was shown that the use of a procedure different from that described in the paper, or of similar apparatus but with smaller spatial and temporal resolution, can lead to an erroneous interpretation of the experimental results. In particular, the conclusions that in strong magnetic fields the DW can become inclined in the course of its motion (diffuse DW), and also that the DW velocity increases with increasing pulsed magnetic field, are apparently in error.

The authors are deeply grateful to V. G. Bar'yakhtar, B. A. Ivanov, F. V. Lisovskiĭ, M. V. Chetkin, and A. T. Morchenko for helpful discussions of the results.

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Translated by J. G. Adashko