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Magnetization Dynamics of Iron Garnet Crystals in Oscillating Magnetic Field

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Abstract
Using direct observations via stroboscopic technique it is shown that in iron garnet crystals placed in an alternating magnetic field aligned perpendicular to the plane of the sample the dynamic magnetization reversal is carried out by the oscillations of the domain walls with their subsequent drift. For the first time the dependences of the maximum speed of domain walls motion during oscillations V_{osc} and of the domain walls oscillations amplitude A_{osc} in external oscillating magnetic field on amplitude of the external magnetic field H_0 are obtained. It is shown that these dependences can be approximated by linear functions. Numerical simulations of domain walls motion in an alternating magnetic field were performed with parameters of the real sample. It is established that the experimental dependences $V_{osc}(H_0)$ and $A_{osc}(H_0)$ at different frequencies are in a qualitative agreement with the results of numerical simulations.

Keywords: Magnetization dynamics, Domain walls oscillations, Drift, Iron garnet crystals, Numerical modeling

1 Introduction

A study of the domain structure (DS) of single crystals in alternating magnetic fields allows to determine the mechanisms of dynamic magnetization reversal. It is known that the magnetization reversal in a harmonic magnetic field occurs by the vibrational motion of the domain walls (DW). It was shown in [1] that in iron garnet single crystals in alternating magnetic fields of various orientation the increase of field amplitude to a certain value leads to the start of the drift of the DW. The drift is defined as a translational motion of the domain structure as a whole in the direction perpendicular to the plane of the domain walls in an oscillating magnetic field. In [1] a dislocation mechanism of the drift of the domain walls was proposed. A number of works were devoted to experimental study of the drift of the domain walls in iron garnet single crystals [2-5]. In [6] the reorientation of the DW in the

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(111) iron garnet plate in a constant magnetic field applied perpendicular to the plane of the sample was investigated and it’s theoretical explanation was given. In [4] a reorientation of DW under the influence of an alternating magnetic field applied perpendicular to the plane of the plate was detected.

In [7] the drift of stripe domain structure was obtained by numerical simulation of vibrational motion of DW system modelled by the system of motion equations with non-homogeneous initial conditions for neighboring DW for frequencies that are close to natural vibration frequency of the DW system. In [3, 4] numerical simulation of DW motion was performed for frequencies around 10^2 Hz, where the drift is observed experimentally, and dependences of DW oscillations amplitude on amplitude of external magnetic field for the process of DW drift with reorientation of DW were presented. In [5] a model of stripe domain structure motion that includes attenuation associated with attenuation of magnetization precession in magnetic field was proposed. In contrast to the earlier results of [3, 4, 7], it was shown that the drift of stripe domain structure takes place in the model in case of homogeneous initial conditions and proceeds despite the presence of attenuation.

In this paper the mechanism of dynamic magnetization reversal in the case of (111) iron garnet crystal-plate is investigated. The dependences of domain walls drift speed, domain structure period, amplitude of domain walls oscillations and maximum speed of DW motion during oscillations on amplitude of external oscillating magnetic field at various frequencies are established. Numerical simulations confirm that the dependences of the maximum speed of DW motion on external field amplitude have linear character and the dependences of DW oscillations amplitude on external field amplitude are close to linear.

2 Experimental Results

In this paper the mechanism of dynamic magnetization reversal is investigated for the case of (111) iron garnet $(TbErGd)_3(FeAl)_5O_{12}$ 73 μm thick crystal-plate. The parameters of the sample: saturation magnetization Ms = 40 Gs, constant of induced uniaxial magnetic anisotropy K_u = 5500 erg/cm^3, magnetocrystalline anisotropy constant K_1 = -3400 erg/cm^3, rhombic anisotropy constant K_p = 3200 erg/cm^3, exchange interaction constant $A \approx 10^{-7}$ erg/cm. The sample was placed in an alternating magnetic field $H = H_0 sin(2\pi ft)$, applied perpendicular to the plane of the sample. The field frequency f was changed in the range of 100 - 800 Hz, the field amplitude H_0 reached up to 350 Oe. Dynamic domain structure (DDS) was revealed by stroboscopic technique using the magneto-optical Faraday effect and was captured by a high-speed camera (at the rates up to 1200 fps). A solid state pulsed laser with a wavelength of 527 nm and a pulse duration of 25 ns was used to visualize the DDS. Generation of pulses of illumination was synchronized with the alternating magnetic field. This allowed to obtain a series of images of DDS for the successive phases of the magnetic field. For each value of the phase of the field the average widths of domains with opposite magnetization were measured. Dependences of the widths of the domains on the phase of the field were approximated by the sine function. The amplitude of DW oscillations A_{osc} and the maximum speed of DW during oscillations V_{osc} were obtained from the fitting parameters. The speed of drift was measured based on the change of DW position in the successive moments of time.

Experimental results are shown in Figures 1-6. The drift of DW is observed in the iron garnet sample in the vertically oriented harmonic magnetic field. The dependences of V_{dr} in the sample for frequencies 100 – 800 Hz are presented on Figure 1.

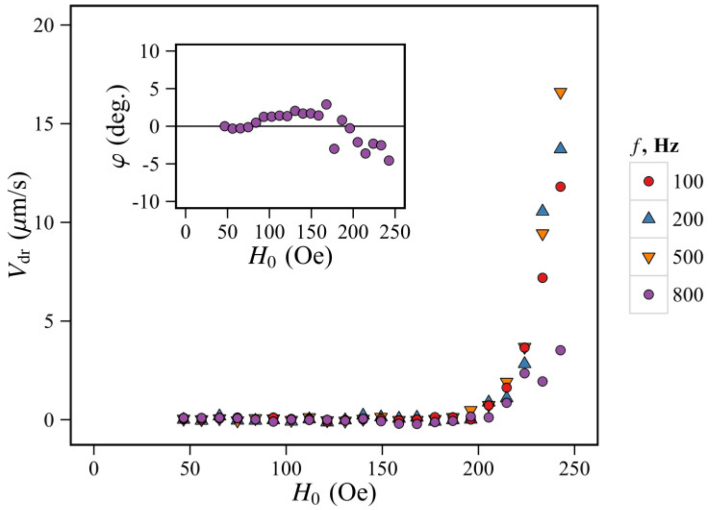

Figure 1: Dependences of domain walls drift speed V_{dr} at frequencies f = 100, 200, 500, 800 Hz and domain walls orientation angle φ at f = 800 Hz on harmonic field amplitude.

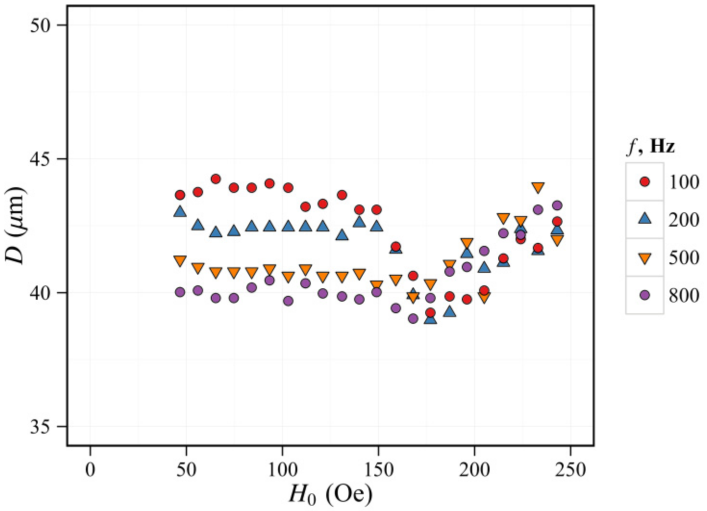

Figure 2: Dependences of domain structure period D on harmonic field amplitude at frequencies f = 100, 200, 500, 800 Hz.

The dependence of the drift speed on the amplitude of the external field has a threshold character: for each frequency the drift of the DW is observed starting from a certain amplitude of external oscillating field H_{dr}. The values of H_{dr} decrease monotonically from H_{dr} = 215 Oe for f = 100 Hz to H_{dr} = 190 Oe for f = 800 Hz. After reaching the amplitude value of H_{dr} the speed of translational motion of the domain walls increases as a quadratic function with increase of the amplitude of the external field. In the investigated range of frequencies the drift speed is almost independent on frequency. The character of the dependence of the drift speed on amplitude and frequency of the external field is consistent with the results of theoretical work [8]. The authors of [8] have developed a phenomenological theory of drift of solitary 180-degree domain walls in a weak linearly polarized oscillating magnetic field in uniaxial ferromagnets. It was shown that for the case, when the external magnetic field is applied perpendicular to the plane of the sample, for frequencies that are much smaller than the frequency of ferromagnetic resonance the drift speed depends on the amplitude of external field as a quadratic function and doesn't depend on frequency.

The observations show that for the field amplitude $H_0 > 150$ Oe there occur changes in orientation of domain walls and in the period of the domain structure, which continue for the field amplitude values $H_0 > H_{dr}$. Figure 2 shows that the period of DS is almost constant until $H_0 = 150$ Oe and decrease of the period of DS is observed with increase of the frequency (decrease of the period of DS with increase of frequency was reported in [9]); for 150 Oe < H_0 < 175 Oe the period of DS decreases; for $H_0 > 175$ Oe the period of DS increases again (e.g. at frequency f = 800 Hz the period changes from 40 μm to 44 μm). The inset in Figure 1 shows the dependence of an angle φ of deviation of DW from equilibrium orientation at frequency f = 800 Hz. At $H_0 > H_{dr}$ the domain walls reorient to an angle $\varphi = 5°$.

Throughout the investigated range of the external field amplitude values the domain walls oscillate with the frequency of the field. In this paper the following characteristics of the vibrational motion of the DW were investigated: the amplitude of oscillations of the DW A_{osc} and the maximum speed of the DW V_{osc} for the period of the field.

Figure 3 shows the dependence of domain walls oscillations amplitude A_{osc} on amplitude of the external magnetic field H_0. It can be seen that amplitude A_{osc} is almost independent on the frequency f in the frequency range of 100-500 Hz and increases monotonically with the field amplitude H_0. The dependence of A_{osc} on the amplitude of the alternating magnetic field H_0 can be approximated by a linear function. A maximum value $A_{osc} \cong 9.5$ μm is reached at $H_0 \cong 250$ Oe.

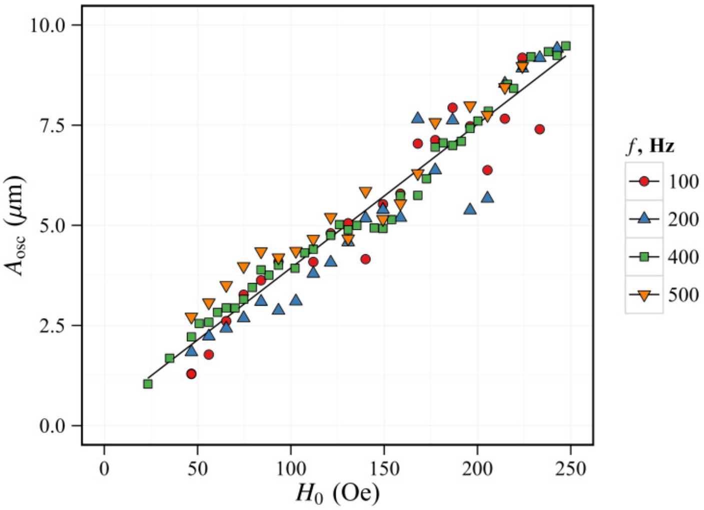

Figure 3: Dependences of amplitude of domain walls oscillations A_{osc} on external oscillating field amplitude H_0 at frequencies f = 100, 200, 400, 500 Hz. The line is a linear approximation of points.

Figure 4 shows the dependences of maximum of DW speed during oscillations V_{osc} on H_0 for frequencies f = 100, 200, 400, 500 Hz. V_{osc} depends linearly on the amplitude and frequency of the field. It should be noted that the value of V_{osc} is by three orders of magnitude greater than the speed of drift at the given parameters of the experiment.

With the increase of the field amplitude H_0 over 250 Oe the regular stripe domain structure that is shown in Figure 5 transforms (Figure 6) and the motion of the domains becomes disordered.

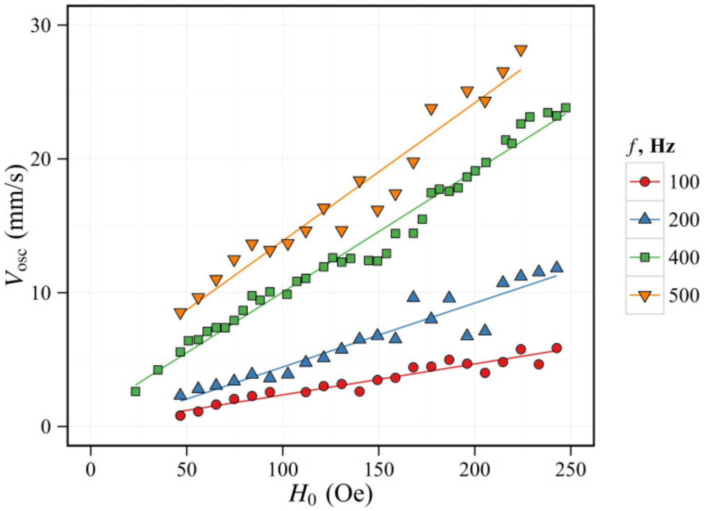

Figure 4: Dependences of maximum speed of DW motion during oscillations V_{osc} on external oscillating field amplitude H_0 at frequencies f = 100, 200, 400, 500 Hz. The lines are linear approximations of points.

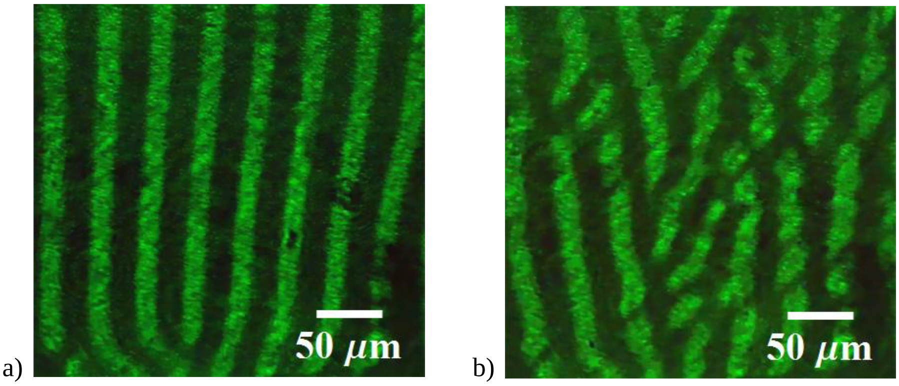

Figure 5: Magneto-optical images of the domain structure in iron garnet sample in harmonic magnetic field at f = 100 Hz a) H_0 = 225 Oe; b) H_0 = 260 Oe.

3 Numerical Simulations

Numerical simulations of DW motion were performed using the model of forced oscillations of a system of coupled harmonic oscillators (see, e.g., [10, 5]). We assume that internal structure of DW does not change during the motion, DW has effective mass and moves due to pressure forces acting on its surface.

The model of stripe domain structure in a plane-parallel uniaxial plate with thickness *L* is given in Figure 6. External magnetic field $H(t) = H_0 \sin(\omega t)$ is applied perpendicular to the plane of the sample parallel to the OZ axis.

The easy axis of magnetization is perpendicular to the sample plate and parallel to the OZ axis. Magnetization vectors $\boldsymbol{M_s}$ in the domains are oriented either along the OZ axis or in the opposite direction. The period of the domain structure is equal to 2*D*, where *D* is the width of a single domain in the absence of external magnetic field.

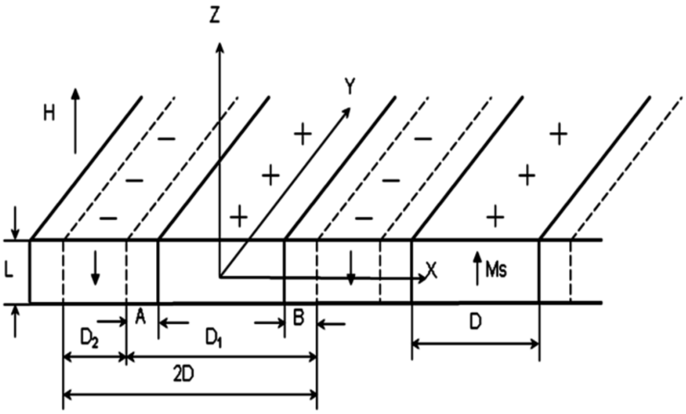

Figure 6: The model of stripe domain structure in a plane-parallel uniaxial plate.

Here the displacements of domain walls from their position in the absence of magnetic field are denoted by *A* and *B*. Such displacements are equal for all periods of the domain structure at any given moment of time. Thus, for every period $D_1 = D + A + B$, $D_2 = D - A - B$.

The following forces are acting on the DW: external oscillating magnetic field force that shifts the DW from equilibrium, “restoring” force associated with magnetostatic energy of stripe domain structure and dynamic friction force associated with attenuation of magnetization precession in magnetic field. Coercivity of domain walls is not considered in this model.

The symmetry of the problem allows to write down the motion equations for two neighboring domain walls, which is sufficient to describe the motion of all domain walls in the given model of domain structure.

The energy densities of external magnetic field γ_H and of magnetostatic energy γ_m have the following form [11]:

$$\gamma_H = M_S H_0 \left(1 - \frac{D_1}{D}\right) \sin \omega t \ , \tag{1}$$

$$\gamma_m = 2\pi M_S^2 \left(\frac{D_1 - D_2}{2D}\right)^2 + \frac{16 M_S^2 D}{\pi^2 L} \sum_{n=1}^{\infty} \left\{ \frac{1}{n^3} \left[1 - \exp\left(\frac{-\pi n L}{D}\right) \right] \sin^2\left(\frac{\pi n D_1}{2D}\right) \right\} \tag{2}$$

Differentiating these expressions with respect to DW offsets and taking attenuation into account, we obtain the following system of motion equations for offsets of two neighboring domain walls (in dimensionless variables):

$$\begin{cases}\dfrac{\partial^2 a}{\partial \tau^2}+\eta\dfrac{\partial a}{\partial \tau}+f(a,b)+\Delta-\pi h\sin(\nu\tau)=0\\ \dfrac{\partial^2 b}{\partial \tau^2}+\eta\dfrac{\partial b}{\partial \tau}+f(a,b)-\pi h\sin(\nu\tau)=0\end{cases}, \qquad (3)$$

where

$$f(a,b)=\frac{a+b}{2}+\frac{2}{\ell}\sum_{n=1}^{\infty}\left[\frac{(-1)^n}{n^2}[1-\exp(-n\ell)]\sin\frac{n(a+b)}{2}\right], \qquad (4)$$

here $a = 2\pi A/D$ and $b = 2\pi B/D$ are dimensionless variables, that correspond to the displacements of left and right domain walls, respectively, $\ell = \pi L/D$, $h = H_0/4\pi M_s$, $\omega = 2\pi f$, $\nu = \omega/\Omega$, $\tau = t\Omega$, $\Omega^2 = 8\pi M_s^2/mD$, m is an effective mass of DW per unit area, $\eta = \alpha(D/(A/K_u)^{1/2})^{1/2}$ is a dimensionless attenuation parameter, $\alpha = 0{,}45$ is an attenuation parameter [12].

Constant term Δ in the first equation in (3) corresponds to the difference of forces that act on the domain walls. At $\Delta = 0$ a homogeneous oscillating magnetic field will only cause oscillations of DW in the model without translational motion of the domains. In [3, 4, 7] the drift in similar models was caused by the difference of initial velocities of two neighboring domain walls. However, in the case when attenuation is present, it is not possible to obtain DW drift in the model using this method. In [5] we have shown that constant term Δ that corresponds to the difference of forces that act on the domain walls may cause the drift in the model with non-zero attenuation and estimated Δ required to attain certain experimentally observed speed of drift. Parameter Δ may correspond to additional inhomogeneous constant magnetic field applied to the sample or to inhomogeneous magnetization in the plate's plane. In the simplest case of weak gradient inhomogeneity, i.e. when the inhomogeneity is described by a linear function of coordinate, the difference of forces that act on the domain walls is proportional to the distance between the DW. For stripe domain structure this will correspond to the force that acts on the domain and doesn't depend on the coordinate.

System (3) was solved using Wolfram Mathematica (c) (LSODA solver) [13] with homogeneous initial conditions and with parameters of the real sample. The behavior of the solution qualitatively agrees with the experiment: the neighboring DW oscillate in antiphase and move translationally.

Figure 7 shows the dependence of maximum speed of the DW during oscillations on amplitude of the external magnetic field for various frequencies. V_{osc} linearly increases with H_0 and the slopes of linear functions increase with increase of frequency which is in qualitative agreement with the experimental data of Figure 4. The effect of drift on the dependences of V_{osc} on the amplitude of the external field in the model is very small due to very low speed of drift in the experimental setup.

The dependence of amplitude of oscillations on the amplitude of the external magnetic field is close to linear. The amplitude increases with increase of the amplitude of external magnetic field which is also in a qualitative agreement with the experimental data of Figure 3.

The motion of stripe DS can be considered as oscillations of DW as a system of coupled oscillators in an alternating magnetic field that are oscillating in opposite phases. Therefore, the oscillations of such system are similar to oscillations of oscillator under the influence of harmonic force. From the theory of oscillations (see, e.g. [14]) it is known that the speed during oscillations of an oscillator is proportional to the amplitude of the force that is applied, that is, to the amplitude of the external magnetic field, and also is a function of the frequency of the external force (in the investigated frequency range the speed is approximately proportional to the frequency of the external force). The amplitude of oscillations of an oscillator is linearly dependent on the amplitude of the external field and is almost independent on frequency. This confirms that the proposed model adequately describes the experimental dependences.

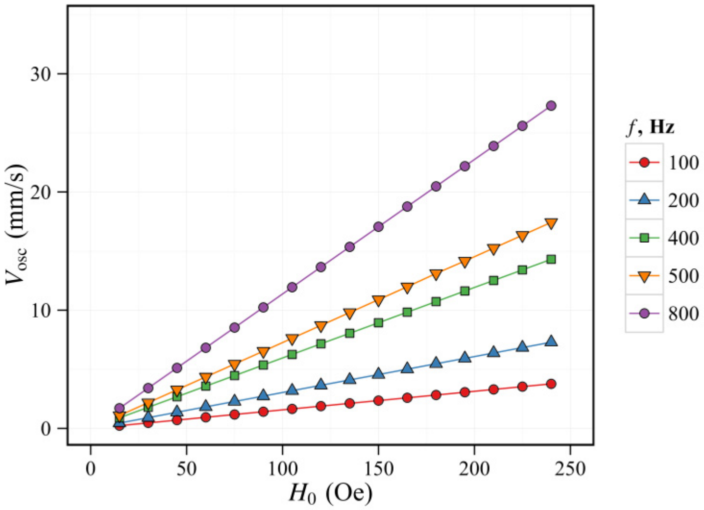

Figure 7: The dependence of maximum speed of the DW during oscillations on amplitude of the external magnetic field for various frequencies.

4 Conclusions

It was established experimentally that dynamic magnetization reversal in iron garnet crystals is carried out by local oscillations of domain walls and their drift. For the first time maximum speeds of DW motion during oscillations were measured using direct method (stroboscopic technique) at frequencies up to 1000 Hz. The dependences of maximum speed of DW motion V_{osc} on the external field amplitude H_0 were obtained. It is established that these dependences can be approximated by linear functions. It was observed that the maximum speed of DW motion during oscillations can be by three orders of magnitude higher than the drift speed of the DW.

Numerical simulations of domain walls motion in an alternating magnetic field were performed with the parameters of the real sample. A qualitative agreement was established between experimental and simulated dependences of maximum DW speed V_{osc} and amplitude of oscillations A_{osc} on the external field amplitude for various frequencies.

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References

[1] L.A. Pamyatnykh, M.S. Lysov, G.S. Kandaurova, Bull. Russ. Acad. Sci. Phys., 71(11) (2007) 1497.

[2] L.A. Pamyatnykh, M.S. Lysov, G.A. Shmatov, G.S. Kandaurova, A.V. Druzhinin, Bull. Russ. Acad. Sci. Phys. 74, (2010) 1417.

[3] L.A. Pamyatnykh, A.V. Druzhinin, M.S. Lysov, S.E. Pamyatnykh, G.A. Shmatov, Bull. Russ. Acad.Sci. Phys.77, (2013) 1231.

[4] L.A. Pamyatnykh, G. A. Shmatov, M.S. Lysov, S.E. Pamyatnykh, D.S. Mehonoshin, Solid State Phenomena, 215 (2014) 437.

[5] L.A. Pamyatnykh, G.A. Shmatov, S.E. Pamyatnykh, M.S. Lysov, D.S. Mekhonoshin and A.V. Druzhinin, Acta Physica Polonica A, 127(2), (2015) 388.

[6] G.S. Kandaurova, L.A. Pamyatnykh, M.A. Shamsutdinov and B.N. Filippov, The Fiz. Met. Metalloved., 78 №4 (1994) 26.

[7] M.M Solov'ev, B.N. Filippov, Phys. Met. Metallogr. 98 (2004) 241.

[8] V.G.Bar’yakhtar,Yu.I.Gorobets, and S.I.Denisov, JETP, 98(4), (1990) 1345.

[9] V.K. Vlasko-Vlasov, L.M. Deduh, V.I. Nikitenko, and L.S. Uspenskaya, Physics of the Solid State, 24(4), (1982) 1255.

[10] S. Chikazumi, *Physics of Ferromagnetism,* Clarendon Press, Oxford, 1997.

[11] G.S. Kandaurova, L.G. Onoprienko, *The main problems of the theory of magnetic domain structure*, UrGU, Sverdlovsk, 1977.

[12] Y.M. Yakovlev, S.S. Gendelev, *Ferrite monocrystals in electronics*, Soviet radio, Moscow, 1975.

[13] A.C. Hindmarsh, ODEPACK, A Systematized Collection of ODE Solvers, *IMACS Transactions on Scientific Computation*, 1, Scientific Computing, North-Holland, Amsterdam, 55 (1983).

[14] I.M. Babakov, *Theory of oscillations*, Drofa publishing, Moscow, 591 p., 2004.