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71°- domain wall in cubic crystal with photoinduced magnetic anisotropy

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The influence of photoinduced anisotropy on Bloch 71°-domain wall in cubic magnetically ordered (100) crystal with negative constant of cubic magnetic anisotropy is studied. Equilibrium domain wall parameters (the surface energy density, orientation, and effective width) of the- wall have been found as functions of parameters (the constant value and easy axis orientation) of the photoinduced magnetic anisotropy. The energy density of the domain wall has been shown to be able both to increase and decrease, depending on the crystal irradiation conditions.

Изучается влияние фотоиндуцированной магнитной анизотропии на 71°- плоскую блоховскую доменную границу в кубическом магнитоупорядоченном (100)-кристалле с отрицательной константой кубической магнитной анизотропии. Найдены равновесные параметры исследуемой доменной границы (поверхностная плотность энергии, ориентация и эффективная ширина) в зависимости от параметров (значение константы и ориентация легкой оси) фотоиндуцированной магнитной анизотропии. Показано, что плотность энергии такой доменной границы может как возрастать, так и уменьшаться в зависимости от условий облучения кристалла.

The structure and parameters of domain walls (DW) in crystals with combined (natural cubic and induced uniaxial) magnetic anisotropy (MA) were studied in [1, 2]. A specific feature of photoinduced magnetic anisotropy (PMA) consists in that its constant value, orientation of its easy axis and spatial distribution of its energy density depend on the polarization vector orientation of the incident radiation [3, 4] and that these characteristics are changed during the irradiation process [5, 6]. An influence of PMA on DW structure in cubic (110) single crystal was investigated in [7], where the incident radiation polarization vector was oriented along the easy magnetization axis (EMA) direction. It is established [7] that as the PMA energy density increases, the DW surface energy density increases and DW effective width decreases, while the dependence of the DW energy density upon the angle between DW plane and surface of the crystal vanishes. The influence of spatial distribution of PMA energy density on the structure of 180°-DW was considered in [8]. It was shown [8] that the appearance of planar inhomogeneities in PMA results in changes in the spatial distribution of the magnetization vector **M** orientation in DW and DW energy density depends upon the linear dimensions of the mentioned inhomogeneous region and the PMA constant change in its volume. A model of photoinduced local deformation of DW different from the 180° one [9] was developed to describe phenomena of DW deformation [9, 10] observed in cubic ferrimagnetic (100) single crystals. It is note that photoinduced changes of DW parameters itself (DW energy density, its plane orientation, etc.) are neglected within the model [10]. The purpose of this work is to study the influence of PMA caused by normal irradiation of (100) crystal with linearly polarized light on the structure of the 71 deg flat Bloch DW (71°-DW).

The energy density of cubic magnetic anisotropy (CMA) [11] is:

$$e_{CMA} = K_1(\alpha_1^2\alpha_2^2 + \alpha_2^2\alpha_3^2 + \alpha_3^2\alpha_1^2) + \ldots,$$

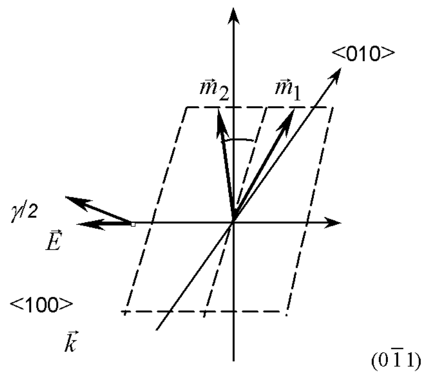

Fig. 1. Coordinate system.

where α_1, α_2 and α_3 are direction cosines of **M** relatively to crystallographic <100>, <010> and <001> directions, respectively; K_1, the first CMA constant [11].

The energy density of PMA, e_{PMA}, at the normal irradiation of cubic photomagnetic (100) crystal is described by the following expression [5]: $e_{PMA} = -2G\mathrm{sign}(p_x p_y)\alpha_2\alpha_3$. At $\mathrm{sign}(p_x p_y) > 0$ it can be presented as the total energy of uniaxial anisotropy with easy magnetization axis (EMA) along <011> direction and plane anisotropy with easy $(0\bar{1}1)$ plane:

$$e_{PMA} = -G\mathrm{sign}(p_x p_y)[(\alpha_2 + \alpha_3)^2 - (\alpha_2 - \alpha_3)^2]/2, \quad (1)$$

where G is PMA constant; p_x and p_y, polarization vector components along <010> and <001> crystallographic directions, respectively. For a crystal with CMA in the initial (prior to irradiation) state, the PMA constant at the arbitrary moment of irradiation has the form:

$$G = (4/3)\bar{\lambda}N|B||p_x p_y| \times [1 - \exp(-4At(3A_0 + B)/3)]/(3A_0 + B), \quad (2)$$

where $\bar{\lambda}$ is spin-orbital splitting constant; N, the number of active centers [12]; t, the irradiation time; $A_0 = [1 + (\nu_1/A)\exp(-E_1/kT) + (\nu_2/A)\exp(-E_2/kT)]$, E_1 and E_2 being low- and high-temperature activation energies of thermoactive transitions, respectively; ν_1 and ν_2, frequency factors corresponding thereto; $A = a_0 KI$, a_0 and B, phenomenological constants, K being the probability of active center transition from an excited state to one of four octahedral orientation inequivalent sites [12] of the cubic crystal; I, the light intensity.

The energy density e_{MA} of combine (cubic and photoinduced) magnetic anisotropy (CPMA) is presented as $e_{MA} = e_{CMA} + e_{PMA}$. If φ and θ are azimuth and polar angles of vector **M**, respectively (θ and φ are counted respectively from the normal to DW and from the direction being perpendicular to the difference $\Delta\mathbf{m} = \mathbf{m}_1 - \mathbf{m}_2$ and lying in DW plane (Fig. 1), where $\mathbf{m}_1$ and $\mathbf{m}_2$ and are unit vectors along vectors **M** in adjacent domains), then $\alpha = \{\alpha_1, \alpha_2, \alpha_3\}$ in Bloch DW takes the form:

$$\alpha = (\mathbf{e}_1\cos(\lambda) + \mathbf{e}_3\sin\lambda)\sin\theta\cos\varphi + \mathbf{e}_2\sin\theta\sin\varphi + (\mathbf{e}_3\cos\lambda - \mathbf{e}_1\sin\lambda)\cos\theta, \quad (3)$$

where $\mathbf{e}_1 = \dfrac{\mathbf{m}_2\times\mathbf{m}_1}{|\mathbf{m}_2\times\mathbf{m}_1|}$; $\mathbf{e}_2 = \dfrac{\mathbf{m}_2 - \mathbf{m}_1}{|\mathbf{m}_2 - \mathbf{m}_1|}$; $\mathbf{e}_3 = \dfrac{\mathbf{m}_2 + \mathbf{m}_1}{|\mathbf{m}_2 + \mathbf{m}_1|}$; $\sin\theta = \sqrt{1 - \cos^2\gamma\cos^2\lambda}$; λ is the angle between the normal to DW plane and the plane of $\mathbf{m}_1$ and $\mathbf{m}_2$. Here, γ is the half angle between vectors $\mathbf{m}_1$ and $\mathbf{m}_2$. For 71°-DW in a crystal with CPMA, γ is determined by $\sin\gamma = \sqrt{1 - 2\eta)/3}$, where $\eta = g \cdot \mathrm{sign}(p_x p_y)$ and $g = G/|K_1|$. The variation ranges of φ in DW with the right and left-handed rotation **M** are $\varphi_1 = -\varphi_0 < \varphi < \varphi_2 = +\varphi_0$ and $\varphi_1 = \varphi_0 < \varphi < \varphi_2 = 2\pi - \varphi_0$, respectively, where $\varphi_0 = \arccos(\cos\gamma\sin\lambda/\sqrt{1 - \cos^2\gamma\cos^2\lambda})$, $(\gamma < \varphi_0 < \pi - \gamma)$.

Then for a 71°-DW, the energy density σ, magnetization distribution $\tilde{z}(\varphi)$, and DW effective width δ can be presented as follows [11, 13]:

$$\sigma = 2\int_{\varphi_1}^{\varphi_2}\sqrt{A_{ex}\sin^2\theta\left(e_{MA}(\theta,\varphi) - e_{MA}(\theta,\varphi_1)\right)}d\varphi, \quad (4)$$

$$\tilde{z}(\varphi) = \int_0^{\varphi}\sqrt{A_{ex}\sin^2\theta/\left(e_{MA}(\theta,\zeta) - e_{MA}(\theta,\varphi_1)\right)}d\zeta,$$

$$\delta = \tilde{z}_2^* - \tilde{z}_1^* + \sqrt{A_{ex}\sin^2\theta}\left(\frac{\varphi_2 - \varphi_2^*}{\sqrt{\left(e_{MA}\left(\theta,\varphi_2^*\right) - e_{MA}\left(\theta,\varphi_1\right)\right)}} - \frac{\varphi_1 - \varphi_1^*}{\sqrt{\left(e_{MA}(\theta,\varphi_1^*) - e_{MA}(\theta,\varphi_1)\right)}}\right), \quad (5)$$

where $\tilde{z}$ is the spatial coordinate along the DW normal, $\tilde{z}_2^*$ and $\tilde{z}_1^*$, the maximum and minimum coordinates of the inflection points in the $\tilde{z}(\varphi)$ dependence, respectively; φ_2^* and φ_1^*, the azimuth angle φ values at $\tilde{z}_2^*$ and $\tilde{z}_1^*$ respectively; A_{ex}, the exchange constant.

Angular dependences of 71°-DW energy density are shown in Fig. 2. In the Figure, $\sigma_0 = \sqrt{|K_1|A_{ex}}$ and $\delta_0 = \sqrt{A_{ex}/|K_1|}$ are characteristic units of DW area energy density and DW effective width, respectively [12]. The mentioned dependences for DW with opposite directions of **M** rotation are symmetric with respect to $\lambda = 0$. Only angular dependences for 71°-DW with right-handed rotation are shown in Fig. 2. The dashed curves show the angular dependence of 71°-DW energy density in crystal with CMA only [12] ($K_1 < 0$; $g = 0$).

The dependence of 71°-DW energy density on the PMA constant is defined by orientation of **E** with respect to crystallographic directions of the medium. If in the initial state ($g = 0$), $\mathbf{m}_1$ and $\mathbf{m}_2$ are directed along $\langle 111\rangle$ and $\langle\bar{1}11\rangle$ directions, respectively, then the 71°-DW energy density decreases for $\lambda > 0$ as the PMA constant rises (Fig. 2a) at $\eta > 0$ (at orientation within the deviations by ±45° from $\pm\langle 011\rangle$, that is the intersection of the plane of $\mathbf{m}_1$ and $\mathbf{m}_2$ with (100)-plane) while it increases (Fig. 2b) within the remaining range of **E** orientations ($\eta < 0$). This is explained by the change of γ with the increasing G ($2\gamma \approx 21°$ at $G = 0.45|K_1|$ for $\eta > 0$ and $2\gamma \approx 109°$ at $G = 0.5|K_1|$ for $\eta < 0$). These changes in γ result in increasing (for $\eta < 0$) or decreasing (for $\eta > 0$) variation range of φ in 71°-DW that results in increasing or decreasing σ, respectively. An opposite situation takes place for $\lambda < 0$ (Fig. 2).

The direction of **E** defines the sign of η and, therefore, the pair of EMA which have projections on (100) plane making up a minimum angle with the direction of vector **E**. The MA energy density along these EMA decreases as g increases. The MA energy density along two other EMA increases. The appearance of directions with e_{MA} lower than in domain volume on the way of **M** rotation, is possible at orientation of $\mathbf{M}_1$ and $\mathbf{M}_1$ along EMA with increasing MA energy density. For $\eta < 0$, there are ranges of λ with the trajectory of **M** including directions with CPMA energy density lower than in domain volume. A Bloch DW with such

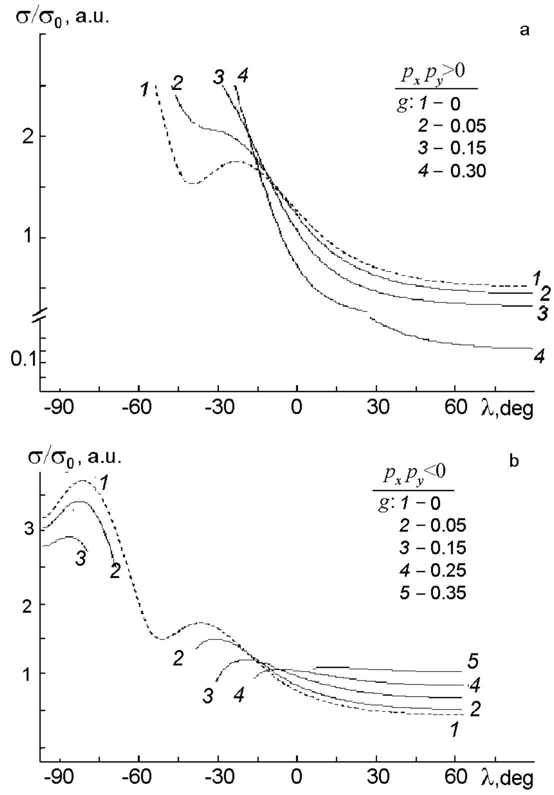

Fig. 2. Angular dependences of 71°-DW energy density for $\eta > 0$ (a) and $\eta < 0$ (b).

orientations is impossible (Fig. 2). These orientations are in the neighborhood of a local minimum in the angular dependence of 71°-DW energy density for $g = 0$. At $g = 0$, the **M** trajectory in a 71°-DW with orientation corresponding to this local minimum passes close to directions of two EMA not collinear with $\mathbf{m}_1$ and $\mathbf{m}_2$.

The equilibrium 71°-DW plane orientation remains parallel to the plane of $\mathbf{m}_1$ and $\mathbf{m}_2$ for both above-mentioned cases, $\eta > 0$ and $\eta < 0$. For this orientation ($\lambda = 90°$ in Fig. 2), the angular dependence of MA energy density on the way of **M** rotation has a single maximum that corresponds to one inflection point in the φ dependence on the coordinate along the DW normal (Fig. 3a). So, taking into account (3) and (5), the effective DW width can be presented as

$$\delta = 2\varphi_0\sqrt{A_{ex}\sin^2\theta}/\sqrt{\left(e_{MA}(\theta,\varphi) - e_{MA}(\theta,\varphi_1)\right)} \quad (5a)$$

In the equilibrium state ($\lambda = 90°$), expressions (4) and (5a) take the simplified form:

$$\sigma = \sigma_0\sqrt{3}([\sin(2\gamma)/2] - [(4\eta + 1)\gamma/3]), \quad (6)$$

$$\delta/\delta_0 = 4\sqrt{3}\gamma/[1 - 2\eta] = 4\gamma/(\sqrt{3}\sin^2\gamma). \quad (7)$$

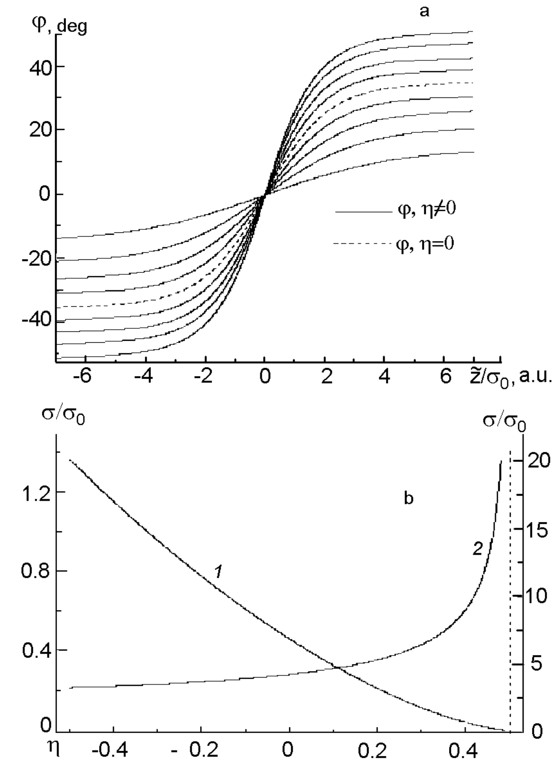

Fig. 3. Distribution of magnetization (a) and the dependence of energy density (curve 1) and effective width (curve 2) of a 71°-DW at the equilibrium orientation on the parameter η (b). The values in Fig (a) vary within the limits −0.4 to 0.4 at 0.1 steps. Larger ranges of φ change correspond to smaller η values.

At $\eta = 0$, (6) and (7) give the values of area energy density and effective width of 71°-DW parallel to (100) type plane in a cubic crystal with $K_1 < 0$ [13]. The dependences of energy density (curve 1) and effective width (curve 2) of a 71°-DW at the equilibrium orientation on the parameter η are shown in Fig. 3b. The effective width of 71°-DW tends to infinity (curve 2 in Fig. 3b) as **M** directions in domains disjoint by the DW become closer (η tends to 1/2 what is a condition for crystal with single-axis MA). This is associated with the fact that the energy barrier which **M** overcomes while turning between the domain directions, decreases as η grows, reaching zero value at $\eta = 1/2$. The low MA energy density on the way of magnetization rotation turn results in slower **M** turn (Fig. 3a), as for one-dimensional distributions of **M** in the volume with homogeneous MA, the densities of exchange and MA energy are equal at each point due to the conservation law.

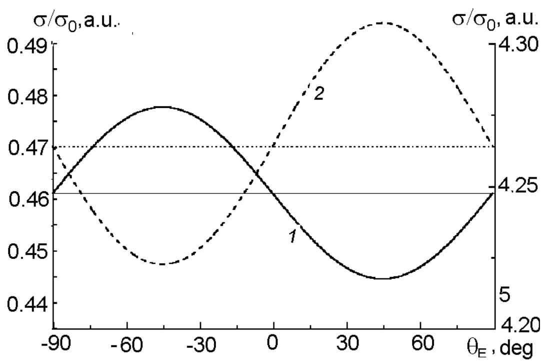

Fig. 4. Polarization dependences of energy density (curve 1) and effective width (curve 2) of a 71°-DW in $Y_2Fe_5O_{12}$:Si.

At $G << K_1$, the corrections $\Delta\sigma$ and $\Delta\delta$ to the initial (for crystal with CMA only) values [14] of 71°-DW energy density and effective width, respectively, can be written according to (6) and (7) as:

$$\Delta\sigma/\sigma_0 \approx -(4/\sqrt{3})\arcsin(1/\sqrt{3})\eta + \sqrt{2/3}\,\eta^2 ...; \quad (8)$$
$$\Delta\delta/\delta_0 \approx 2\sqrt{3}(4\arcsin(1/\sqrt{3}) - \sqrt{2})\eta + ...$$

It is seen from (8) how the energy density of 71°-DW increases with the growth of PMA constant at $\eta < 0$ and decreases at $\eta > 0$. The 71°-DW width decreases with increasing G for $\eta < 0$ and grows at $\eta > 0$. This is a consequence of an approach of domain magnetization directions to the PMA axis and, so, to each other.

The changes in 71°-DW energy density and effective width are equal to zero and change their signs at **E** direction collinear with <010> and <001> directions, while rising their absolute values when as the **E** orientations approaches the <011> and <0$\bar{1}$1> directions. Polarization dependences of 71°-DW parameters variations (6, 7) are shown in Fig. 4 for the values of parameters typical of $Y_2Fe_5O_{12}$:Si crystal used in (2) ($N = 3.376*10^{18}$, $\lambda = 5$ cm^{-1}, $A_0 = 1.13$, $B = -0.35$). The straight lines show values of DW parameters at $\eta = 0$. The values of $\theta_E = -90°$, $-45°$, $0°$, $45°$ and $90°$ correspond to **E** orientations parallel to <00$\bar{1}$>–<0$\bar{1}$1>–<010>–<011> and <001> directions, respectively (the sign of θ_E coincides that of η).

To conclude, the equilibrium orientation of 71°-DW plane does not depend on the polarization vector orientation and remains parallel to the plane of $\mathbf{m}_1$ and $\mathbf{m}_2$. The 71°-DW energy density decreases or increases as the PMA constant rises, at orientation of polarization vector within the deviations by ±45° from the intersection of the plane of $\mathbf{m}_1$ and $\mathbf{m}_2$ with (100) plane or in the remaining range of **E** orientations, respectively. The 71°-DW effective width increases as the PMA constant rises in the first case and decreases in second one. The above-mentioned regularities are due to changes in magnetization distribution in DW volume, conditioned by the decrease of the energy barrier that the magnetization vector overcomes at rotation between the domain directions, as these directions approach to the PMA axis. The photoinduced changes of energy density and effective width of 71°-DW are absent and change their signs at the polarization vector orientation collinear with <010> and <001> directions and increase their absolute values as its orientation approaches <011> and $<0\bar{1}1>$ directions.

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71°-доменна границя у кубічному кристалі з фотоіндукованою магнітною анізотропією

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Вивчається вплив фотоіндукованої магнітної анізотропії на 71°-плоску блохівську доменну границю в кубічному магнітовпорядкованому (100)-кристалі з від'ємною константою кубічної магнітної анізотропії. Знайдено рівноважні параметри досліджуваної доменної границі (поверхневу густину енергії, орієнтацію та ефективну ширину) в залежності від параметрів (значення константи та орієнтації легкої осі) фотоіндукованої магнітної анізотропії. Показано, що густина енергії такої доменної границі може як зростати, так і зменшуватися в залежності від умов опромінення кристалу.