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Energy and orientation of Bloch type domain walls in magnetics with mixed anisotropy

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Theoretical energy calculation has been carried out for domain walls (DW) of several types with different gyration angles of the magnetization vector in ferrite-garnet crystals with mixed anisotropy (presence of the uniaxial E_{K_U} and cubic anisotropy E_{K_1}). The DW orientations satisfying to the energy minimum have been determined. It is shown that at parameter $\nu = K_U/K_1$, the 1-st type DW (the magnetization vector in the neighboring domains have the same positive projection onto the axis [111], the normal to the film surface) are transformed into the 2-nd type DW (the projections of opposite signs, the angle between magnetization vectors being distinct from 180°).

Проведен теоретический расчет энергии доменных границ (ДГ) нескольких типов с разными углами поворота вектора намагниченности в кристаллах ферритов-гранатов, обладающих смешанной анизотропией (наличие одноосной E_{K_U} и кубической анизотропии E_{K_1}). Определены ориентации ДГ, удовлетворяющие минимуму энергии. Показано, что при значении параметра $\nu = K_U/K_1$ происходит преобразование ДГ 1-го типа (векторы намагниченности в соседних доменах имеют одинаковую положительную проекцию на ось [111] — нормаль к поверхности пленки) в ДГ 2-го типа (проекции разного знака; угол между векторами намагниченности отличен от 180°).

A characteristic feature of ferrite-garnet films is the mixed anisotropy character, that is, the presence of cubic E_{K_U} and uniaxial anisotropy E_{K_1} [1, 2]. The anisotropy energy density normalized to K_1 for films with the mixed anisotropy of (111) orientation in coordinate system (CS) where the axes x, y, z coincide with axes $\langle 1\bar{1}0\rangle$, $\langle 11\bar{2}\rangle$, $\langle 111\rangle$, respectively, is defined as [3]:

$$\frac{E_A}{K_1} = \nu\sin^2\theta + \frac{1}{3}\cos^4\theta + \frac{1}{4}\sin^4\theta - \frac{\sqrt{2}}{3}\cos\theta\,\sin^3\theta\,\sin3\varphi, \quad (1)$$

where θ, φ are polar and azimuth angles of magnetization vector $\mathbf{m}$, $\nu = K_U/K_1$. In [3], stable directions of $\mathbf{m}$ in domains have been determined by minimization (1) with respect to θ and φ, and the phase diagram (PD) have been built. In the PD, three areas can be distinguished. Area **I** ($\nu > 0.762$, area of axial phase existence) and area **II** ($0.66 < \nu < 0.762$, area of a metastability) were considered in [3, 5]. Area **III** ($\nu < 0.75$), being that of angular phases where domain walls (DW) can be of different types with different magnetization vector gyration angles therein: Type 1 DW corresponding to rotational displacements $1 \to 2$ ($2 \to 3$, $3 \to 1$) and to similar rotational displacements under the film plane; Type 2 DW, $1 \to \bar{2}$ ($2 \to \bar{3}$, $3 \to \bar{1}$; and 3 type, or 180° DW, $1 \to \bar{1}$ ($2 \to \bar{2}$, $3 \to \bar{3}$. In what follows, the DW energy is calculated for different DW types and the most favorable DW orientations with respect to the film plane are determined.

The calculation will be done assuming that the domain wall is an isolated Bloch type DW. The requirement of absence of magnetic fields in Bloch DW implies that when passing from one domain to another, the rotational displacement of magnetization vector will occur along the side surface of a cone. Thus, the normal to DW should be co-planar with the bisector between magnetization vectors in the neighboring domains, as well as perpendicular to the plane containing two magnetization vectors. When calculating the DW energy, we shall use a new CS η_{1i}, η_{2i}, η_{3i} associated with the flat DW. The axis η_{3i} is oriented along the normal to DW. Orientation of the vector **m** with respect to the new CS will be given by polar and azimuthal angles θ_i and φ_i, respectively (i = 1, 2, 3 being the index which specifies the DW type). Then it is easy to calculate the DW energy and its orientation, making use of the formula

$$\gamma_i = 2\sqrt{A_i K_1}\int_{\varphi_i^{(1)}}^{\varphi_i^{(2)}}\sqrt{E_{Ai} - E_\infty}\sin\theta_i d\varphi_i, \quad (2)$$

where E_∞ is the anisotropy energy density in the domain; $\varphi_i^{(1)}$, $\varphi_i^{(2)}$ angles of the magnetization vectors in the neighboring domains; E_{Ai}, the anisotropy energy density written in the coordinate system η_{1i}, η_{2i}, η_{3i}.

To explain more clearly theoretical results, let the transitions $1 \to 2$, $1 \to \bar{2}$, $1 \to \bar{1}$ be considered, i.e. one of three equivalent transitions of each type. Then let the angles characterizing geometry of the problem be described in more detail as well as connection between those (Fig. 1): $2\alpha_i$ is the angle between vectors **m** in the neighboring domains in the plane A_i containing these two vectors (in our case, in the plane $1\ 2\ \bar{1}$ plane) ($\sin\alpha_1 = \sin\pi/3\ \sin\theta$, $2(\alpha_1 + \alpha_2) = 2\alpha_3 = \pi$; β, the angle of the plane $12\bar{1}$ to the axis [111] ($\cos\beta = \cos\theta/(1 - 3/4\ \sin^2\theta)^{1/2}$; ψ_i, the angle describing a deviation of the perpendicular $\mathbf{n}_i$ to DW of i type out of the plane A_i. The angle ψ_i varies within limits $-\pi/2$; $\pi/2$. The value $\psi_i = 0$ means that the DW plane is perpendicular to plane A_i while $\psi_i = \pm\pi/2$ shows that the rotational displacement of **m** from one domain to another occurs in a plane parallel to the DW plane. That is, as ψ_i varies from 0 up to $\pi/2$, opening θ_i of the gyration cone increases ($\cos\theta_i = \cos\psi_i\ \cos\alpha_i$ $\mathrm{tg}\varphi_i = \mathrm{tg}\alpha_i/\sin\psi_i$). Let us put $\psi_i > 0$ if the normal is above the plane $12\bar{1}$ and $\psi_i < 0$ if the normal is under that plane. Let us distinguish also gyration of **m** in the DW along the "lower" and "upper" surface of the cone, i.e. under and

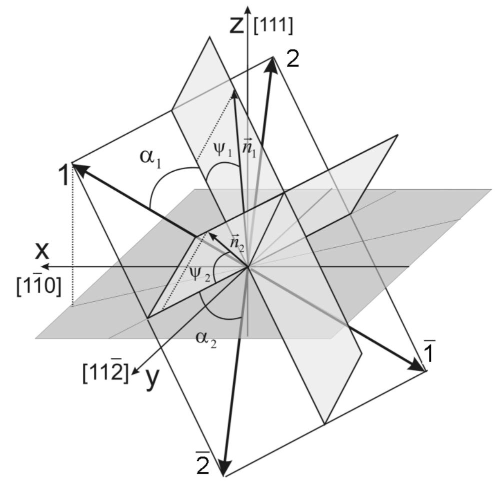

Fig. 1. Geometry of the problem.

above the plane $12\bar{1}$, respectively. This is necessary to calculate the DW energy at different gyration directions of **m**, because a shorter path does not mean an energy gain.

Now the obtained theoretical results will be explained. The dependences $\gamma_i = f(\psi_i)$ have been determined from the formula (2) by numerical calculations at various ν values. Hence, it is easy to define the DW orientation with respect to the plane (111) as well as the dependence $\gamma_i = f(\nu)$ (Figs. 2, 3). In the case of the 1-st type Bloch DW, there are 4 different paths for vector **m** gyration from the state 1 into the state 2: γ_1^{21} and γ_1^{22} are DW energies in the case of gyration along the upper and lower cone surface, when $\psi_i < 0$; γ_1^{12} and γ_1^{11}, the same when $\psi_i > 0$. At $\nu > 0$, the minimal energy value is attained in the diagram γ_1^{21} at a certain value of the angle $\psi_i < 0$. This can be explained as follows: at a given value of the angle ψ_i (different for different ν), the gyration will pass through the inflection in the diagram of anisotropy energy in polar coordinate system (PCS). At $\psi_i = 0$, a nonequivalence of gyration along the lower and upper cone arc is observed: for this ψ_i value, the DW energy γ_1^{11} coincides with γ_1^{22}, and γ_1^{12}, with γ_1^{21}; the gyration arc lengths are equal to one another. Nevertheless, it is favorable to make gyration on a upper cone face near to the inflection in the diagram in the PCS. Only at a certain positive value of the angle ψ_1 energy γ_1^{12} and γ_1^{11} become equal. As the parameter ν attains $\nu = 0$, we have only cubic anisotropy (Fig. 1,d). The gyration goes immediately in

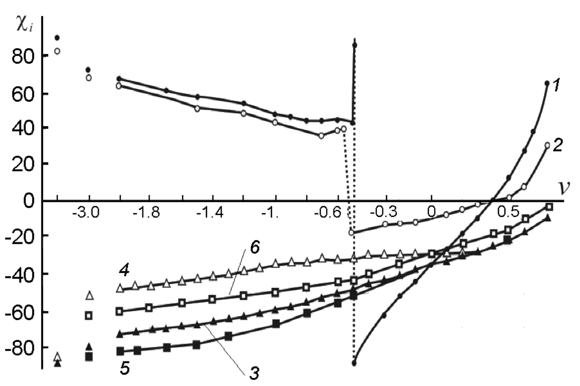

Fig. 2. Dependence of the angle χ_i between DW of various types and the axis [111] on parameter ν: *1* – DW of 1-st type; *2* – DW of 1-st type with account of DW area; *3* – DW of 2-nd type; *4* – DW of 2-nd type with account of DW area; *5* – DW of 3-d type; *6* –

the plane A_i containing magnetization vectors in the neighboring domains, and includes an axis of <110> type, a difficult axis of cubic anisotropy (inflection). Thus, the opening of the gyration cone (i.e. the angle θ_i) increases as the ν parameter decreases, and at $\nu = 0$, it attains $\theta_1 = 90°$.

The minimal DW energy value increases as the ν parameter decreases (Fig. 3). This can be explained by the fact that, in accordance with the increase of the angle θ (and, hence, the angle α_1) the gyration arc length grows. At $\nu = 0$, $\gamma_1{}^{21}{}_{min} = \sqrt{AK_i}$, thus coinciding with the 90° DW energy in magnetics with a cubic anisotropy, the magnetostriction being not taken into account ($\alpha_1 = \alpha_2 = \pi/4$).

In Fig. 2, dependence of the angle χ_1 between the DW plane and the [111] axis on the parameter ν is shown. Here, the positive χ_1 values characterize the state when the plane A_1 and the DW plane are at different sides with respect to the [111] axis while the negative ones specify the presence of these two planes at the same hand from [111].

As the parameter $\nu < 0$ (when the influence of uniaxial anisotropy is reduced to presence of a light plane, and cubic one, to presence of light axes of [100] type), it is favorable for the 1-st type domain walls to be oriented so that the magnetization vector gyration occurs along the "lower" surface of a cone near to the light plane ($\psi_1 > 0$). That is, the minimum of DW energy is now attained not at $\gamma_1{}^{21}$ but at $\gamma_1{}^{11}$, and the gyration will pass the inflection in the an-

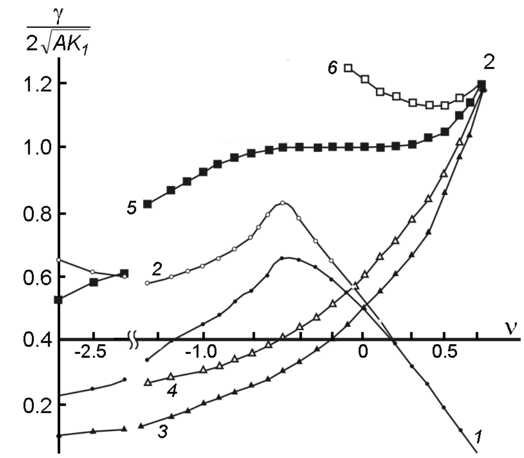

Fig. 3. Dependence of energy on parameter ν for various types DW: *1* – DW of 1-st type; *1* – DW of 1-st type; *2* – DW of 1-st type with account of DW area; *3* – DW of 2-nd type; *4* – DW of 2-nd type with account of DW area; *5* – DW of 3-d type; *6* – DW of 3-d type with account of DW area.

isotropy energy diagram in PCS. At $\nu = -0.5$, as the inflection disappears, gyration starts to occur below the plane (111). At negative ν values, the gyration nonequivalence at the "upper" and "lower" cone surfaces is observed again at $\psi_1 = 0$ (at the same gyration path).

Thus, as only the anisotropy energy and exchange energy are taken into account, the 1-st type DW tend to be oriented so that the magnetization vector gyration from one domain to another occurs along the path with minimal anisotropy energy.

Similar calculations have been carried out under condition of a competition between the DW area and the minimal anisotropy energy. If without taking into account DW area at change of the parameter ν sign, the minimum of DW energy showed the transition $\gamma_1{}^{21} \to \gamma_1{}^{11}$ (and DW area gradually increased with dimitution of γ), now such transformation occurs through an intermediate value, i.e. $\gamma 1^{21} \to \gamma_1{}^{22} \to \gamma_1{}^{11}$. Due to that intermediate value, the magnetization vector gyration direction varies gradually, while the DW orientation (and hence the DW area) remaining unchanged.

Similar calculations have been carried out for the 2-nd type DW. The DW energy and DW orientation in unlimited magnetic have been found, as well as taking into consideration the DW area. At $\nu > 0$, the 2-nd type DW energy is higher as compared to the 1-st type DW energy (Fig. 3), since the gyration arc in this case is longer. However, as the parameter ν decreases, the 2-nd type DW energy decreases and at $\nu = 0$ is equalized with the 1-st type DW one. At negative ν values, it is just the 2-nd type DW that has lower value energy. That is, for $\nu = 0$, a transition of the 1-st type DW into the 2-nd type one can be stated: the gyration arc lengths for DW of different type become equal, also different type DW take the same spatial orientations.

In Fig. 2, the dependence of angle χ_2 between the DW plane and the axis [111] on the ν parameter is shown. As the temperature drops, the angle χ_2 is increased, the DW plane tilts more and more to the film surface, and at a sufficiently negative value of parameter ν becomes parallel to the film plane. Thus, under account only for anisotropy energy and exchange energy, the 2-nd type DW are oriented so that the magnetization vector gyration in DW occurs through the inflection in the PCS diagram. At a competition only between path length and the anisotropy energy value in this path, the DW orientation may be arbitrary, including the position parallel to the film plane, that results in an unbounded growth of the DW area in case of a single crystal plate cut in parallel to the plane (111). The account for 2-nd type DW area makes the following corrections to the DW energy and DW orientation. At $\nu > 0.2$, the minimal DW energy is attained for $\psi_2 = \pi/2$; at $\nu \le 0.2$, $\psi_2 < \pi/2$ and the magnetization vector gyration occurs along the cone surface, instead of in a plane as it was earlier. In such a way, a diminution of the domain wall area is provided though the anisotropy energy is increased. Disappearance of the inflection for 1-st type DW of at $\nu = -0.5$ does not influence in any way the inflection for 2-nd type DW. The character of of 2-nd type DW energy dependence on parameter ν under account for the area is similar to that for 2-nd type DW in a unlimited crystal: as the parameter ν decreases, the DW energy drops monotonously. At some nonzero value of parameter ν, the domain wall type is observed to change: the 2-nd type domain walls become more favorable in energy than the 1-st type ones (Fig. 3). However, in this case, the DW of different types take different orientations with respect to the film plane.

The 180° domain walls in magnetics with mixed anisotropy have the highest energy as compared to DW of other types at any ν values. This evidences not only that the magnetization vector gyration arc length is the greatest, but also that the domain wall tends to occupy some equilibrium position between two inflections in the PCS diagram of anisotropy energy, since the plane of 3-rd type DW cannot simultaneously contain two inflections (for 1-st and 2-nd DW types). As a consequence, the inequality $\gamma_{1min} + \gamma_{2min} \neq \gamma_{3min}$ is not valid at any values of parameter ν (except for $\nu = 0$ when, in case of unlimited crystal, DW planes of all three types coincide and the magnetization vector gyration occurs in the DW plane). The orientation of 3-rd type DW also is selected basing on path length competition with anisotropy energy on this path.

Thus, the calculations allow for the following conclusions. In magnetics with mixed anisotropy, three types of domain walls may be realized. Calculation of DW energy and DW orientation in unlimited crystal has shown that the domain walls tend to be arranged so that gyration occurs along a path with minimal anisotropy energy (through different sorts of inflections in the anisotropy energy diagram in polar coordinates) at simultaneous shortening of the rotation path. The DW may take quite different orientations with respect to the plane (111) which is the surface plane of the films under study. Under account for the area, the domain walls are oriented not quite favorably as to anisotropy energy (there is a competition between the path length, anisotropy energy in this path and DW area): the gyration occurs near to an inflection, but not immediately through it. Such a situation can result in that in real magnetics with mixed anisotropy, the domain walls of a complex structure will be realized, when it is favorable for magnetization vector to form magnetic field strengths at the DW surface (i.e., the DW will not be of exactly Bloch or Neel type), but to rotate through the inflection, thus simultaneously reducing the DW area. In fact, the experiments described in [4, 6] specify such complex character of magnetization vector gyration in the DW plane. For an unlimited crystal and a single crystal plate, the theoretical model indicates the transformation of a 1-st type DW into 2-nd type one at a particular value of parameter ν. Unfortunately, the presented simple enough theoretical model taking into account only the anisotropy energy and exchange energy does not feature the magnetization vector rotational displacement process itself at the DW type change. However, according to the experimental results described in [6], such transformation occurs by turning of the magnetization vector in one of domains at insignificant alteration in DW orientation.

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Енергія та орієнтація доменних границь типу Блоха у магнетиках зі змішаною анізотропією

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Проведено теоретичний розрахунок енергії доменних границь (ДГ) кількох типів з різними кутами розвороту вектора намагнічення у кристалах феритів-гранатів, що мають змішану анізотропію (наявність одновісної E_{K_U} та кубічної анізотропії E_{K_1}). Визначено орієнтації ДГ, що задовольняють мінімуму енергії. Показано, що при умові $\nu = K_U/K_1$ відбувається перетворення ДГ 1-го типу (вектори намагнічення у сусідніх доменах мають однакову позитивну проекцію на вісь [111] — нормаль до поверхні плівки) в ДГ 2-го типу (проекції різного знаку, кут між векторами намагнічення відрізняється від 180°).