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Spin-reorientation phase transitions in soft magnetic films of different anisotropy

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The spin-reorientation phase transitions (SRPT) in thin magnetic ferrite-garnet films of mixed anisotropy have been studied. In a film with strong uniaxial anisotropy, a first order SRPT from axial to angular phase occurs, the new angular phase being nucleated from the old domain boundary. In a low anisotropy film, the nucleation occurs from one angular phase to another with no boundary between new and old phases, no nuclei being formed by domain magnetization vector rotation to a more energetically favorable state. The SRPT in bilayer film with T_K in one of layers takes place due to combined action of rare-earth sublattice magnetization and bias-field of another layer.

Исследованы спин-переориентационные фазовые переходы (СПФП) в тонких магнитных пленках ферритов-гранатов со смешанной анизотропией. В пленке с сильной одноосной анизотропией происходит СПФП 1 рода от осевой к угловой фазе с зародышеобразованием новой фазы из старой доменной границы. Рост зародышей происходит из угловой фазы в другую угловую фазу без образования зародышей путем поворота вектора намагниченности в энергетически более выгодное состояние. В двуслойной пленке, имеющей в одном из слоев T_K, наблюдается СПФП вследствие суммарного действия намагниченности редкоземельной подрешетки и подмагничивающего поля другого слоя.

Investigation of mixed-anisotropy effect on the behavior of single-layer film domain structure (DS) is a complex problem which can be solved by using simultaneously experimental and theoretical approaches. Investigation of DS behavior in bilayer films, where the interlayer interaction should be taken into account together with the mixed anisotropy, is an even more complex problem which can be solved experimentally.

The SRPT were studied in [1–5]. In [1], orientation transitions and the existence of magnetic phases in cubic rare-earth ferromagnetic have been studied. In [2, 3], the spin-reorientation phase transition (SRPT) was observed in a labyrinth DS under temperature change and recorded by a diffraction pattern from a regular DS. It has been found that the magnetization reorientation in domains results in a jump-like increase of DS period. The SRPT from anisotropy of the "easy axis" type to the "easy plane" type one showed no hysteresis, but it was accompanied by coexistence of two phases in the temperature range near 3 K.

The situation when SRPT temperature and T_K are close to each other or coincide is the most interesting one. In [4, 5], the DS has been investigated in the temperature range including the magnetic compensation and spin reorientation regions, both in the absence of any external magnetic field (spontaneous transitions) and in magnetic fields (induced transitions). In [5], it has been determined during the DS studies that for $Er_3Fe_5O_{12}$, the temperatures of the first-order SRPT between phases with magnetization orientation along <111> and <100> coincide with T_K. In [4], the DS was studied by the magnetooptical Faraday effect, the phases being identified by the color contrast method. It has been deter-

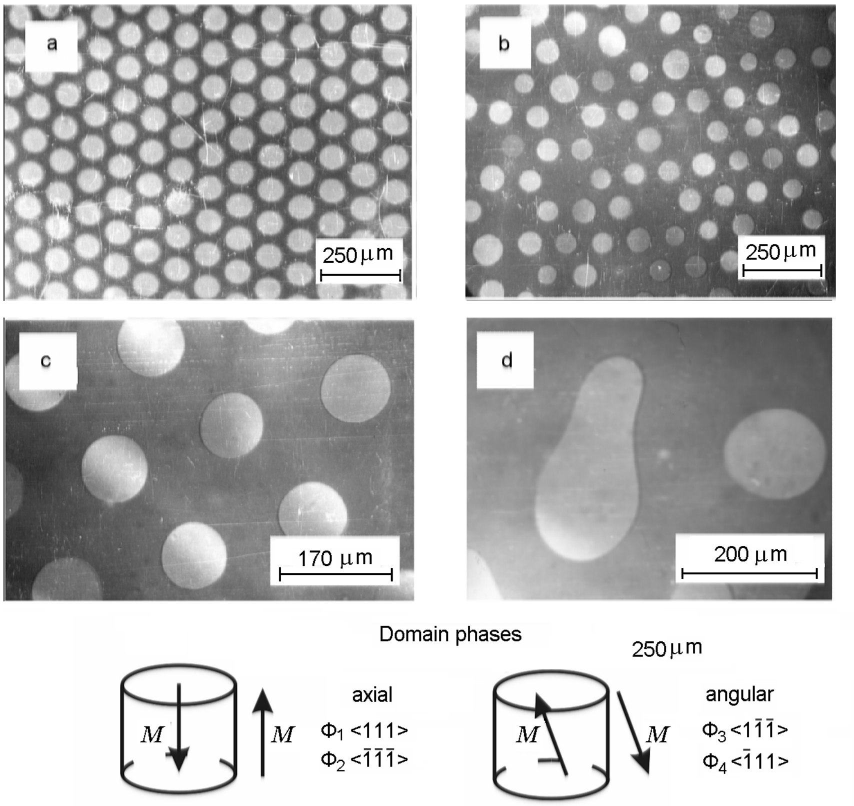

Fig. 1. View of $(TmBi)_3(FeGa)_5O_{12}$ film DS at 215 K (a), 172 K (b,c), 158 K (d).

mined that in the substituted erbium garnet, the ranges of magnetic compensation and spin reorientation are overlapped.

This paper deals with a study of the SRPT mechanism in single-layer films of different uniaxial anisotropy values and in a bilayer film with T_K in one of the layers. The objects of investigation were films with the developed <111> plane grown by the liquid-phase epitaxy method on gadolinium-gallium garnet. The DS was studied by the method applied by us in [6].

SRPT in a film with high uniaxial anisotropy. The SRPT was observed with T variation in bubble lattice in $(TmBi)_3(FeGa)_5O_{12}$ film with magnetic compensation temperature of 120 K. In [6], the experiment was described in detail. The bubble lattice has been formed at 215 K by a pulsed magnetic field normal to the film plane. Two axial phases Φ_1 and Φ_2 with $\mathbf{M}_1\downarrow\uparrow\mathbf{M}_2$ were obtained: orange bubbles against brown background. At 185 K, there occurred areas of other colors were appeared: white on the bubble and green on the background, i.e. two angular phases Φ_3 and Φ_4 were obtained. In Fig. 1, it is seen that some sections of domain boundaries (DB) became broadened with an angular phase nearby. It should be noted that there was no boundary between angular and axial phases. The axial-to-angular phase transition took place in the 185–160 K range. At 160 K, only an angular phase was observed (white bubbles against green background). At 172 K, the areas occupied by axial and angular phases were equal to each other. At the same temperature, the bubble diameter and DB width were increased jump-like. The bubble lattice was changed, too. The thermodynamically equilibrium bubble lattice is characterized by the packing parameter $y = d/a$, where d is the bubble diameter; a, lattice constant [7]. At 172 K, the lattice packing parameter was changed from 0.74 to 0.45. Thus, it has been shown experimentally that at 172 K, a hysteresis-free first-order SRPT from axial to angular phase occurred.

Theoretical investigation of DB structure has shown that the first-order SRPT proceeded by the "new" phase nucleation within the domain boundaries of the "old" phase; in a certain temperature range, it was accompanied by redistribution of the phase volumes. The absence of DB between

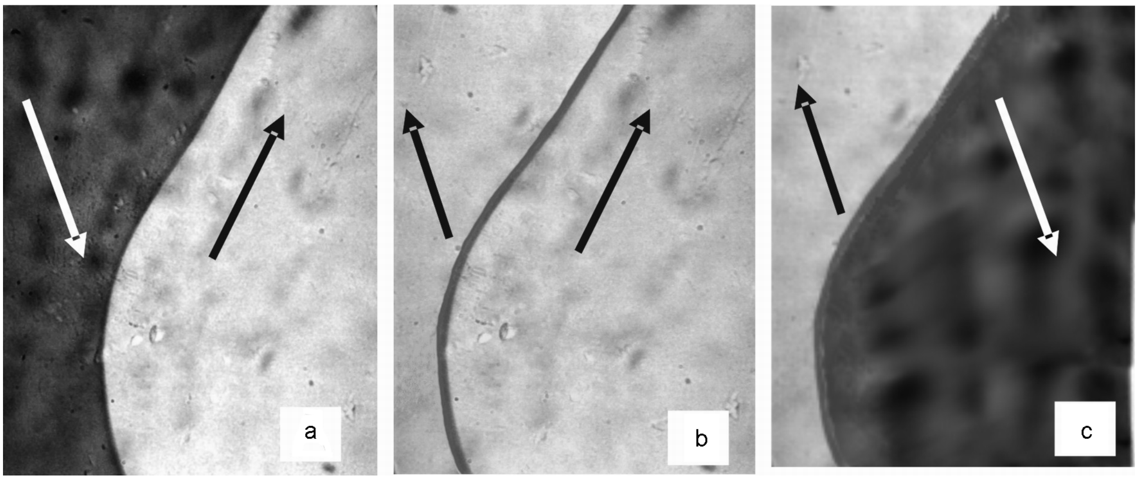

Fig. 2. View of $(YBi)_3(FeGa)_5O_{12}$ film DS at 173 K (a), 176 K (b), 178 K (c).

domains of new and old phases has been proved to be possible [8].

SRPT in a film of low uniaxial anisotropy. A film of the $(YBi)_3(FeGa)_5O_{12}$ composition with the magnetic compensation point at 212 K was investigated. The DS was observed under variation of the film temperature T. Experimental investigations are described in detail in [9]. The bubble lattice could be formed only at $T\geq370$ K. At $T<370$ K, only the angular domain structure existed. Yellow and green domains were observed having branches directed along the three axes, being the <111> projections onto the film plane. As the temperature approached T_K, the branches were disappeared and the domain shape was changed. At 176 K there was an interesting color change was observed. The green domains took yellow color of the surrounding field. On a continuous yellow field, only a broad brown DB was seen. Next, the yellow domains became green. During the film heating, the process of color change was repeated in reverse order (Fig. 2). Thus, in the 178–173 K temperature range, a hysteresis-free SRPT from one angular phase to another took place. As the DS was periodically affected by magnetic field, the SRPT was displaced to a lower T and turned out to be irreversible.

Theoretical investigations of DB in the film with angular DS have shown the SRPT to be a second order one. DB of two types and transformation of one DB type into another have been observed visually. The DB types change was occurred by **M** rotation in one of the domains in the absence of DS rearrangement and nucleation. The DB type was that of the minimal energy for a given T [10].

SRPT in a bilayer film. Investigated was a film with layer 1 of $(YGdTm)_3(FeGa)_5O_{12}$ composition and T_K near 120 K, layer 2 being $(YEu)_3(FeGa)_5O_{12}$ having no T_K in the temperature range under investigation. The equilibrium DS in the bilayer film and in single-layer "witness" films was studied experimentally at T variation, for details, see [11]. At 300 K, two types of strip DS (SDS) of different periods (Fig. 3a) were observed in the bilayer film. At T_2, a through SDS has occurred. As layer 1 temperature approached T_K, the pulsed field induced bubbles and then the bubble lattice. At T_{SRPT}, the DS color has changed suddenly from orange to dark-brown. The bubbles took the form of ellipse. When the temperature of layer 1 approached T_K, the DS became subdivided into monodomain state in layer 1 and orange-colored SDS in layer 2.

At 300 K, in strip domains of the two layers, the saturation magnetization vectors are antiparallel ($\mathbf{M}_1\downarrow\uparrow\mathbf{M}_2$) (Fig. 3a). Since $M_1>M_2$(Fig. 3b), then as T decreases, the biasing field of layer 1 forced $\mathbf{M}_2$ of layer 2 to turn in parallel to $\mathbf{M}_1$ of layer 1. The domains have become through with $\mathbf{M}_1\uparrow\uparrow\mathbf{M}_2$. In this temperature range such a structure is energetically favorable [12]. Here, the magnetostatic interaction between the layers should be taken into account only, because in bilayer films, the exchange interactions is minimum if the iron sublattices in the layers are parallel [13]. At T_2, there was a jump of SDS magnetostatic pressure (Fig. 3b) which was calculated by using experimental data [11]. This implies that a phase transition occurred in DS, since $\mathbf{M}_2$ was turned by 180 degrees. At T_{SPRT}, $\mathbf{M}_1\approx\mathbf{M}_2$ (Fig. 3b). In this tempera-

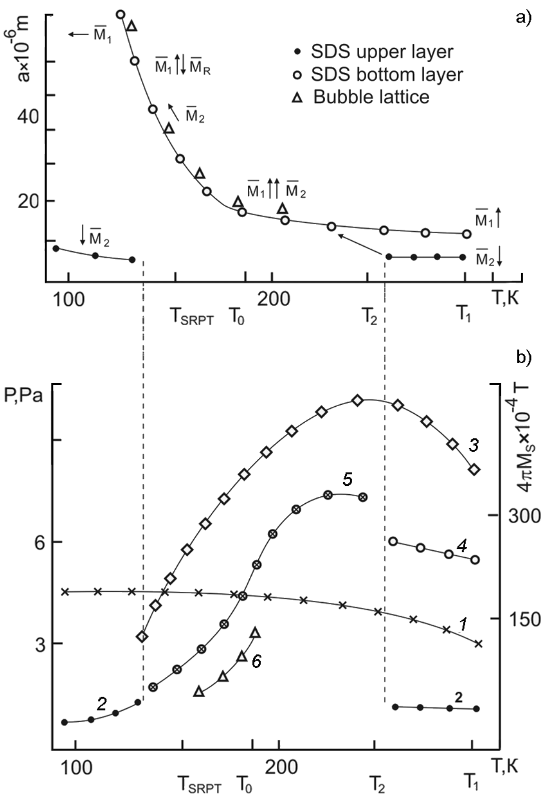

Fig. 3. Temperature dependences for $(YGdTm)_3(FeGa)_5O_{12}/(YEu)_3(FeGa)_5O_{12}$ film: of stripe structure period (a); of saturation magnetization and magnetostatic pressure, respectively; *1*,*2* – first layer; *3*,*4* – second layer; *5*,*6* – pressure of through DS (b).

ture range, there exists the magnetization of the rare-earth sublattice of layer 1, and $\mathbf{M}_R\downarrow\uparrow\mathbf{M}_1$ of the iron sublattice. The total action of $\mathbf{M}_R$ of layer 1 and bias field of layer 2 results in $\mathbf{M}_2$ rotation from axial phase to angular one (Fig. 3a) and the DS changes its color. In the film, the SRPT takes place. The transition could not be caused only by the rare-earth sublattice in the absence of bias field. This is confirmed by the absence of SRPT in the $(YGdTm)_3(FeGa)_5O_{12}$ "witness" film. At T_K of film 1, $\mathbf{M}_2$ takes the orientation which existed at 300 K, i.e. favorable for layer 2. At a distance from T_K (heating), $\mathbf{M}_1$ orientation becomes parallel to $\mathbf{M}_2$ ($\mathbf{M}_1\downarrow\downarrow\mathbf{M}_2$) while $\mathbf{M}_R\uparrow\downarrow\mathbf{M}_2$. No SRPT is observed. This is one more confirmation of the fact that the action of the rare-earth sublattice is insufficient to rotate the vector of iron sublattice magnetization.

Thus, in the three films studied, the SRPT is observed near T_K. In single-layer films differing in the value of uniaxial anisotropy, both SRPT are hysteresis-free. In the film of high uniaxial anisotropy, the SRPT occurs from the axial phase to the angular one. This is a first order SRPT. The coexistence region of axial and angular phases is 25 K wide. The angular phase nucleates from the 180-degree domain boundary. There is no boundary between axial and angular phases. In the film of low uniaxial anisotropy, the SRPT occurs from one angular phase to another angular one. This is a second-order SRPT. It occurs in the absence of nucleation process by rotating **M** of the whole domain to a more energetically favorable state. Under a field, the SRPT is displaced to lower T and becomes irreversible. The role of DB in the first- and second-order phase transitions is different. In the first case, the DB acts as the origin of the new phase domains. In the second case, the DB rearranges to attain the minimum energy. In one of the domains, **M** rotates. Thus, the DB effects the DS rearrangement very much. In the bilayer film with T_K in one of the layers close to T_K, a combined total action of rare-earth sublattice magnetization and of biasing field of another layer is observed. When T_K is approached (cooling), the angular phase originates and the SRPT occurs. At a distance from T_K (heating), no SRPT is observed. The SRPT was also absent in single-layer "witness" films. Hence, the action of the rare-earth sublattice only is insufficient to rotate the magnetization vector. The investigations have shown that different mechanisms of magnetization vector rotation correspond to the SRPT in the films.

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Спін-переорієнтаційні фазові переходи у тонких магнітних плівках з різною анізотропією

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Досліджено спін-переорієнтовані фазові переходи (СПФП) у тонких плівках феритів-гранатів зі змішаною анізотропією. У плівці з сильною одновісною анізотропією відбувається СПФП першого роду від вісьової до кутової фази з зародкоутворенням нової фази із старої доменної межі. Ріст зародків відбувається без утворення межі між новою та старою фазами. У плівці з малою анізотропією СПФП відбувається із кутової фази в другу кутову фазу без утворення зародків шляхом повороту вектора намагніченості у енергетично більш вигідний стан. У двошаровій плівці, що має в одному з шарів T_K, спостерігається СПФП внаслідок сумарної дії намагніченості рідкісноземельної підгратки та підмагнічуючого поля другого шару.