Functional Materials 11, No.3 (2004)

Domain structure of bilayer magnetic films with different characteristics of layers

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In uniaxial bilayer film of $(YGdTm)_3(FeGa)_5O_{12}/(YEu)_3(FeGa)_5O_{12}$ ferrite-garnet with the upper layer compensation point 120 K, the domain structure behavior and the external pulse field effect on the energy equality points of different domain structures has been studied experimentally in the temperature range 300 to 90 K. A model has been proposed that makes it possible to describe most precisely the observed domain structure reorganization as a function of the interlayer domain wall. Furthermore, the model can be used to explain the spin-reorientation phase transition observed in the film at T = 142 K.

В одноосной двухслойной пленке феррита-граната $(YGdTm)_3(FeGa)_5O_{12}/(YEu)_3(FeGa)_5O_{12}$ с точкой компенсации верхнего слоя 120 К экспериментально исследовано поведение доменной структуры (ДС) и влияние внешнего импульсного поля на точки равенства энергий различных ДС в температурном интервале 300–90 К. Предложена модель, позволяющая наиболее точно отразить наблюдаемую перестройку ДС в зависимости от типа доменной границы между слоями. Кроме того, данная модель позволяет объяснить спин-переориентационный фазовый переход, наблюдающийся в пленке при температуре T = 142 К.

In this work, presented are the visual study results of inhomogeneous states in a bilayer epitaxial ferrite-garnet film and the domain structure (DS) behavior under external pulse magnetic field within the temperature range 300 to 90 K. The experimental data made it possible to suggest that the magnetization ratio of the film layers affects the DS behavior as well as to develop the models proposed in [1] and allowing to explain the DS reorganization being observed. Consideration of the models has allowed to judge the layer interaction type within the temperature range studied.

To study the layer interaction in magnetic films under assumption that it is just the magnetostatic interaction that is of a considerable importance, a film is required where the total magnetization (M_s) of one layer depends heavily on temperature while that of second layers is almost temperature-independent. That is why a bilayer ferrite-garnet film was studied grown by liquid epitaxy technique on Gd–Ga garnet with induced uniaxial anisotropy along the <111> axis perpendicular to the film surface. The first layer of the film, $(YGdTm)_3(FeGa)_5O_{12}$, exhibits the compensation point near 120 K while another layer, $(YEu)_3(FeGa)_5O_{12}$, has no compensation point within the studied temperature range. The characteristics of single-layer "witness" films are presented in Table.

The studies were performed within the temperature range 300 to 90 K using the Faraday effect. The DS was formed by a single-pole pulse magnetic field perpendicular to the film surface, no bias field was used. The pulse field parameters are as follows: amplitude, 120 Oe; frequency, 400 Hz.

The DS behavior was studied under temperature action on the film, and judging from the DS view, the interlayer domain wall (DW) type was determined as well as its temperature-depending changes. The layer interaction was taken into account by introducing a 180° DW at the interface where moments of iron sublattices are turned. Here, four cases shown in Fig. 1 may be realized:

Table. Characteristics of studied films at room temperature (h, the film thickness; $4\pi M_s$, saturation magnetization; T_N, Neel temperature)

No.	Composition	h, µm	$4\pi M_s$, Gs	T_N, K
1	$(YGdTm)_3(FeGa)_5O_{12}$	3.30	410	443
2	$(YEu)_3(FeGa)_5O_{12}$	11.78	155	405

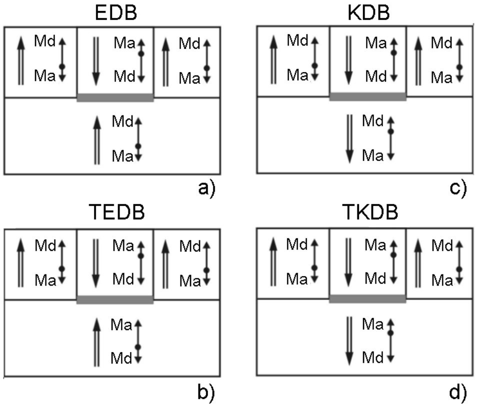

Fig. 1. Schematic representation of DW types: butt (*1*), transition butt (*2*), compensatory (*3*), transition compensatory (*4*).

(I) A butt domain wall (BDW) existing in the layer interface sections where the total moments of the layers are defined by like iron sublattices and the total magnetizations are antiparallel (Fig. 1a);

(II) A transitional butt domain wall (TBDW) existing in the layer interface sections where the total moments of the layers are defined by unlike iron sublattices and the total magnetizations are also antiparallel (Fig. 1b);

(III) A compensatory domain wall (CDW) existing in the layer interface sections where the total moments of the layers are defined by unlike iron sublattices and the total magnetizations are parallel (Fig. 1c);

(IV) A transitional compensatory domain wall (TCDW) existing in the layer interface sections where the total moments of the layers are defined by like iron sublattices and the total magnetizations are also parallel (Fig. 1d).

In the course of cooling from 300 down to 90 K, a complex reorganization of DS takes place in the bilayer film. However, a series of characteristics DS kinds with different types of the layer interface can be distinguished that are realized within certain temperature intervals. These cases are presented in Fig. 2. Basing on the experimental data, the following models are proposed for the corresponding DW [2], see Fig. 3.

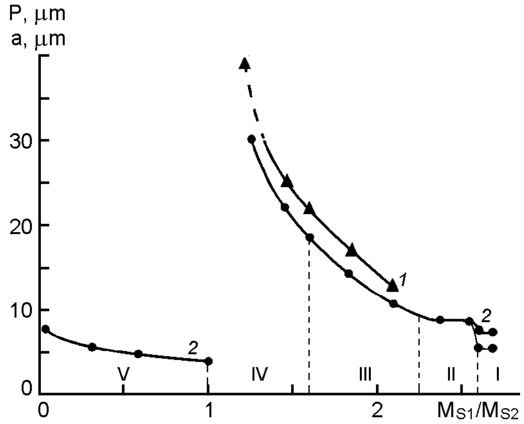

Fig. 2. Dependence of a parameter in CMD lattice (*1*) and strip structure parameter P_{02} (*2*) on relative magnetization of the film layers under cooling.

In the 360 to 270 K temperature range, at $2.6 \le M_1/M_2 \le 2.7$, the DS is described by the DS1 model, namely, the strip domains of both layers with different periods (Fig. 2) and TCDW and BDW (Fig. 2). As the temperature falls, the domains in both layers increase and at $M_1/M_2 = 2.6$, the strip domains of the layers become fused together, so that continuous domains appear, i.e. DS1 transits into DS2, the TCDW is kept. In the 260 to 215 K temperature range, at $2.4 \le M_1/M_2 \le 2.55$, the continuous strip domains of DS2 exist. At $M_1/M_2 = 2.3$, the DS2 is transformed into DS3 with a normal interlayer CDW; along with strip domains, cylindric magnetic domains (CMD) are formed and then a hexagonal CMD lattice; circular domains of $d_1 = 8.7$ µm and $d_2 = 10.5$ µm appear, too (Fig. 2). In the 190 to 155 K range corresponding to $1.6 \le M_1/M_2 \le 2.25$, the DS3 is observed; both strip domains and a CMD lattice are formed (Fig. 2). At 155 K and $M_1/M_2 = 1.6$, the DW become more sharp, the DS4 appears with TBDW between layers. At 142 K and $M_1/M_2 = 1.25$, the domain color changes sharply from light orange to dark brown. At the further temperature decrease, no strip domains are formed, there is only the CMD lattice having brown color

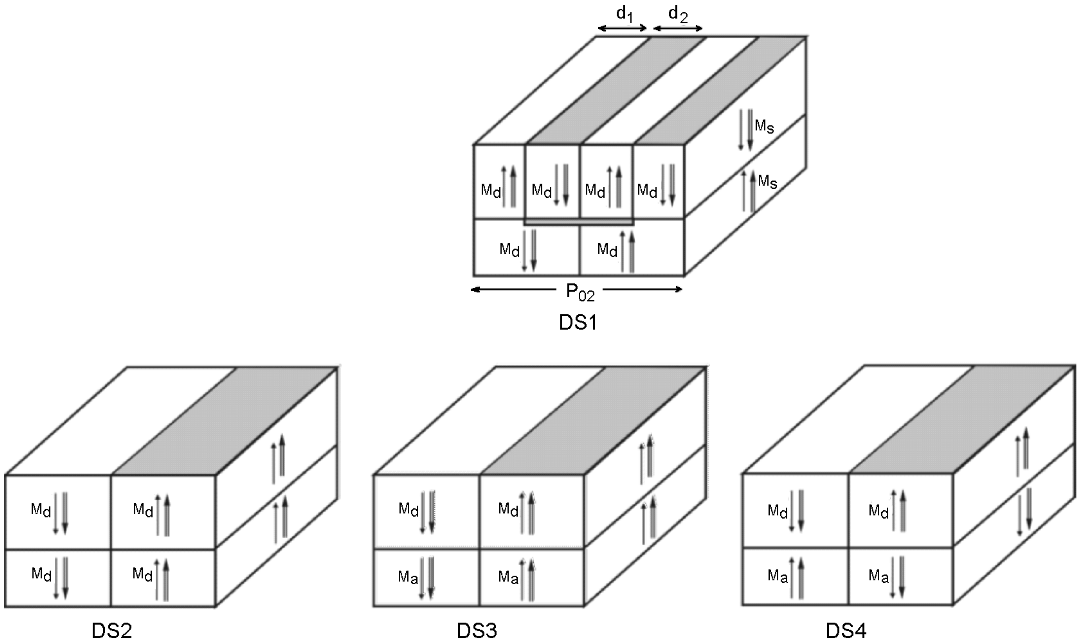

Fig. 3. DS models for bilayer film. M_s, total magnetization; M_d, M_a, magnetization values of iron sublattices.

and the domain become elliptic. The $1 \leq M_1/M_2 \leq 1.6$ range is the region where DS4 exists. At 130 K and $M_1/M_2 = 1$, the first film layer goes to single-domain state, strip domains of the initial orange color appear in the second layer with a small period that are observed as the film is cooled down to 90 K (Fig. 2). This is the case of DS5 with normal BDW (Fig. 2). It is to note, however, that no DS color change took place at the film heating.

Fig. 3 presents schematically the DS change process in the bilayer film. Near the compensation temperature, the compromise DS3 exists in both layers. In this case, both DS are identical, the domain magnetization direction is the same in both layers, no interlayer butt wall appears, there is no exchange interaction, only the magnetostatic one is present, the DW is a CDW. As the temperature falls, the underlayer becomes magnetized. As a result, the film must go to DS4 state where a compromise DS exists in both layers but with an interlayer TBDW. The exchange interaction takes place between the layers that is described by introduction of a DW with the surface energy σ, the DWs being parallel to the layer interface [3]. Thus, due to the interaction type change, the magnetization vector in the underlayer domains becomes turned, resulting in a color change of the domains and the background. So, a spin reorientation phase transition (SRPT) has been revealed caused by the change of the layer interaction type in the film. This transition is qualitatively different from known ones [4].

Let the models of Fig. 3 be considered that make it possible to judge the effect of a pulse field applied during the DS formation on the energy equality point of different DS within the 300 to 90 K temperature range in the absence of bias field. Basing on theoretical models proposed in [1] for $H_p = 0$, the total magnetic energy per unit area of the bilayer film is

$$E = E_M + E_\sigma + E_{\sigma c} E_H, \qquad (1)$$

where E_M is the intrinsic magnetostatic energy; E_σ, the energy sum of side DW perpendicular to the layer interface in the first and second layers; $E_{\sigma c}$, the interaction energy; E_H, the pulse field energy. The effect of external pulse field was taken into account as the width change difference between adjacent domains oriented parallel and antiparallel to the external pulse field. The equilibrium values of the energy and parameters of the DS1 through DS5 models are determined basing on the condition of minimal corresponding total energy values. The magnetic parameters of the layers being preset, the DS having the lowest energy is formed.

It is obvious that the DS reorganization observed in experiment during the cooling i due not only to the pulse field that forms the Ds but also to temperature dependences of magnetization for the film layers. It is known that the underlayer magnetization is weakly temperature-dependent. To elucidate the peculiarities of DS transitions observed in experiment, let the equilibrium energy values be found as a function of the M_{S1}/M_{S2} ratio and the pulse field strength, the other magnetic constants of the layers being assumed to be constant and equal to their values at room temperature.

The E_{DS1} was minimized with respect to d_1 and d_2 parameters (Fig. 3) where d is the domain width in the upper layer, and $E_{DS2} - E_{DS5}$ were minimized to the P_{02} parameter (Fig. 3) that is the period of the strip structure in the underlayer. The minimization was made for each Hp value using numerical methods. The results are presented in Fig. 4. The curves constructed show that as the pulse field rises, the energy equality points for corresponding DS are shifted towards higher M_{S1}/M_{S2} values, i.e., towards higher temperatures as compared to the case $H_p = 0$. Furthermore, it is seen that the existence range of continuous DS is rather narrow, no matter what DW type is present therein, thus, both at low and high temperatures, it is just a non-compromise structure that is favorable. The total energy decrease as H_p rises can be explained by the fact that the DS observed in the film is not an equilibrium one, since the upper layer is the single-domain one and its magnetization influences the underlayer DS, i.e., it generates an additional magnetization in the underlayer [7]. The calculation results reflect precisely enough the main peculiarities of the observed DS reorganization in the film within a wide temperature range.

Thus, the study of a complex DS reorganization in the bilayer film under cooling made it possible to distinguish the characteristic DS types being realized within certain temperature intervals. Considering the film magnetization processes in the 300 to 90 K range, five temperature intervals can be distinguished corresponding to different layer interface types. The study of DS transition temperature as a function of the pulse magnetic field strength has shown that the energy equality points of different DS types are shifted towards higher temperatures as the field strength increases. Furthermore, the existence range of compromise DS becomes narrower under these circumstances. The magnetization process of the bilayer film near the compensation point has been studied visually. A temperature-induced SRPT has been revealed. Consideration of the DS models and layer interfaces made it possible to understand the nature of that transition which is due to exchange interaction between the layers.

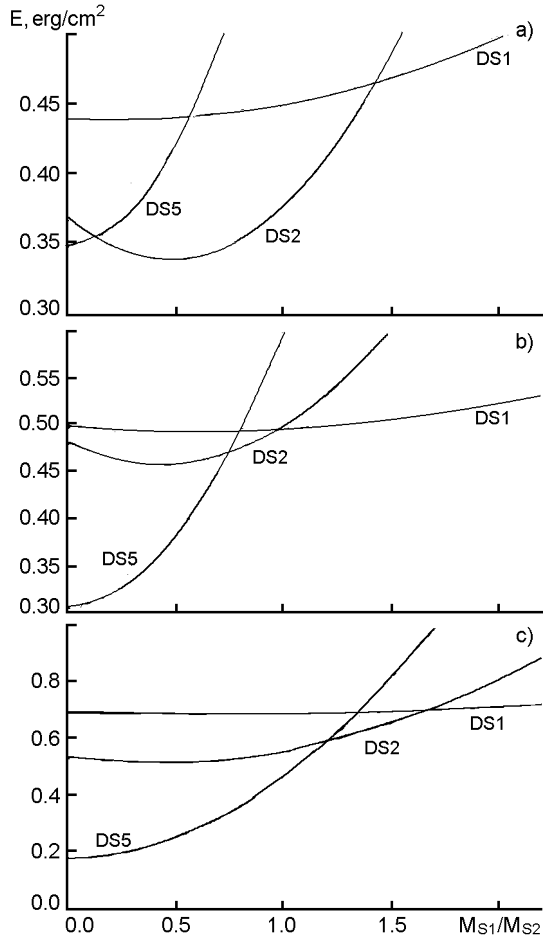

Fig. 4. Energy of different DS as function of magnetization ratio of film layers at different pulse magnetic field strength (Oe): 0 (a), 60 (b), 120 (c).

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Доменна структура двошарових магнітних плівок з різними характеристиками шарів

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В одноосній двошаровій плівці фериту-граната $(\mathrm{YGdTm})_3(\mathrm{FeGa})_5\mathrm{O}_{12}/(\mathrm{YEu})_3(\mathrm{FeGa})_5\mathrm{O}_{12}$ з точкою компенсації верхнього шару 120 К експериментально досліджено поведінку доменної структури та вплив зовнішнього імпульсного поля на точки рівності енергій різних доменних структур у температурному інтервалі 300–90 К. Запропоновано модель, яка дозволяє найбільш точно відобразити перебудову, що спостерігається, в залежності від типу доменної межі між шарами. Крім того, дана модель дозволяє пояснити спін-переорієнтаційний фазовий перехід, який спостерігається у плівці при температурі T = 142 К.