

Magnetostatic pressure as a factor of spiral domain stabilization in ferrite-garnet films

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Stable spiral domains (SpD) surrounded by bubble lattice (LBD) and existing in the absence of magnetic fields have been experimentally studied in epitaxial ferrite-garnet films. Thermodynamic approach and the concept of magnetostatic pressure are used to explain the SpD behavior with bias field (H) and temperature (T) change. It is shown that T- or H-induced phase transitions (PT) in LBD initiate PT in SpD.

В эпитаксиальных пленках ферритов-гранатов экспериментально изучены устойчивые спиральные домены (СпД), окруженные решеткой ЦМД (РЦД) и существующие при отсутствии магнитных полей. Для объяснения поведения СпД при изменении поля смещения (H) или температуры (T) используется термодинамический подход с введением понятия магнитостатического давления. Показано, что индуцированные T или H фазовые переходы (ФП) в РЦД вызывают ФП в СпД.

In the ferrite-garnet films, there is a large variety of domain structures due to both the physical properties of the film material and the influence of magnetic fields and temperature. Recently, new experimental and theoretical works have been published aimed at a new type of domain structure (DS), the spiral domains (SpD) originating in the films under the action of variable and constant magnetic fields. The SpD possess different properties depending on their formation conditions. Single- and two-arm SpDs were observed first in bulk samples of the Mn–Al–Ge alloy [1]. In ferrite-garnet films, the SpD originated from a labyrinth DS under the influence of a pulsed or sinusoidal high-frequency magnetic field in the presence of bias field H [2–4]. Such SpD structure existed in a certain range of frequencies and magnetic field values, it was fluently traveling within the sample for a certain time, i.e. the structure was dynamic. After the field switching off, the labyrinth DS was observed. In [5, 6], the SpD were also formed from the labyrinth DS under the influence of bias field H. In the presence of H, these were the stable SpD. After the field removal, there were SpD with a lesser number of turns and surrounded by the labyrinth SpD. All the described SpD structures were non-equilibrium ones. In [7], the SpD were created by a single-pole pulsed magnetic field (H_{pul}), the bias H being absent. Then the fiels was switched off. The SpD were stabilized by the surrounding bubble lattice (LBD) and existed for an infinite time in the absence of magnetic field. Moreover, those were reproducible at the same formation conditions. Thus, the equilibrium spiral domains were first obtained. We have studied the equilibrium condition of two coexisting domain systems, a spiral domain and an LBD by superposing an $H > 0$ onto a domain structure [8, 9].The effect of $H < 0$ and temperature (T) on the SpD are not studied to date.

This work continues studies of stable SpD [7–9]. Its aim is to study the behavior of SpD with changes in H or T and to determine the regularities and peculiarities of phase transition (PT) mechanism in a spiral domain. The work novelty consists in a simultaneous experimental study and explanation of the results obtained using a thermodynamic approach and the magnetostatic pressure concept.

A magnetooptical unit was used to study DS. It provided the temperature change from 90 K to the Neel temperature (T_N) and the action of magnetic fields normal to film plane: a single-pole pulsed field (H_{pul}) of 400 Hz with $60\cdot10^3/4\pi$ A/m and a bias field of two directions. For **H**↑↓ to magnetization **M** inside the bubble, then $H>0$; if **H**↓↓**M**, then $H < 0$. Moreover, the film could be additionally influenced by an in-plane field. The investigated $(TmBi)_3(FeGa)_5O_{12}$ film was grown on gadolinium-gallium garnet by the liquid-phase epitaxy method. The easy magnetization axis is normal to the film plane. The film had the magnetic compensation point (T_C) of 120 K and the Neel temperature of 437 K. At room temperature, the saturation magnetization of the film $4\pi M_S = 160\cdot10^{-4}$ T, the anisotropy field $1200\cdot10^3/4\pi$ A/m. The DS was observed due to the Faraday effect.

Spiral domains were formed by H_{pul} in the absence of H. Then the H_{pul} was switched off. The LBD was also formed; it surrounded at stabilized the SpD. The SpD behavior at changes in T or H is therefore connected with that of LBD. Thermodynamic approach together with the concept of magnetostatic pressure was used to explain the coexistence of the two domain structures and their behavior at T or H changes. In [8], the LBD pressure has been calculated as a derivative of the lattice energy with respect to the area with the opposite sign:

$$P = 6C(2\pi M_S)^2\left(\frac{d}{a}\right)^4\frac{h}{a},$$

where a is the lattice constant; d, the BD diameter; h, the film thickness; M_S, the saturation magnetization; C, a constant. In [9], the total SpD energy was calculated; in [10], it has been theoretically shown that the SpD pressure increases with its radius. In [11], it has been experimentally proved that coexistence of SpD and bubble lattice requires the magnetostatic pressures to be of the same value.

The spiral domain consists of two strip domains (SD) of opposite magnetization and coiled to form an Archimedean spiral, i.e. it has internal and external ends (Fig. 1a). The coiling is in any direction. SpDs including 3 to 30 turns can be obtained. The diameter of such spirals is 100 to 1200 μm, respectively. The period of SD forming the spiral in the absence of H is the same as in an ordinary strip structure, it does not depend on the ordinal number of the spiral turn. When the DS is influenced by $H > 0$, there are changes in spiral length, number of turns, inner and outer diameter, and the period of SD forming the spiral. The spiral can be uncoiled in two ways. With the external end fixed, the spiral is uncoiled from inside on. Inside the spiral, occurs a single-domain nucleus arises (Fig. 1b). The spiral could transform to a ring domain [12]. If the external end of SpD is uncoiled, the surrounding LBD occupies the free space (Fig. 1c). For any H, the SpD pressure is equal to that of LBD [11]. For $H < H_C$ of LBD collapse, the spiral is disappeared. In its place, a dumbbell-like domain remains consisting of two rigid BD connected with a small stripe (Fig. 1d). This is SpD nucleus. If the dumbbell-like domains are numerous, then a group of spirals is formed among which there are one- and two-arm spirals of any coiling direction. In an planar field, the dumbbell-like domain disappears and the already formed SpD becomes destroyed.

If the SpD is influenced by $H > 0$ and then the field is switched off, then there was a phase transition (PT) occurs in the BD lattice to a two-phase structure consisting of LBD plus stripes. The strip domains forming the spiral have transformed into a wave DS (WDS). Thus, a PT occurs also in SpD. The spiral shape takes the "flower"-like shape similar to that shown in Fig. 1g. This can be explained by LBD and SD pressure decrease at $H > 0$ [13, 14]. That is why nuclei of stripes and WDS are originated in LBD and SD, respectively. When H is removed, the DS pressure increases and, as a result, a PT occurs. Under $H < 0$, the bubble diameter increases and it takes hexagonal shape at $H = -35\cdot10^3/4\pi$ A/m. The LBD becomes transformed into a honeycombed DS. The structure pressure increases [13]. As the SpD radius could not increase, the internal end of SpD is uncoiled. Inside the SpD, a single domain area arises (Fig. 1e,f) which counterbalanced the external pressure.

The SpD shape depends on its formation temperature. This is connected with the temperature dependence of the magnetostatic pressure of bubble lattice. The pressure of equilibrium LBDs decreases when

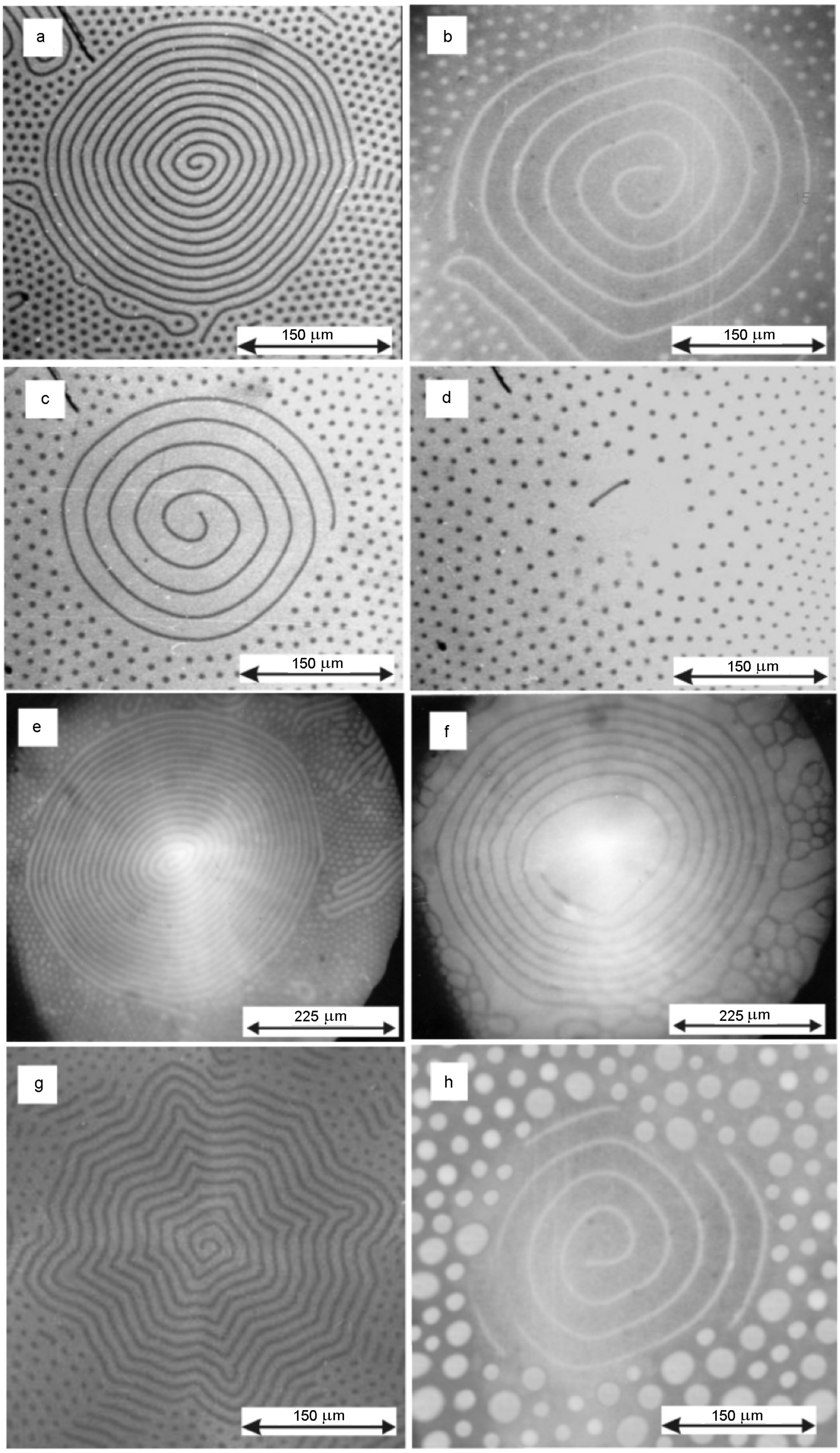

Fig. 1. Species of domain structures. Effect of bias field, $H \cdot 10^3/4\pi$ A/m (T = 300 K): Equilibrium DS at H = 0 (a); SpD with fixed outer end, H = 100 (b); SpD with free outer end, H = 90 (c); DS at H = 118 (d); SpD at H = −35 (e) and H = −45 (f). Effect of temperature on DS (H = 0): SpD at T = 370 K (PT in SpD) (g); SpD at T = 215 K (h).

the T_N point is approached. Thus, the SpD radius should also be decreased fto retain the coexisting DS in equilibrium. In [11], it has been shown that there exists the limiting pressure below which the SpD is not formed. Besides, for T close to T_N, the dumbbell domains do not exist. When T_C is approached, the LBD pressure decreases as well, and the SpD is not formed.

The SpD formed at 300 K survived, with T variation, in the ΔT interval. Destruction at the both ends of ΔT is connected with PT to the LBD [15]. At a distance from T_C, the LBD is transformed into a two-phase structure as the pressure decrease and this initiated the SD spiral transition to WDS. A DS of the "flower" type is observed in SpD place (Fig. 1g), i.e. a PT takes place in the SpD. At the other ΔT end value, on approaching T_C, a PT occurs in the LBD with the decrease in the domain number and, as a result, the SpD is disintegrated into separate blocks of stripes (Fig. 1h). So, the temperature-induced PT in the LBD is the reason of phase transition in SpD.

Thus, from the above experimental results the following conclusions can be drawn. An SpD nucleus is a dumbbell domain and it follows that the energy of SpD boundaries is high. These are the 180-degree Bloch boundaries. A dumbbell domain is created by H_{pul} in the temperature range of a high magnetization of the film, that is far from T_N and T_C. Thus, the SpD can be formed in this temperature range only. The SpD surrounded by bubble lattice is an equilibrium DS. Two domain structures may coexist when their magnetostatic pressures are equal to each other. This equality is satisfied at any changes of T or H. That is why the SpD behavior at temperature or field changes is invariably connected with the LBD behavior. T- or H-induced phase transitions in the LBD initiate PT in the SpD. SpD formation and its diameter depend on magnetostatic pressure of bubble lattice. Thus, the magnetostatic pressure in the LBD not only stabilizes the SpD, but defines a possibility of SpD formation and its behavior at T or H changes.

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Роль магнітостатичного тиску у стабілізації спіральних доменів у плівках феритів-гранатів

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В епітаксійних плівках феритів-гранатів експериментально вивчено стійкі спіральні домени (СпД), які оточені граткою ЦМД (ГЦД) та існуючі при відсутності магнітних полів. Для пояснення поведінки СпД при змінах поля зміщення (H) або температури (T) використовується термодинамічний підхід з введенням поняття магнітостатичного тиску. Показано, що індуковані T або H фазові переходи (ФП) у ГЦД призводять до ФП у СпД.