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Thermal influence on magnetoelectric characteristics of yttrium iron garnet epitaxial films

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The thermal influence on magnetoelectric characteristics of the epitaxial yttrium iron garnet films has been studied. Changes in field dependences of electromagneto-optical effect after thermal annealing of films have been revealed. It is shown that the relaxation of non-uniform mechanical stresses in the sample under study and the relaxation of substrate-induced strains in the film may cause the specified changes.

Исследовано влияние термического воздействия на магнитоэлектрические характеристики эпитаксиальных пленок железоиттриевых гранатов. Экспериментально выявлены изменения в полевых зависимостях электромагнито-оптического эффекта после термического отжига пленок. Показано, что причиной указанных изменений может быть релаксация неоднородных механических напряжений в изучаемом образце и релаксация деформаций пленки подложкой.

Some previous publications reported the magnetoelectric effect (MEE) in single crystals and epitaxial films of yttrium iron garnets (YIG) [1–3]. The MEE consists in induction of a magnetization by an electric field **E** or polarization by a magnetic field **H**. YIG showed the magnetoelectric interaction of a low value, however, numerous researches on the technological aspects of MEE in YIG have been carried out to demonstrate this material as a potential candidate for some devices (optical diodes, modulation of amplitude, polarization, and phase of optical waves, etc.) [4]. A good isolator material must be magneto-optically active as well as transparent in the range of interest. YIG is just such a material. In this paper, we report the results of some experimental studies of thermal influence on magnetoelectric characteristics of epitaxial YIG films.

We used laser polarimeter technique (described in detail in [5, 6]) for our researches. The method consists in the recording of the electric field-induced changes of the magneto-optical Faraday rotation in investigated structure — α_{EMO}, and referred to in [7] as the electromagneto-optical (EMO) effect (EMOE). Considering the high sensitivity of EMOE to changes in structural characteristics of magnetoelectric films [8, 9], we have studied the thermal annealing effect on the character of the recorded magnetoelectric manifestations in epitaxial YIG films. Measured were the magnetic field and electric field dependences of EMOE (the angle of light polarization plane rotation — α_{EMO}) for two conditions of the YIG film, prior to and after thermal treatment of the sample. The measurements were carried out at $\lambda = 0.63$ μm (He–Ne laser was used as a probing beam in the experiment) in the $\mathbf{H}\|\mathbf{E}\|\mathbf{k}$ geometry, where **H** is the static magnetic field; **E**, the low-frequency variable electric field; **k**, the light wave vector.

The YIG film was placed between two optically transparent electrodes used to apply an external electric field at the fre-

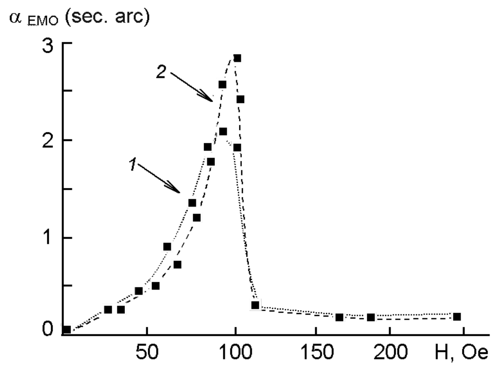

Fig. 1. The magnetic-field dependences of EMOE for YIG film, *1* – before thermal influence on YIG film, *2* – after thermal influence.

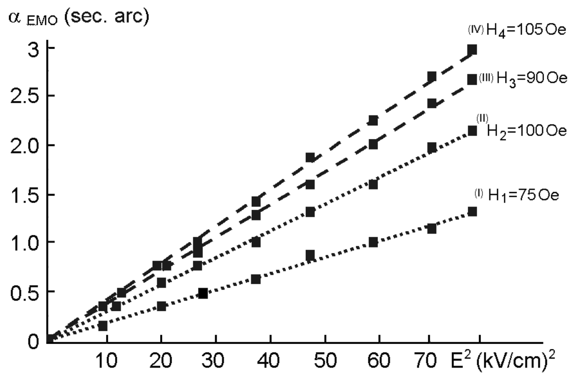

Fig. 2. The electric-field dependences of EMOE in YIG film for different values of a magnetic field, I,II – before thermal influence on YIG film and III,IV – after thermal influence.

quency ω = 800 Hz. The epitaxial YIG film (of about 12 μm thickness) was grown on an about 600 μm thick gallium gadolinium garnet (GGG) substrate. The sample was thermally treated at T = 650°C for 50 min followed by slow cooling.

In Fig. 1, shown are the experimental magnetic field dependences of EMOE: curve *1* is taken prior to thermal anneal YIG film, and curve *2*, thereafter. The effect is registered using the doubled frequency of electric field (a EMO effect quadratic with respect to electric field). As is seen from Fig. 1, $\alpha_{EMO} \approx 0$ in fields corresponding to transition to magnetic saturation of the YIG film ($H > 120$ Oe), i.e. the value of film magnetisation **M** in electric field remains essentially constant. These dependences show that a low-temperature thermal influence on the sample results in an increase of α_{EMO} in maximum, but the character of magnetic-field EMOE dependences does not change essentially. The EMOE rotation amplitude (α_{EMO}) increases by a factor of about 1.3 as compared to that for unannealed YIG film. The causes of this increase will be considered below.

In Fig. 2, the electric-field dependences of EMO effect (I, II, prior to thermal influence and III, IV, thereafter) are shown for four magnetic field values (H_1 = 75 Oe, H_2 = 100 Oe, H_3 = 90 Oe, and H_4 = 105 Oe). It is seen in Fig. 2 that the registered signal (α_{EMO}) value depends linearly on the squared **E** field.

In our opinion, such change in the magnetic field dependences of α_{EMO} in YIG film after thermal annealing can be explained as follows. The YIG films can be obtained using various thin film techniques, including the liquid phase epitaxy. During formation of epitaxial YIG films, mechanical stresses and strains arise therein [10]. The strains in the surface epitaxial film layer are inhomogeneous because of difference between the lattice constants of the film and substrate. Temperature conditions of synthesis the epitaxial film volume and film surface are different. That causes the formation of superficial transitive layers at the substrate/film and film/air interfaces. These layers differ from the YIG film volume not only in the microcrystalline homogeneity over the thickness (and, as a consequence, in micromagnetic parameters), but also in the chemical composition. Thus, the garnet films grown on mismatched substrates may be strained and, as a result, local areas or thin layers may arise in the YIG film volume where the center-symmetric cubic crystal structure (typical of ferrite-garnet single crystals) is distorted. Thermal influence on the sample may eliminate those local stresses in YIG films. The EMO effect square-law in electric field is characteristic only for center-symmetric magnetoelectric materials [7, 11] and the increase or decrease of EMO signal value at the same site of YIG can testify changing in center-symmetric structure of the sample. In particular, increase of EMO signal in maximum (Fig. 1) may be a response to elimination of inhomogeneous mechanical stresses in the primary center-symmetric magnetoelectric material.

Besides, not excluded is the mechanism of impurity redistribution in the crystallographic positions under the thermal annealing of YIG films. The YIG films are known to be inhomogeneous in concentration due to conditions of their growth. On occupancy of different crystallographic positions essentially influence. When the epitaxial YIG film being formed on a substrate is withdrawn from the solution (separated from the solution-melt surface), the temperature conditions change (after the separation, the film formation still proceeds for some time).

The magnetic anisotropy changing in YIG films as a response to temperature influence in this case may be cannot be essential, as the annealing temperature and time are quite small. Though it is known [12] that a rather long thermal annealing of epitaxial films (10 hours and more) at $T > 1200°C$ (high-temperature annealing) may result in an essential reduction or full disappearance of the uniaxial anisotropy field which arises at the film growth.

Thus, we have revealed in experiment changes in magnetic-field and electric-field dependences of EMOE in epitaxial YIG films after thermal annealing. The results of our experiments show that the relaxation of inhomogeneous mechanical stresses in the studied sample and relaxation of the film strains by the substrate can be the principal cause of the specified changes.

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Вплив термічного відпалу на магнітоелектричні характеристики епітаксійних плівок залізоітрієвих гранатів

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Досліджено вплив термічного відпалу на магнітоелектричні характеристики епітаксійних плівок залізоітрієвих гранатів. Виявлено зміни у польових залежностях електромагніто-оптичного ефекту після термічного відпалу плівок. Показано, що причиною вказаних змін може бути релаксація неоднорідних механічних напруг у зразку, що досліджено та релаксація деформацій плівки підкладинкою.