Susceptibility and FMR in ferrite garnet epitaxial films for eddy current magneto-optical defectoscopy

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Abstract. The paper presents the magnetic properties of easy plane and easy axis films on the base of Bi-ferrite garnet experimentally investigated by ferromagnetic resonance and the inductive-frequency method. The possibilities and features of the operation of these films as sensors in eddy current magneto-optical introscopy are shown on the example of visualization of linear defects in products made from aluminium alloys.

1. Introduction
The interest in the study of multilayer magnetic structures does not dry out because it is caused by the very unusual properties of such structures, which are very different from the properties of single-layer magnetic films. One of the first theoretical studies of bilayer magnetic films is the work that formulated the problem of the distribution of magnetization in a film consisting of two exchange-related ferromagnetic layers with different orientations of the “easy” axes [1, 2].

The dynamic properties of such structures play a decisive role when used in various devices. Dynamic methods such as ferromagnetic resonance (FMR) or low-frequency susceptibility are useful tools for studying the effects of interaction between layers [3], as well as in the development of optimal conditions for the synthesis of magnetic structures with predetermined properties.

The films consisting of magnetic layers with various types of magnetic crystallographic anisotropy are of great interest. The increased attention to such structures is due to the possibilities for their practical application in a number of technical devices. An example of such device is a magneto-optical (MO) eddy current (EC) introscope.

Magnetooptic eddy current introscopy has certain advantages over other methods of non-destructive testing of products from magnetic and non-magnetic metals and alloys [4-6]. MO ferrite garnet epitaxial films (FGEF) grown by the method of liquid phase epitaxy act as the main sensory element in this method. The films can have three types of magnetic crystallographic anisotropy: “easy axis” (EA), “easy plane” (EP) and “angular phase” (APh) [7]. The main disadvantage of sensors with EA and APh anisotropy is the stochastization of the domain structure (DS) at high fields of excitation of eddy currents. In the easy plane films, which have practically no DS, there is no such drawback, but at the same time EP films have a much higher magnetization and saturation
field (normalization). The type of magnetic crystallographic anisotropy of films is easily determined from the orientation dependences of the spectra of ferromagnetic resonance.

Another important parameter of FGEF is the low-frequency susceptibility that characterizes the connection of the magnetization of a substance with magnetic field. The resulting susceptibility of magnetic films in the fields lower than saturation field $H_s$ is determined by two contributions: susceptibility due to the processes of domain boundaries displacement and susceptibility due to the process of rotation of magnetic moments. Depending on the type of magnetic anisotropy of the films, the domain boundaries displacements or the rotation of the magnetic moment dominate, which determines the efficiency of a MO sensor.

The aim of this work is an experimental study of the properties of easy axis and easy plain films used as sensors in magneto-optical eddy current introscopy by ferromagnetic resonance and the inductive-frequency methods.

2. Experimental results and discussion

2.1. Samples
Several films of the general composition $(Bi,Re)\_3(Fe,Me)\_5O\_12$, where $Re = Y, Lu, Pr, Me-Al, Ga, Sc$, synthesized by liquid phase epitaxy (LPE) method on paramagnetic GGG (gadolinium gallium garnet) substrates were selected for the studies. A number of films had the easy-plane anisotropy and other films had the easy-axis anisotropy with different values of the effective magnetic anisotropy field. The thickness of the samples varies from 1.9 to 12 $\mu$m. For EA sensors the period of the domain structure varies from 5.5 to 32 $\mu$m and the saturation field from 22 to 77 Oe. The normalization field for EP sensors is 228-250 Oe.

2.2. Ferromagnetic resonance
Figure 1 shows the FMR spectrum one of the samples of EA sensors measured at a frequency of 9.4 GHz with the orientation of a dc magnetic field normal to the film surface. It is seen that, along with the FMR signal from the main layer in stronger fields there is a signal from the additional layer, the intensity of which is an order of magnitude lower than the main resonance. Such additional layers, as a rule, are formed in the process of liquid phase epitaxy and are realized at the film – substrate interface [7]. These layers are found on both EA and EP films. The additional layer can have the same type of magnetic anisotropy with the main layer, as well and the opposite.

![Figure 1](image_url)

**Figure 1.** FMR profile for FGEF $(BiSmLuCa)\_3(FeGaSi)\_5O\_12$ with easy axis anisotropy. (a) The main layer, (b) the additional layer.

Figure 2 are presented the orientation dependences of ferromagnetic resonance for an easy axis (a) and easy plane (b) films. It can be seen that for easy axis films an additional layer has easy plane anisotropy and for easy plane films it has the same anisotropy with the main layer.
Figure 2. The orientation dependences of the FMR signals on the main (a) and additional (b) layers in the FGEF; (I) easy-axis film (BiYLuCa)₃(FeGaSi)₅O₁₂ with an easy-plane additional layer, (II) easy-plane film (BiY)₃(FeAlSc)₅O₁₂ with an easy-plane additional layer, β is the angle between the normal to the film and the direction of the magnetic field.

Resonance conditions for a film magnetized to the normal β = 0° and along the film surface β = 90° are given by the Kittel equations [8]:

\[ \frac{\omega}{\gamma} = H_{r0} + H_{\text{eff}}, \]

\[ (\frac{\omega}{\gamma}) = H_{r90} (H_{e0} - H_{r0}), \]

where \( \omega = 9400 \text{ MHz, } \gamma = \frac{g_e}{2mc} \) is the gyromagnetic ratio, \( H_{r0} \) and \( H_{r90} \) are resonance fields for perpendicular (β = 0°) and parallel (β = 90°) resonances, \( H_{\text{eff}} \) is the effective anisotropy field that looks like

\[ H_{\text{eff}} = H_{\text{dem}} + H_u + H_k, \]

where \( H_{\text{dem}} = 4\pi M_s \) is demagnetizing field of the sample form, \( H_u = 2K_u/M_s \) is the field of uniaxial anisotropy, \( H_k = -4/3 K_1/M_s \) is the field of cubic magnetic anisotropy.

The field of cubic anisotropy in ferrite-garnets is usually much less than the field of uniaxial anisotropy [9]. According to formulas (1), γ and \( H_{\text{eff}} \) can be determined for the main layers in EA and EP films. The values of γ for dilute ferrimagnetic materials may differ from the value of γ for a free electron. Since the resonant fields for additional layers are measured only up to 40 degrees, we will use only the expression (1) for estimating \( H_{\text{eff}} \) in the additional layers, assuming that the gyromagnetic ratio values of the layers are close. Thus, for EA films in figure 2 (a), we have \( H_{\text{eff}} = 380 \text{ Oe, } H_{\text{eff}} = -842 \text{ Oe, for an EP film } H_{\text{eff}} = -295 \text{ Oe, } H_{\text{eff}} = -412 \text{ Oe. It can be seen that the effective anisotropy fields of the additional layers are much larger than those of the main layers, and in the easy axis film they even have opposite sign. This may be due to different contributions of magnetoelastic stresses at the film - substrate interface in easy - plane and easy axis films.}

2.3. Low frequency susceptibility

Figure 3 shows the field dependences of the magnetic susceptibility of the easy plane film measured by the inductive-frequency method at a frequency of 1 MHz in a normal β = 0° (a) and parallel β = 90° (b) field. A characteristic susceptibility peak is observed at weak magnetic fields, the strongest peak for β = 0°. The abnormal susceptibility behaviour at normal magnetization β = 0° near H = 200 Oe indicates the processes caused by the presence of an additional layer.
Figure 3. The dc magnetic field dependencies of susceptibility for the easy plane film (BiLuTmPrGd)3(FeAlGa)5O12 at the angles $\beta = 0^\circ$ and $\beta = 90^\circ$.

Also, as in the case of FMR, the signal from the underlayer of easy plane film is observed not in the whole range of angles, but only near $\beta = 0^\circ$.

In easy axis films, an additional layer with an easy plane anisotropy can lead to the resultant angular phase anisotropy which will be easier to track various configurations of eddy current magnetic fields. On the other hand, it is known that such easy plane layers contribute to the suppression of the Bloch lines arising from the motion of domain boundaries in uniaxial films, providing a higher dynamics of domain boundaries in magnetic films [10].

In the studied EA sensors, the fields of the effective anisotropy for the base layer have values from 3300 Oe to 500 Oe. According to the type and efficiency of the magneto-optical visualization, the EA sensors were divided into 2 groups. The first type has an effective magnetic anisotropy field $H_{a_{eff1}} > 1000$ Oe, and the second one $H_{a_{eff1}} < 1000$ Oe.

2.4. Magneto-optical images
Figure 4 shows the magneto-optical images of model defects, which were a set of linear defects of the “through-slit” type in the aluminium sample with an opening width of 20 to 500 $\mu$m. The experimental conditions were the same for all sensors: the operating frequency $f$ of the introscope is in the range from 8 to 80 kHz, the amplitude of the alternating field $H_\sim$ of the inductor is from 2 to 400 Oe, the bias field $H_-$ is from 0 to 40 Oe.

Sensors with anisotropy of EA and anisotropy field above $H_{a_{eff1}} > 1000$ Oe, display defects with binary character: dark areas in the center and light halo near the edges, and represent 1 group (figure 4a, b). As the excitation field increases, a stochastic domain structure appears on a dark background (figure 4a). EA sensors of the second group, with an anisotropy field of $H_{a_{eff1}} < 1000$ Oe, depict a defect in the form of a light band of approximately the same width. The bias field broadens the MO image and
enhances its contrast in EA sensors (figure 4b), increasing the sensitivity of sensors of group 1, and has a weak effect on the sensors of the second group. The images obtained by the EP sensors (\(H_{\text{eff}} < 0\)) have not a binary, but an analogue character in the form of a bright band in the centre (figure 4d), herewith the bias field practically does not affect the quality of MO imaging.

3. Summary
In thin films of garnet ferrites grown by liquid phase epitaxy, in certain cases an additional layers is formed at the film – substrate interface, which creates a coherent intergrowth of two crystal lattices. Transition layers can be identified by the method of FMR or inductive-frequency magnetometry and may have the same or different type of magnetic crystallographic anisotropy from the base layer.

The value and sign of the effective anisotropy field of the sensors have a decisive effect on the type of MO imaging in the MO sensors. In the EA films at certain excitation fields, linear defects, depending on the magnitude of \(H_{\text{eff}}\), are displayed as light or dark stripes; in EP films, MO images are analogue character.

A small bias field in the EA sensors with large values of \(H_{\text{eff}}\) allows one to obtain the MO image of a defect at much lower excitation fields, which allows minimizing the power consumption of the eddy current intrescope. The bias field also increases the contrast and clarity of the display of the MO images of defects, including by suppressing the stochastization of the domain structure.

Acknowledgments
This work was supported by the RF Ministry of Education and Science in the framework of the base part of the state task (Project No. 3.7126.2017/8.9) and the V.I. Vernadsky Crimean Federal University Development Program (Project No. BF11/2018).

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