Specific features of magnetic domain structure in epitaxial magneto-optical ferrite-garnet films

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Abstract. We describe the experimental studies of both domain and crystal defect structure of magneto-optical bismuth-substituted ferrite–garnet films (FGF) with high Faraday effect. Indentation and scratching (sclerometric) tests of either magnetically uniaxial or easy plane anisotropy (“planar”) films were carried out in parallel with traditional chemical etching. We demonstrate the effect of strong local changes of magnetic anisotropy on the domain structure due to local mechanical stresses. New types of biperiodic domain structure imposed by external stresses were found to exist.

1. Introduction

The interest in epitaxial Bi-substituted ferrite-garnet films Bi$_x$Gd$_{1-y}$Lu$_{3-y}$Ga$_y$Fe$_5$O$_{12}$ (Bi:FGF), thickness 3–7 μm, deposited on oriented Gd$_3$Ga$_5$O$_{12}$ substrates is related to the possibility of using them in various devices (visualizators of spatial magnetic field microdistributions, optical switches, modulators, isolators, etc.). Among the advantages of FGF are high resolution and contrast imaging of the magnetic field distributions associated with large values of Faraday rotation. To achieve such values, Bi ions are introduced into the crystallographic lattice of the FGF. The domain structure (DS) of uniaxial FGF was investigated in great detail by many researchers. [1-4]. At the same time, however, the studies of planar DS till now have received but scant attention.

In this paper we examine both uniaxial films with the easy axis direction normal to the plane of the film having a "labyrinth" domain structure, and planar films with magnetic moment oriented in the plane of the film. Domain structure of magnetic films is determined by the balance of many factors, of which the exchange interaction, magnetization, anisotropy, the shape of a magnetic sample, the energy of domain walls, the magnitude and direction of external magnetic field, temperature, defects, magnetostriction, the surface structure. Defects of the GGG substrate and films which arise during the growth and processing, various kinds of surface disturbances affect the magnetic characteristics of FGF. Generally high-quality FGF should possess defect density as low as possible, so the study of defects, both structural and mechanically induced, is an important research task.

We study the intrinsic (DS) of “planar” FGF. For this film type the magnetocrystalline anisotropy $E_a$ is small compared with the shape anisotropy $E_s = \mu_0 M_s^2 \sin^2 \varphi$, where $M_s$ is saturation magnetization and $\varphi$ is the angle between the film plane and $\mathbf{M}$. The total energy $E = E_s + E_{\text{ext}} = K_s \sin^2 \varphi - H_{\text{ext}} M_z \cos (\theta - \varphi)$, where $\theta$ is the angle between $\mathbf{H}_{\text{ext}}$ and film plane. For $\theta = \pi/2$, the magnetization $z$-component $M_z$ is a linear function of the external field and $M_z \leq M_s$ [5]. This property of planar FGF favours their use as magneto-optical sensors visualizing the microfield. Both uniaxial and planar FGF are finding their use for this purpose. Here it should be stressed, however, that in these both cases it is normal field component that is solely applied for sensing. Moreover, in standard microscope arrangement the
intrinsic DS of planar FGR remains invisible due to Faraday effect symmetry. In the present work we identify the intrinsic DS of planar FGF and observe directly the processes of domain wall displacement. To this end we developed a manipulation tool enabling to orient the sample at the microscope table at any desired angle. Optimum is chosen on the basis of negotiation between the Faraday contrast and image distortion due to sample inclination. In this way we were able to prove that FGF under study possesses well developed structure of 90- and 180-degree domains (Figure 1). By direct observation evidence was obtained of the smallness of the “planar” coercive field, \( H_c \), and Barkhausen jumps typical of domain wall displacement processes. This property will be useful for the improvement of development of high-sensitivity magnetometry.

**Figure 1.** Domain structure of planar transparent FGF as revealed by Faraday effect

### 2. Experimental
Bi-FG films are transparent single-crystal layers grown by liquid-phase epitaxy on a non-magnetic crystalline Gd$_3$Ga$_5$O$_{12}$ substrates was obtained by Czochralski method. In the experiment in addition to domain structure we studied structural and mechanically induced defects in the film and in the GGG substrate. Defects in the substrate are formed during crystal growth (inclusions, growth and dislocation bands) and during processing (scratches, chips, etc.). Defects and heterogeneities of the substrate are inherited by the film, causing local changes in the magnetic properties. The dislocation structure of crystalline Gd$_3$Ga$_5$O$_{12}$ substrates, uniaxial and planar magnetic films was revealed by the method of selective chemical etching. The mechanically polished GGG substrate and magnetic films were etched in 85% phosphoric acid at temperature of 160°C and 100°C respectively. The scratching experiments were carried out on Vicker's hardness meter, dislocation structure was investigated by optical interference profilometry and scanning electron microscopy (SEM) with secondary electron (SEI) and back-scattered electrons (BSE) while the magnetic domains were observed by means of magneto-optical microscopy.

### 3. Results and discussion
The dislocation structure of GGG substrate and FG film grown in [111] was determined by selective chemical etching. Figure 2 (a, b) shows large (150-170 µm) etch pits of the jogged screw dislocations with a sharp bottom indicating the growth origin of the dislocation. The small (5-7µm) etch pits of the magnetic film correspond to the straight edge dislocations (Figure 2 c). Dimensions of dislocation pits and bottom form are determined by optical profilometry.

**Figure 2.** SEM image of dislocation etch pit: a) GGG (SEI), b) GGG (BSE), c) FGF surface (SEI).
Single dislocations do not have a noticeable effect on the magnetic properties of the film, but dislocation clusters cause formation of microdomains, shape distortion of domain walls and the change of domain sizes. Defects in the film, caused by non-conformities of parameters of the lattices of the substrate and of the film, lead to the formation of dislocations, rupture of the film and negatively affect the quality of thermomagnetic recording on the ferrite-garnet film.

The motivation for our research were studies of Jordi Sort [6-7] and Broese van Groenou [8]. Using sclerometry (scratching an edge of a quadrangular pyramid) with a load of 20 g we scratched on uniaxial films with a labyrinth domain structure. We observed a shift of domains in the defect region by the magneto-optic (MO) microscopy based on polar Kerr effect (Figure 2a). The external magnetic field (10 mT) applied in the direction normal to the film plane caused changes of configuration of domains and the inclusion of this defect in the domain of one sign (Figure 2b).

![Figure 3](image)

**Figure 3.** MO image of scratch-modified domain structure:

a – zero external field, b – applied field 10 mT.

The effect of induced mechanical defects on the domain structure was also investigated on planar ferrite-garnet films. The indentation and scratch tests were carried out on Vicker’s hardness metter with a load of 20 g and 50 g. The appearance of closure domains in the defect region was visualized (Figure 4a). Under the action of a NdFeB permanent magnet (10 mT) along the film plane and normal to it, we observed a partial restructuring of closure domains and the alignment of part of the domains along the stress fields. On the scratch in the form of “zigzag”, the closure domains with their own fine domain structure were visualized (Figure 4b). The appearance of induced anisotropy in a planar film is associated with a local mechanical effect. As a result of scratching the normal component of the magnetization vectors appears, which allows us to reveal the domain structure of planar film by the polar Kerr effect.

![Figure 4](image)

**Figure 4.** MO image of scratch-modified domain structure of planar FG film.

A perpendicular easy axis can be induced by scratching of quadrangular diamond pyramid, loaded up more than 50N on planar FG film. A 180° domain walls, oriented relative to each other at an angle of 90°, were visualized by the polar Kerr effect. The competition between planar film’s own cubic and induced uniaxial anisotropy leads to the appearance of a biperiodic domain structure (Figure 4c).
A biperiodic domain structure was described in [9-10]: periodic domain structures appeared in magnetic thin films under the influence of an internal magnetic field directed normally to the film plane and can be presented as a diffraction grating which modulates the linear as well as the nonlinear magneto-optical susceptibilities. In our case, local mechanical scratching led to a biperiodic magnetic structure.

4. Conclusion
The results of our experiments show that defects in magneto-optical bismuth-ferrite – garnet films leads to the formation of closure domains in Bi:FGF with different types of magnetic anisotropy.

The behaviour of the domain structure in the vicinity of a defect in the case of magnetization reversal of uniaxial films is considered. It is shown that after the magnetization reversal of the film, a continuous defect is included in the domain of one sign. Our research demonstrated that the domain structure is sensitive to indentation and scratch tests. It has been shown that local mechanical stresses can lead to the appearance of a biperiodic domain structure not observed earlier in these magnetic materials. The observed effects should be taken into account in magnetoelectronic technology.

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