Scanning probe microscopy investigation of iron garnet films for magnetoplasmonics

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Abstract. Topography and domain structures of Bi-substituted iron garnet films proposed for magnetoplasmonic applications are presented. Investigations were carried out by scanning probe microscopy methods, including polarization near-field optical microscopy. The most suitable films with less rough surface were chosen. The period of domain structure of sputtered film of composition Bi\textsubscript{2.8}Y\textsubscript{0.2}Fe\textsubscript{5}O\textsubscript{12} were determined, 2\textit{W} = 0.5 \textmu m.

1. Introduction

Synthesis and investigation of magnetoplasmonic (MP) nanostructures is relevant for construction of micro-dimensional optical isolators, modulators and switches, miniature integrated nanophotonic devices for fast multi-mode and multi-directional control, plasmonic circuit elements controlled by magnetic field [1,2]. For example, nanostructure “iron garnet (IG) – perforated Au film” experimentally demonstrated the effective modulation of transmission with contrast up to 98\% using a weak external magnetic field [3]. Creation of metallic coating on IG films imposes specific surface requirements. Additionally, the films should have definite magnetic and magnetooptical properties [4]. In the work, authors present the investigation of topography and domain structures of IG films proposed for MP applications by scanning probe microscopy methods, including polarization near-field optical microscopy [5].

2. Experimental

Films of bismuth-substituted IG with micro- and nanoscale thicknesses were synthesized by liquid-phase epitaxy (LPE) and reactive ion beam sputtering (RIBS). For RIBS-films, the garnet phase was formed by crystallization annealing process in the air and high temperature \( T_a \) (above 650 °C) after deposition on respective substrate from ceramic target [4,6-8]. Substrates of gadolinium gallium garnet (GGG), calcium niobium gallium garnet (CNGG), and fused quartz SiO\textsubscript{2} were used for RIBS-films. All LPE-films were synthesized on GGG substrates.

Grown LPE-films have the compositions of (Gd,Bi,Lu)\textsubscript{3}(Fe,Ga,Ge)\textsubscript{5}O\textsubscript{12} (No.1), (Bi,Y,Eu)\textsubscript{3}(Fe,Al,Ga)O\textsubscript{12} (No.2), and (Gd,Bi,Lu)\textsubscript{3}(Fe,Ga,Ge)\textsubscript{5}O\textsubscript{12} (No.3). The thicknesses of films are 1.9, 5.1, and 11.7 \textmu m, respectively.

Two sets of RIBS films were realized.
Table 1. Annealing regimes of double layer RIBS-films No. 6-9.

| No. | Layer of films | $T_a$, °C | $t_a$, min | Heating rate |
|-----|----------------|-----------|-------------|--------------|
| 6   | M2             | 710       | 60          | low          |
|     | M3             | 680       | 60          | low          |
| 7   | M2             | 700       | 20          | dipping      |
|     | M3             | 680       | 20          | dipping      |
| 8   | M2             | 700       | 60          | low          |
|     | M1             | 650       | 25          | dipping      |
| 9   | M2             | 700       | 60          | low          |
|     | M1             | 660       | 60          | low          |

The first set contained the single layer films of composition $\text{Bi}_{2.8}\text{Y}_{0.2}\text{Fe}_{5}\text{O}_{12}$ (M1) on the substrates of GGG and CNGG. The films are denoted as GGG/M1 (No.4) and CNGG/M1 (No.5) hereinafter. The samples were synthesized at the same temperature $T_a = 650$ °C during annealing time $t_a = 20$ min. Garnet thickness is 100 nm.

The second set contained double layer films $\text{SiO}_2/\text{M2/M3}$ (No.6), GGG/M2/M3 (No.7), $\text{SiO}_2/\text{M2/M1}$ (No.8), and GGG/M2/M1 (No.9), where M2 and M3 are bismuth-substituted IG $\text{Bi}_{1.0}\text{Gd}_{1.3}\text{Fe}_{4.2}\text{Al}_{0.8}\text{O}_{12}$ and $\text{Bi}_{1.5}\text{Gd}_{1.5}\text{Fe}_{4.5}\text{Al}_{0.5}\text{O}_{12}$, respectively. The layers M2, M3, and M1 have the thicknesses of 63, 195, and 177 nm, correspondingly. The double layer films given successful results in magnetophotonic crystals and Tamm structures design [4,8-11]. Different annealing regimes were used to reduce the roughness of RIBS-layers. Annealing conditions are given in the Table 1.

Semicontact atomic force microscopy (AFM) was applied to describe the surface and measure its parameters – height range $R_{max}$, average roughness $R_a$, root mean square roughness $rms$, and polycrystalline size $Z$ (for RIBS-films only). To visualize the domain structure of films, semicontact two-pass or parallel magnetic force microscopy (MFM) and scanning near-field optical microscopy (SNOM) were used. The measurements were carried out by cantilevers of HA_HR ETALON, MFM01, and SNOM_NC with typical aperture diameter of $(120 \pm 25)$ nm. The scheme of used experimental equipment, scanning probe microscope (SPM) NTEGRA (NT-MDT) with configuration that allows combining the AFM and SNOM techniques, is illustrated in Figure 1.

3. Results and discussion

Table 2 lists the determined parameters of surface topography of investigated samples and total thicknesses of films $h$. Data were obtained by AFM measurements on frames with area of 2x2 $\mu$m$^2$ using standard AFM cantilever.

Figure 1. Scheme of used configuration of SPM NTEGRA (NT-MDT).
Table 2. Surface parameters of investigated LPE- (No.1-3) and RIBS-films (No.4-9).

| No. | $R_{\text{max}},$ nm | $R_{\alpha},$ nm | $rms,$ nm | $Z,$ nm | $h,$ nm |
|-----|---------------------|----------------|----------|--------|---------|
| 1   | 12.6                | 0.6            | 0.8      | -      | 1900    |
| 2   | 8.2                 | 0.6            | 0.75     | -      | 5100    |
| 3   | 13.4                | 1.0            | 1.47     | -      | 11700   |
| 4   | 58                  | 6.4            | 7.6      | 90     | 100     |
| 5   | 39.5                | 7.6            | 9.0      | 65     | 100     |
| 6   | 27                  | 3.2            | 4.0      | 130    | 258     |
| 7   | 24                  | 3.2            | 4.0      | 150    | 258     |
| 8   | 49                  | 5.5            | 6.9      | 125    | 240     |
| 9   | 63                  | 6.0            | 7.9      | 150    | 240     |

Measurements of various LPE-films showed that $rms$ could reach values less than 0.9 nm. Figure 2 shows the typical domain structure of LPE-film No.1 with period of 16 μm. From obtained data we notice that width of domain wall of film No.1 is $w_{dw} = 895$ nm measured as distance from minima to maxima of optical intensity signal. Nevertheless, the structure of domain walls and domain edges is not obvious and may be more complicated as Figure 2b,c,d demonstrates.

Figure 3 shows the surface and domain structure of RIBS-film No. 4. MFM and SNOM data give the same domain period of the film that is $2w = 0.5$ μm. The film before measurements was heated. We calculated the parameters of surface from the images obtained by SNOM tip. The values of $R_{\text{max}}, R_{\alpha}$ and $rms$ decrease to 33.7, 3.9, and 4.8 nm in comparison to the same values in the Table 2. Average size of crystallites increases to $Z = 270$ nm. So, the surface parameters of polycrystalline films with the rough surface are not defined correctly by SNOM tip due to its pyramidal geometry, and development of SNOM tip with more appropriate forms is necessary [12, 13].

![Figure 2](image-url)  
*Figure 2. Domain structure of LPE-film No.1: (a) MFM image; (b) SNOM image with optical polarization contrast at a domain wall (left part of image) and domain (right part of image); (c) SNOM image and (d) profile of a domain wall.*
Figure 3. (a, c) Topography and (b, d) domain structure of RIBS-film No.4 of the surface area measured by (a, b) MFM and (c, d) combination of AFM and SNOM.

Figure 4. (a) AFM images of RIBS-film No.6 and (b) LPE-film No.2.

Figure 4 shows the surfaces of LPE-film No.2 and RIBS-film No.6 with the smallest roughness (Table 2). We propose these films for further experiments.

4. Conclusion
LPE and RIBS Bi-substituted IG films were investigated by AFM, MFM, and SNOM to choose the most suitable films with less rough surface for magnetoplasmonic applications. Typical value of $rms$ of synthesized LPE-films is 0.8 nm. The $rms$ of LPE-films increases with thickening the samples. The structure of domain wall of LPE-film with uniaxial anisotropy was presented.

Topography of RIBS-films strongly depended on annealing regimes. We reduced $rms$ of RIBS polycrystalline films to 4.0 nm. The double layer films of composition $\text{Bi}_{1.0}\text{Y}_{0.5}\text{Gd}_{1.5}\text{Fe}_{4.2}\text{Al}_{0.8}\text{O}_{12}$/ $\text{Bi}_{1.5}\text{Gd}_{1.5}\text{Fe}_{4.5}\text{Al}_{0.5}\text{O}_{12}$ had the smallest values of $rms$.

The period of domain structure of RIBS-film of composition $\text{Bi}_{2.8}\text{Y}_{0.2}\text{Fe}_{3}\text{O}_{12}$ was determined as $2w = 0.5 \mu\text{m}$.
Acknowledgements
Research performed by grant of Russian Science Foundation (project no. 19-72-20154).

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