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Microanalysis of magnetic structure of yttrium-iron garnet films by using the scanning probe microscopy methods

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Abstract. In this paper, the features of the microstructure of magnetic domains observed in ferrite-garnet films (FGF) have been presented. The studied FGF with orientation (111) were grown on gallium-gadolinium substrate by using liquid-phase epitaxy. The study of distribution inherent to magnetic domains was carried out using magnetic force microscopy (MFM) with the scanning probe microscope NanoScope IIIa Dimension 3000^{TM}. In the course of these researches, optimization of the MFM method was carried out to obtain high-quality and correct images of magnetic domains in FGF. Nanorelief and magnetic microstructure of FGF surface were studied, depending on their thickness, on external magnetic field and doses of boron ion implantation. For these objects, it was established that stripe domain structure is characteristic, the period of which depends on the film thickness. The nature of transformation of domain structure depending on thickness is close to that theoretically predictable at low thicknesses (up to 10 μm). Nanorelief of film surfaces is virtually unchanged depending on thickness. An external magnetic field with the magnitude 4 mT causes significant changes in domain configuration and allows to visualize heterogeneity of magnetic structure. Ion implantation leads to a slight smoothing of nanorelief films (roughness of 0.2 nm) and to more accurate displaying the magnetic microstructure, which is associated with processes of structural ordering under ionic bombardment.

Keywords: magnetic force microscopy, stripe domain structure, epitaxial yttrium-iron garnet films, ion implantation.

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1. Introduction

Epitaxial ferrite-garnet films are related to a wide range of magnetic media that have been intensively studied and developed for a various applications in devices of information recording and processing as well as applied magnetooptics in recent 70–80 years [1, 2].

Currently, they are used as active medium for devices of microwave technology, as elements of solid state lasers, magneto-optical devices, sensor devices for imaging and measurement of magnetic fields, and also can be used as materials for nonvolatile magnetic memory systems [3]. Recently, emerging development aimed at using ferrite-garnet films in devices of new generation of spin nanoelectronics at high frequencies [4, 5].

However, the development and production of devices for the above-mentioned applications are not possible without comprehensive study of the physical properties of the ferrite-garnet films (FGF) structures and improvement of technological processes that allow precise management of their properties [6-8]. Many works are devoted to the study of structural, magneto-optical, temperature and other properties of FGF. However, the study of local magnetic properties lacks especial attention. This is primarily caused by a weak methodological base for such researches. Methods of scanning probe microscopy (SPM) [9] and, in particular, scanning magnetic force microscopy (MFM) [10] are able to fill this gap.

The surface tensions and presence of defects that arise during epitaxial deposition cause a significant influence on magnetic microstructure of FGFs. A characteristic feature of crystal growth by liquid-phase epitaxy (LPE) is the competitive entry of various types of cations (ions of main garnet-making components, atoms of solvent, material of crucible) in certain crystallographic positions. The result of this process is appearance of point defects (structural and antistructural) and extended defects (complexes, deployments, clusters). As a result, layered crystal structure is formed, and spatial heterogeneity of magnetic material parameters is observed.

One of the most effective methods of the influence on surface layers of crystals and ferrite-garnet films is ion implantation. It allows to create in crystal structure local areas with desirable physical properties, which causes practical interest for magneto-microelectronics and integrated magneto-optics. The feature of ion implantation by light ions is the opportunity to obtain various degrees of deformation of surface layers with little destruction of the matrix structure. The main aim of FGF ion implantation is to obtain given distribution of magnetic microstructure of the surface layers. Modification of the crystal structure of garnet, which is in implanted bulk, allows to set the micro- and macromagnetic parameters in the surface layer [11]. Therefore, the study of processes that occur in the surface layers of single crystal material after ion implantation is essential for purposeful changing their properties.

The influence of boron ions implanted with the energies within the range 60…150 keV and doses up to $10^{14}\ cm^{-2}$ at the surface topography and domain microstructure of FGF and influence of permanent magnetic field of small magnitude were studied in this paper.

Currently, one of the most promising methods of magnetic structural analysis of magnetic medium is scanning force microscopy in the MFM mode. Getting high-quality MFM images depends on the selected parameters of measurements. Therefore, to provide correct observation of the domain structure on the surface of FGFs, it is necessary to optimize the MFM method for studying these objects. The aim of our study was to investigate distribution of magnetic domains on the surface of FGF depending on the film thickness, behavior of domains in an external magnetic field, and the influence of ion implantation on domain structure.

2. Methodology

Now, there are different implementations of MFM, the main of them are static and dynamic techniques. The static method (Fig. 1) is the movement of probe above the sample at a fixed distance. The value of the cantilever bending is written as MFM image that represents distribution of strength of the magnetic interaction between the probe and the sample.

However, this method is insensitive (it is difficult to detect small changes of attraction-repulsion). Then, for the magnetic field detection, application of resonance phenomenon was proposed. The probe oscillates at a frequency of its own mechanical resonance, owing to the influence of a magnetic field the resonance frequency is changed, and thus one can detect magnetic field gradients.

The dynamic method (as compared to the static one) achieves higher sensitivity and provides better MFM images of samples. The presence of a gradient of magnetic interaction between the probe and the sample leads to changes in its frequency fluctuations, and, consequently, to the shift of amplitude-frequency and phase-frequency characteristics of the sample-probe system. Changes in the resonance properties of the system are used for obtaining information about inhomogeneous distribution of magnetization of the sample surface.

The resonance method of obtaining MFM images is based on the fact that the effective coefficient of own stiffness of the elastic oscillating system (cantilever) is changed by interaction between the magnetic field of the probe and dispersion field of the sample, which is created by its domain structure, and is equal to

$$c = c_0 - \partial F_z / \partial z ,$$

where c_0 is the effective coefficient of own stiffness inherent to the elastic oscillation system, z – coordinate measured from the scanned surface, F_z – z-component of interaction force (usually it is dominant), which is

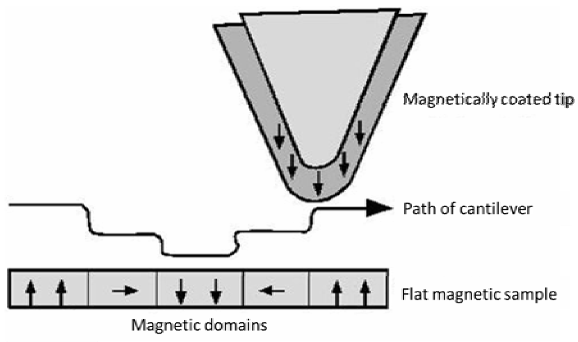

Fig. 1. Contrast formation of MFM image.

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$$F_z = \int_V \left(M_x \frac{\partial H_x}{\partial z} + M_y \frac{\partial H_y}{\partial z} + M_z \frac{\partial H_z}{\partial z} \right) dV',$$

where M_i is the probe magnetization components, H_i – scattered magnetic field components of the domain structure, V – integrated volume of the probe magnetic layer.

The accurate quantitative calculation of the interaction force F_z, depending on the geometry of the probe and the type of magnetic coating, is a difficult task even for the static mode of scanning. However, to visualize distribution of magnetization of the domain structure, it is sufficient to take into account the fact that attraction ($\partial F_z/\partial z > 0$) makes the system more flexible, while repulsion ($\partial F_z/\partial z < 0$) – more rigid. Accordingly, the console oscillation frequency is dependent on $\partial F_z/\partial z$:

$$\omega = \omega_0 \sqrt{1 - \frac{1}{c_0} \frac{\partial F_z}{\partial z}},$$

where ω_0 is the proper resonant frequency of the elastic system.

To exclude the influence of relief on the MFM result, we used the two-pass technique of measurements (Fig. 2).

At the first pass, the probe records the relief profile, then returns to the starting point of this scan line and lifts at a given height (for avoiding the van der Waals forces) and doing a second pass, which repeats the surface profile that was registered before. During the second pass magnetic field gradient measured using the shift of resonance frequency of mechanically oscillated magnetized tip appeared due to interaction with a magnetic field of a sample.

The probe has to be chosen correctly to prevent influence of magnetic field inherent to the probe on the surface magnetic structure and, conversely, influence of magnetic field of the sample on the magnetic field of the probe. Among the tested probes, the best results were obtained with the hard magnetic probes with coercivity of approximately 30 mT and effective magnetic moment of 0.010…0.013 A·m^2 (the NANOSENSORS™ PPP-MFMR probe).

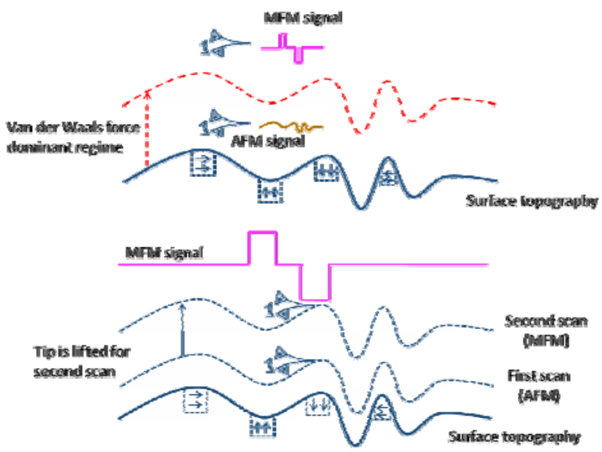

Fig. 2. Scheme of two-pass measurement technique.

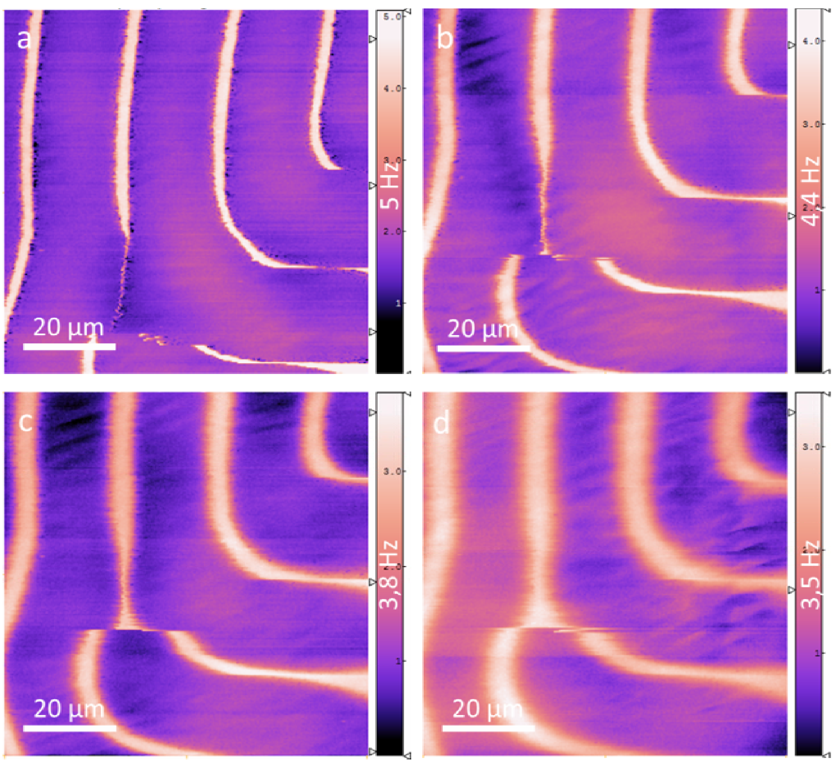

Fig. 3. MFM images of the same area of FGF $(YSmLuCa)_3(FeGe)_5O_{12}$ that were scanned with different lift heights: H = 400 nm (*a*), 800 (*b*), 1200 (*c*), 1600 (*d*).

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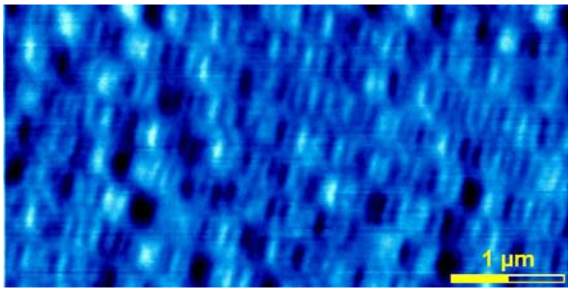

Fig. 4. The magnetic domains on a surface of the 120 GB computer hard disk drive.

In addition, it was necessary to choose the most favorable height of the probe above the surface, which determines the magnitude of magnetic interaction between the probe and surface as well as resolution of the obtained MFM image.

Selection of the optimum probe height above the surface was carried out experimentally. MFM images of the surface of $(YSmLuCa)_3(FeGe)_5O_{12}$ film with the thickness 3.3 µm for the four values of the probe height above the surface were obtained. If the height is too low, then there are the "rupture" magnetic domains (Fig. 3). This phenomenon is the result of the probe influence on the surface – if the surface is the soft magnetic material and probe is the hard magnetic material, one deals with a strong influence on the domain structure. Similar results are presented in [12].

It can be seen that, with increasing the height, phenomenon of "rupture" of magnetic domains disappears, but resolution becomes worse.

It was also studied the influence of the probe oscillation amplitude on the MFM image quality. We found experimentally that, in this configuration of measurements, the value of the probe oscillation amplitude slightly affects on the image, as compared to the probe height above surface, and the difference is insensible. However, too big value of the probe amplitude leads to appearance of noise in the magnetic contrast due to the influence of topographic heterogeneities of relief. On the other hand, too small value of this quantity leads to the loss of sensitivity of MFM registration system.

The resolution of our MFM was tested using the pattern of conventional hard drive. Fig. 4 shows the MFM image of the 120-Gb hard disk surface. The domain width is 50 nm, and the resolution (the smallest distance between two objects that can be discern) is less than 10 nm. Since the width of the studied domains of FGF is about 1 µm, this value of resolution is quite sufficient.

3. Experimental

Series of non-implanted FGF ($Y_3Fe_5O_{12}$) films with different thicknesses was investigated. The stripe domain structure with different periods of domains was observed for all the samples. Fig. 5 shows the MFM-images of studied films.

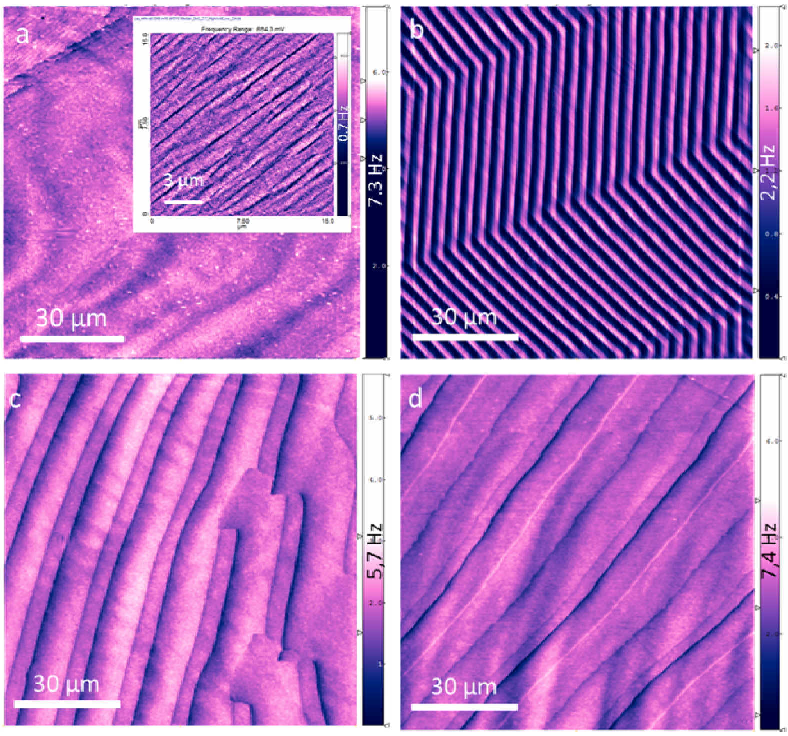

Fig. 5. MFM map illustrating distribution of the gradient of scattered field of magnetic domains in surface layers of epitaxial FGF ($Y_3Fe_5O_{12}$) with the various thicknesses: a) 0.49, b) 2.9, c) 10.3, and d) 24 µm. The vertical scale characterizes the amplitude changes of field gradient.

In samples, stripe domain structure with different periods of domains is observed due to the presence of the normal to the film plane component of the magnetization. It is seen from the images how the period of domain structure is changed, depending on the film thickness: with increasing the thickness the period increases (from 1 μm for 0.49 μm film up to 3 μm for the thickness 2.9 μm), but the value of domain periods saturates (13 μm) at the thicknesses greater than 10.3 μm. The magnetization vector of FGF is oriented closely to the axes of easy magnetization of bulk FGF (with 19° angle to the film plane) and depends on contribution of different types of magnetic anisotropy and magnetostriction contribution caused by mechanical stress related with growth. Except the difference between the lattice constant of the film and the substrate, the film thickness also influences. The ratio between the perpendicular to the film surface component of the magnetic anisotropy and saturation magnetization determines the possible micromagnetic structure of the thin film [13].

Fig. 6 shows the images of distribution of magnetic domains on the surface of the FGF films with thicknesses of 2.9 μm (*a*–*c* – the top row) and 5.11 μm (*d*–*f* – bottom row) before applying the magnetic field (*a*, *d*), under applied field (*b*, *e*) and after applying (*c*, *f*). The constant magnetic field was created by two neodymium magnets. The magnitude of the field was 4 mT. Application of the magnetic field allows to explore redistribution of magnetization and behavior of domain walls.

For thinner film, the expansion and small rotation of the domain angle during application of the magnetic field is observed. The stripe domains pattern could be reconfigured (series of 120° rotations, Fig. 6c) upon termination of magnetic field influence. The influence of field on the thicker film is weaker, expansion of domains is not observed, but there is alignment of domain structure (Fig. 6, *d*–*f*). Based on the fact that the ratio of the areas occupied by the light and dark stripes is almost the same, one can say that rejection of the magnetization vector in the direction normal to the film in domains is approximately the same in both directions. Application of the magnetic field leads to changing the ratio of the volume of domains with different orientation, changing the orientation of local magnetic moments of domains and displacement of domain walls.

Domain walls (Bloch walls in our case) undergo a slow change in the direction of the magnetization vector between two domains. Shift of domain walls under the influence of a magnetic field is the change of orientation of the local magnetic moments inherent to domains separated by the wall.

When the magnetic field is applied, rotation of the magnetization in the Bloch wall with the same probability can occur on both sides. For various reasons, it is possible to observe availability of areas with opposite directions of magnetization rotation in one wall. The transition region at the junction of sections with different directions of magnetization rotation is called the Bloch line.

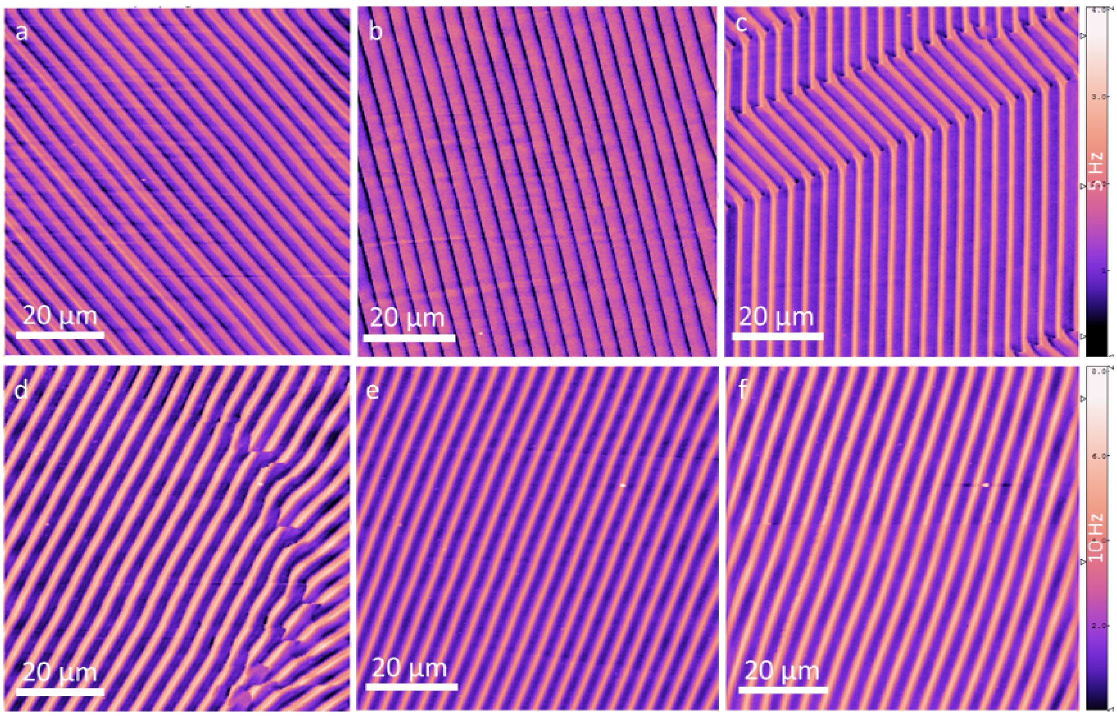

Fig. 6. MFM images of the same area on the 2.9 μm and 5.11 μm FGF scanned before (*a*, *d*), during (*b*, *e*) and after (*c*, *f*) application of external magnetic field close to 4 mT. The field was applied along horizontal direction.

Alignment or bending of domain structure caused by the presence in domain walls the Bloch vertical lines that during the movement of domain walls make movement more slow for the domain wall sections where they are. There are also Bloch points, which are characterized by the fact that, on the sphere with infinitely small radius centered at the Bloch point, all possible orientations of magnetization exist. An example of Bloch point is the magnetic configuration in the vertical Bloch line at the intersection of two areas that have opposite directions of magnetization rotation around *z*-axis. The Bloch lines and points determine the observed changes in the domain structure FGF under the influence of a magnetic field [14].

The influence of ion implantation of FGF on surface topography and domain structure was also studied.

The surface relief may be different, depending on the dose and method of implantation. Fig. 7 shows non-implanted and implanted by boron ions B^+ $(YSmCaBi)_3(FeSi)_5O_{12}$ films with the thickness 1.25 µm. As we can see, the non-implanted FGFs are quite smooth, and implantation of boron ions in these modes smoothes irregularities on the surface, which decreases height differences of the surface by about 30%. As noted above, the FGF domain structure is very sensitive to weak magnetic fields and can significantly change by the influence of probe, especially for thin films with low magnetization. From MFM images (Fig. 7), it can be concluded that the implantation leads to a reduction of opportunities of reorientation of domains under the probe influence and to deceleration of mobility of domain walls in the surface layer, as evidenced by the increase in areas of ordered stripe domain structure

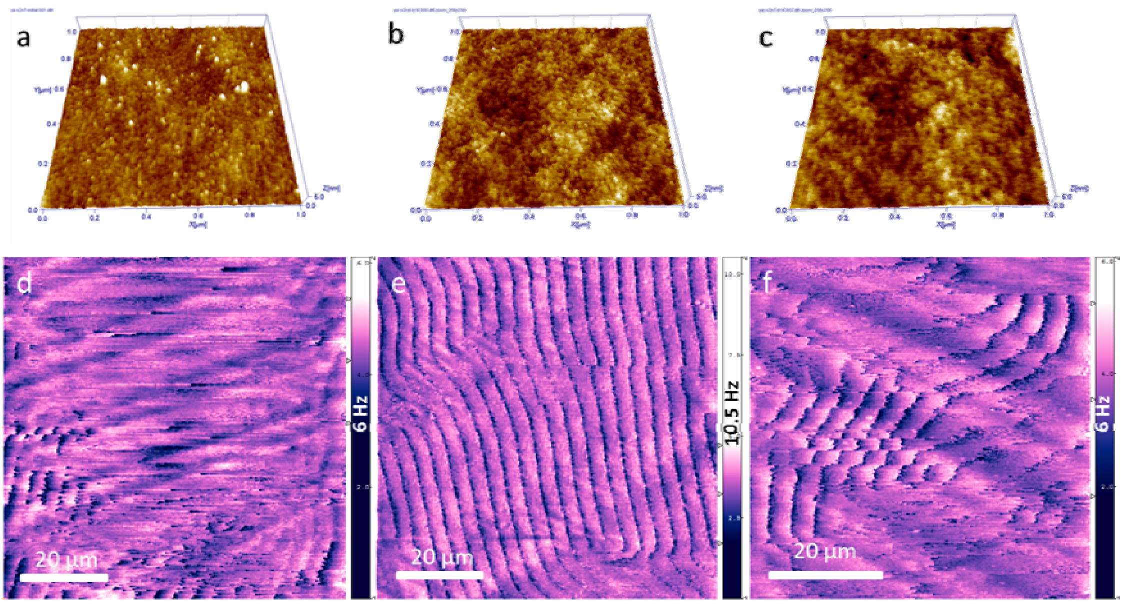

Fig. 7. 3D AFM topography (*a*, *b*, *c*, RMS: 0.28, 0.21, and 0.20 nm, respectively) and MFM (beneath) images of $(YSmCaBi)_3(FeSi)_5O_{12}$ films: non-implanted (*a*, *d*) and implanted by boron ions B^+ $E = 60$ keV, $D = 10^{14}$ cm^{-2} + B^+ $E = 150$ keV, $D = 0.7\cdot10^{14}$ cm^{-2} (*b*, *e*), B^+ $E = 80$ keV, $D = 10^{14}$ cm^{-2} (*c*, *f*).

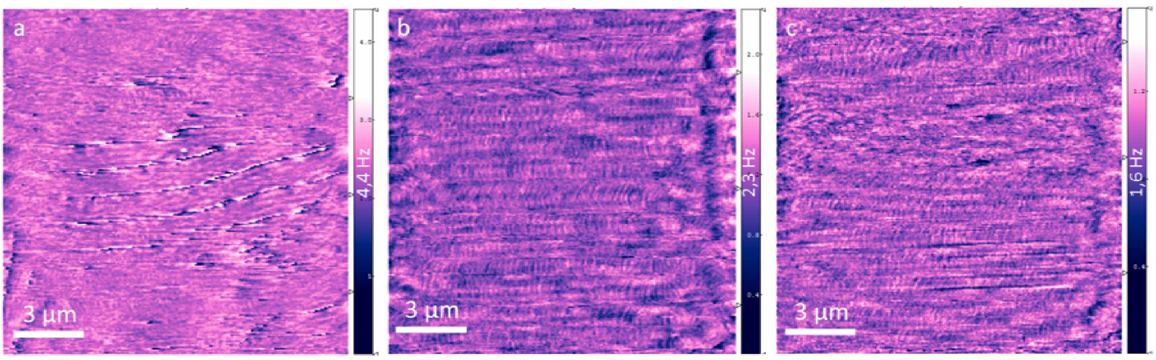

Fig. 8. MFM-images of surfaces of non-implanted (*a*) and implanted (*b*, *c*) FGF films. a) non-implanted, b) B^+ $E = 60$ keV, $D = 10^{14}$ cm^{-2} + B^+ $E = 150$ keV, $D = 0.7\cdot10^{14}$ cm^{-2}, c) B^+ $E = 150$ keV, $D = 10^{14}$ cm^{-2} + B^+ $E = 60$ keV, $D = 0.7\cdot10^{14}$ cm^{-2}.

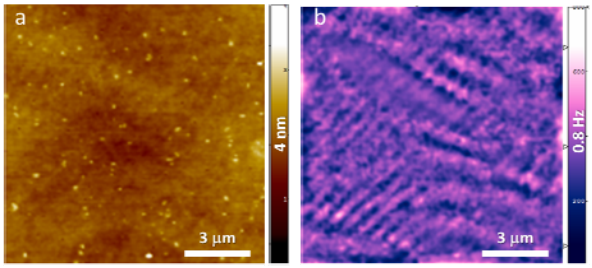

Fig. 9. AFM (*a*) and MFM (*b*) images of LaGa:YIG film.

during ion implantation (especially for double-implanted sample, the total dose of implantation, which is almost 2 times higher than that for one time implanted sample). The method of Mossbauer spectroscopy revealed that for studied films the angles of orientation of the magnetization of different sublattices and the normal to the film plane are close and are about 32°. The period of the domain structure of the non-implanted sample is equal to 3.86 µm, and in the ion-implanted films in all modes periods are in the range 3.95…4.04 µm, which is the result of mechanical stress following implantation and tilt of the magnetization vector of domains to the plane of the film.

There are no significant changes of magnetic structure in the implanted $(YSmCaBi)_3(FeSi)_5O_{12}$ films (thickness 0.54 µm) depending on the method of implantation (Fig. 8). Although the magnetic stripe structure of non-implanted film is recorded worse. It should be noted that as in the FGF thickness of 0.49 µm, the size of domains in this film is much less than in other studied films with a greater thickness. Thus, these studies are consistent with the known conclusion about proportionality of domain sizes and film thicknesses.

For the main types of MFM images from FGF with different orientation of the magnetization vector studied also were films where the magnetization lies in the plane of film surface. According to Mossbauer studies, these films are the LaGa:yttrium iron garnet (YIG) films with the appropriate degree of substitution (Figs. 9a, 9b). MFM images show thin lines with the period 1.66 µm, which obviously are the stripe domains formed by oscillation of the magnetization vector relatively to the plane of the film. Significant changes of the domain structure after ion implantation were not found.

It can be concluded that ion implantation improves domain structure. As shown by independent studies [15, 16], it is associated with the processes of structural ordering the material of the film owing to the influence of implantation.

4. Conclusions

The optimal MFM parameters for investigation of FGF films have been ascertained. It has been shown that for all the samples stripe domain structure is observed, with different configurations and domain period, depending on the technical parameters of films deposition. Magnetic contrast is reliably recorded when the magnetization vector of the film is oriented at an angle to the plane of the surface. It is difficult to detect the domain structure when the magnetization vector lies in the plane of film surface.

For a film series with different thicknesses, the authors have found that, with increasing the thickness of the epitaxial FGF, the period of domain structure on the film surface increases, but saturates after exceeding the value of the thickness of 10.3 µm.

Application of an external magnetic field affects on the magnetic structure of FGF films. Domains react differently to the external magnetic field depending on the thickness of the film: expansion of domains is observed for thinner film, for thicker film the domain thickness remains unchanged. Structural defects cause formation of Bloch lines and points, which leads to a bending or realignment of domain walls.

The surface topography of the initial and implanted FGF films has been studied. It has been revealed that, for certain conditions of implantation, the roughness of surface decreases, and ion implantation leads to slight ordering of magnetic structure of FGF films.

These results are important for understanding physics of the processes occurring in thin films of FGF.

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