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Modification of Bi:YIG film properties by substrate surface ion pre-treatment

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ABSTRACT

The effect of a controlled ion beam pre-treatment of (111)-oriented $Gd_3Ga_5O_{12}$ substrates on the magneto-optical properties and surface morphology of the ultrathin bismuth-substituted yttrium–iron garnet films with a composition $Bi_{2.8}Y_{0.2}Fe_5O_{12}$ was studied. It has been shown that the observed sign inversion of magneto-optical effects (Faraday rotation and magnetic circular dichroism) observed in films that were deposited on the GGG substrate pre-treated by 1 keV and 4 keV Ar^+ ion beams is a result of the substrate surface amorphization caused by the ion bombardment.

1. Introduction

Bismuth-substituted yttrium–iron garnet (Bi:YIG) films are often used as basic elements of one-dimensional magneto-photonic crystals (1D-MPC) as they exhibit high transmittance and large specific Faraday rotation (FR) in the visible and near-infrared optical spectrum regions [1–4]. Depending on the 1D-MPC optical spectrum operating range, the thicknesses of these films can vary from a few tens to several hundred nanometers. The structural quality of the magneto-active layer and in particular, characteristics of film-substrate transitional interface can significantly affect the 1D-MPC parameters such as the FR magnitude and transmittance. So the investigation of the optical and magneto-optical (MO) properties of ultra-thin Bi:YIG films, as a function of the substrate surface condition, are of great interest. The understanding of the kinetics of the film growth processes will further aid to the development of the new generation of MO devices.

Ferrites with garnet structures are ferrimagnetics with three magnetic sublattices: octahedral (*a*), tetrahedral (*d*) and dodecahedral (*c*) sublattices [5]. The magnetizations of *a* and *c* sublattices have the same direction and are opposite to magnetizations of *d* sublattice. The direction of the integral magnetization vector in pure bismuth ferrite garnet is determined by *d* sublattice. However, partial substitution of magnetic ions may lead to decrease of *d* sublattice magnetization, and the integral magnetization direction of such a garnet can be determined by *c* and *a* sublattices. The situation when the magnetizations of the sublattices compensate each other and the integral magnetization turns into zero is called a magnetic compensation point. For some garnets compositions, due to the different temperature dependences of the sublattices magnetization, the compensation point can be reached varying the temperature. The transition through the compensation point is accompanied by the FR sign change.

It should be noted that there is a lack of information in the literature about the relation between properties of ultrathin Bi:YIG films and the state of the substrate surface. The formation of a transitional non-magnetic layer on the film-substrate interface of the $Bi_2Dy_1Fe_4Ga_1O_{12}$ films deposited by rf-magnetron sputtering at room temperature was reported in [6]. Unfortunately, no information about the substrate surface pre-treatment was

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presented in this paper. An impeded epitaxial growth of $(GdBi)_3(Fe,Al,Ga)_5O_{12}$ garnet films sputtered and in situ crystallized on the (111)-oriented $(GdCa)_3(Ga,Mg,Zr)_5O_{12}$ and $Sm_3(Ga,Mg,Zr)_5O_{12}$ garnet substrates bombarded by low-energy (100 eV) Ar^+ ions before the films deposition was discussed in [7]. Reflection high-energy electron diffraction data analysis showed that impeded growth is related to the bombardment-induced bond angles disorder on the substrate surfaces, mainly produced by the re-sputtering of oxygen. The reported thickness of the damaged layer was of about 0.5 nm. The formation of structurally damaged 12 nm thick layer on the surface of epitaxial YIG films after the bombardment by 0.5–2 keV oxygen ions was also demonstrated in [8].

In this paper, we study the effects of controlled ion beam pre-treatment and pre-annealing of the gadolinium gallium garnet $Gd_3Ga_5O_{12}$ (GGG) substrates on the MO properties (Faraday rotation and magnetic circular dichroism) of ultrathin Bi:YIG films.

2. Experimental

$Bi_{2.8}Y_{0.2}Fe_5O_{12}$ target was sintered using the conventional ceramics sintering technique. Bi:YIG films were deposited by reactive ion-beam sputtering technique on cold (111) GGG substrates in argon–oxygen mixture as described earlier [9–11]. The as-prepared films were amorphous. Film crystallization was performed in the air at normal atmospheric pressure at the temperature $T_{crys} = 650\,^{\circ}C$ during $t = 20$ min. The heating rate of the films at pre-crystallization annealing was $\sim 40\,^{\circ}C$/min. The films thickness, h, ranged from 2.9 nm to 180 nm. The thickness was calculated based on the sputtering rate (5.8 nm per minute) and the deposition times.

To determine the effect of substrate pre-treatment on the properties of synthesized Bi:YIG films, the substrates were processed before the film deposition by argon and oxygen ions with varying energy and current. The duration of ion pre-treatment was 5 min. Some of the GGG substrates were also pre-annealed in air at the atmospheric pressure. According to the substrates pre-treatment regimes, the films were divided into four types (see Table 1).

The specific Faraday rotation θ_F, the coercivity H_c, Curie T_C and compensation temperatures T_{comp} were determined from the Faraday rotation hysteresis loops (FRHLs) using the Faraday magneto-polarimeter operating at $\lambda = 655$ nm in 20–150 °C temperature range. The magnetic field was applied along the light beam direction and perpendicular to the film plane. Magnetic circular dichroism (MCD) spectral measurements were performed using a Jobin-Yvon dichrograph at $H = 5.5$ kOe in 270–850 nm wavelength range with the step 1 nm. The MCD signal was calculated as

$$\left[\frac{(I_+ - I_-)}{(I_+ - I_-)}\right]/h$$

where I_+ and I_- are the intensities of right- and left-hand circularly polarized light waves.

Table 1
The regimes of the substrate pre-treatment.

Film types	Gas	Ion energy	Ion current density ($mA\,cm^{-2}$)	Substrate pre-annealing
A	Argon	Low-energy plasma	1.0	–
B	Argon	Ion beam, 1.0 keV	2.5	–
C	Argon	Ion beam, 4.0 keV	5.0	–
D	Oxygen	Low-energy plasma	1.0	One hour at 800 °C (in air)

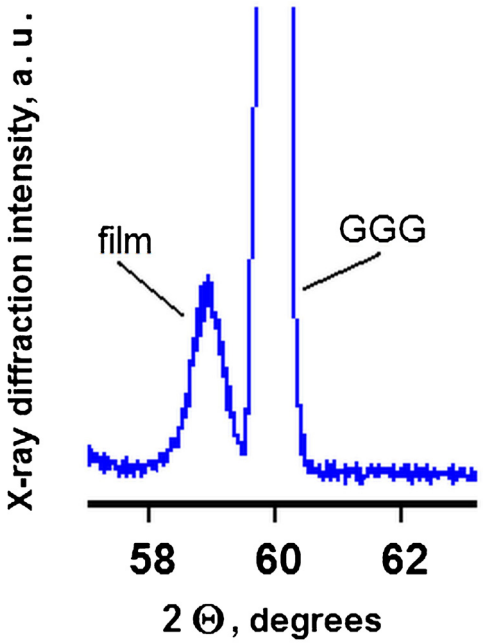

Fig. 1. XRD profile for 100 nm thick Bi:YIG A-type film. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The structure of the samples was controlled by X-ray diffractometer. Solver PRO atomic force microscope (AFM) was used for the substrates and films surface visualization.

According to the electron probe microanalysis data, the composition of the thick Bi:YIG films was close to the target composition. This confirms the nearly equivalent composition transfer during the deposition. It also correlates with X-ray diffraction data showing a formation of the garnet epitaxial phase with a lattice parameter $a = 1.2602$ (see Fig. 1). The evaluation of Bi contents based on the Vegard's law [12] yields $X_{Bi} = 2.8$ atoms per formula unit (at./f.u.). The determined lattice mismatch between lattice parameters of the film and the substrate is $\Delta a = a_{film} - a_{sub} = 0.0208$ nm, $a_{sub} = 1.2383$ nm. The epitaxial growth of of Bi:YIG films has also been confirmed by our previous ferromagnetic resonance measurements [10].

3. Results and discussion

The dependences of the specific Faraday rotation θ_F on the films thicknesses, h, for three types of Bi:YIG films are shown in Fig. 2. The corresponding FRHLs are schematically shown in the insets. At

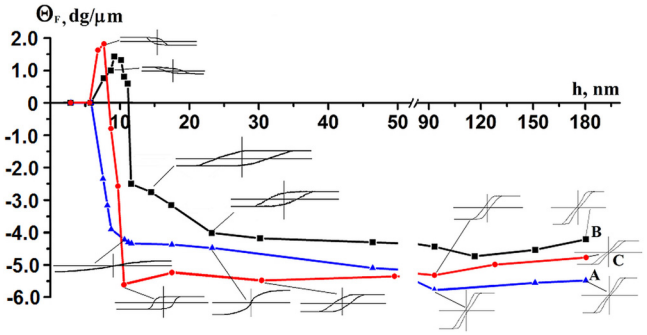

Fig. 2. θ_F (h) dependencies and Faraday hysteresis loops for the A-, B- and C-type films. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)