Magnetic and magneto-optical properties of RIB-sputtered ultra-thin Bi-substituted iron-garnet films for MPC applications

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Abstract

Magnetic properties, Faraday rotation (FR) and magnetic circular dichroism (MCD) effect of reactive ion beam sputtered (RIBS) ultra-thin $Bi_{2.8}Y_{0.2}Fe_5O_{12}$ films on $Gd_3Ga_5O_{12}$ substrate for magnetic photonic crystal (MPC) applications were investigated. It was found the fine structure of substrate - film transitional layer including 5 nm nonmagnetic at room temperature sublayer, 3.5 nm magnetic sublayer of sharp changing composition $(BiGdY)_3(FeGa)_5O_{12}$ with negative sign of MCD, and 2.5 nm magnetic sublayer with positive sign of MCD where the composition changed from $(BiGdY)_3Fe_{3.75}Ga_{1.35}O_{12}$ to $Bi_{2.8}Y_{0.2}Fe_5O_{12}$ main part of film with nominal composition $Bi_{2.8}Y_{0.2}Fe_5O_{12}$.

1. Introduction

Magnetic photonic crystals (MPC) are expected to be important generation of new metamaterials intended to create high efficient magneto-optical devices like nonreciprocal element (optical isolator), optical circulators, modulators, switches, and phase shifter. There were many attempts to improve seriously optical and magneto-optical properties of such devices using MPC structure instead single layer film [1]. Unfortunately until now we are far away from expected practical applications.
There are two main problem in MPC applications related with extremely high optical absorption level of sputtered and pulsed laser deposited Bi-substituted iron-garnet films comparing with liquid phase epitaxial films in visible and near infrared spectral region, the second one is related with existence of fine structure of sputtered film including substrate – film transitional layer and film – upper layer transitional layer. We have shown that existence of such layers deteriorate optical and MO characteristics of MPC structures especially when we use thin (λ/4n) MO layer to prepare the MPC structure. The typical thickness of (λ/4n) Bi-substituted iron-garnet layer of MPC structure is near 60 nm in visible spectral region.

2. Experimental results

In order to clarify this problem we investigate the batch of ultra thin films of nominal composition $Bi_{2.8}Y_{0.2}Fe_5O_{12}$ prepared by reactive ion beam sputtering on $Gd_3Ga_5O_{12}$ (111) substrate. The thicknesses of the films calculated based on the sputtering velocity 5.6 nm per minute were changed from 2.8 to 16.8 nm. The sputtering was provided on substrate at room temperature in argon-oxygen mixture resulting in amorphous films. In order to crystallize film the additional crystallization annealing was used at temperature $T = 650\ ^{o}C$ during 20 minutes [2, 3].

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We investigated magnetic circular dichroism (MCD) effect in spectral region 850 – 270 nm and Faraday rotation (FR) spectra in spectral region 820 – 390 nm. The Jobin-Yvon dichrograph model Mark IV was used to measure MCD spectra. The typical MCD spectra for two samples of thickness 8.4 and 11.2 nm are shown in Fig. 1. The MCD signal is measured as $\Delta D/D = \log [(I_+ - I\_)/(I_+ + I\_)]$, where I_+ and I_- the intensities of right and left circular polarized light.

The type I dispersion of specific MCD (-■-) with negative sign of MCD signal at peak wavelength 451 nm are typical for samples of thickness 5.6 and 8.4 nm and we can conclude that these samples possessed compensation point above room temperature. It means that octahedral sublattice magnetization exceeds the tetrahedral sublattice magnetization. The explanation of such result may be the next. The Ga^{3+} and Gd^{3+} ions penetrate from $Gd_3Ga_5O_{12}$ substrate into the film up to thickness near 10 nm resulting in change the composition between $Gd_3Ga_5O_{12}$ at the physical frontier between substrate and film to $Bi_{2.8}Y_{0.2}Fe_5O_{12}$ near 10 nm. The Curie temperature (T_c) measurement for sample of nominal thickness 8.4 nm have shown to be $T_c = 150\ ^oC$ for upper sublayer. The composition of this sublayer must be near $Bi_{2.8}Y_{0.2}Fe_{3.7}Ga_{1.3}O_{12}$.

The type II dispersion of specific MCD (-♦-) with positive sign of MCD signal at peak wavelength 468 nm are typical for samples of thickness 11.2 nm and all thicker samples. The term specific MCD signal means the full value of MCD signal divided on the thickness of the film. The full thickness of the samples was used to calculate the specific MCD signal without correction on the value of nonmagnetic at room temperature layer.

The results of MCD measurements demonstrate spectral position red shift of the main magneto-optical transitions related with introduction of Bi^{3+} ions in iron-garnet structure as we can see in Fig. 1. For example, the first MCD peak positioned at wavelength 451 nm for samples of thickness 5.6 and 8.4 nm. For thicker samples of thickness 11.2, 14, and 16.8 nm the position of the peak shifted to 468 nm. We suppose that red shift of positions the main magneto-optical transitions in Bi-substituted iron-garnet is determined mainly by growth the lattice parameter with increase the bismuth content. In iron-garnet film of composition $Bi_{0.45}Tm_{2.55}Fe_{3.8}Ga_{1.2}O_{12}$ with lattice parameter 1.2385 nm grown by liquid phase epitaxial process on $Gd_3Ga_5O_{12}$ (111) substrate the first prominent MCD peak is positioned near 440 nm [4].

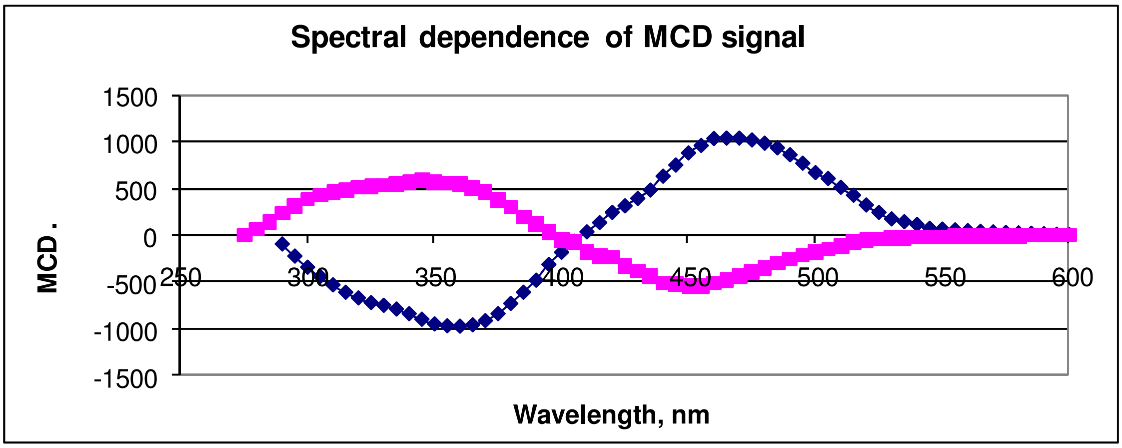

Fig. 1 Spectral MCD dependences of 8.4 nm (-■-) and 11.2 nm (-♦-) samples.

The dependence of integrated MCD signal on the thickness of the sample is shown in Fig. 2. As we can see near 8 nm there is a negative peak of MCD signal. The observed dependence can be explained as appearance of sublayer with positive sing of MCD signal on the upper side of the film. It means that near 8 nm the compensation plane must exist where the magnetic moments of tetrahedral and octahedral sublattices are equal by modulo but had opposite signs and composition at this point is near $Bi_{2.8}Y_{0.2}Fe_{3.7}Ga_{1.3}O_{12}$. The linear growth of integrated MCD signal for samples of thickness 11.2, 14, and 16.8 nm means that composition of the films stayed unchanged and is near $Bi_{2.8}Y_{0.2}Fe_5O_{12}$.

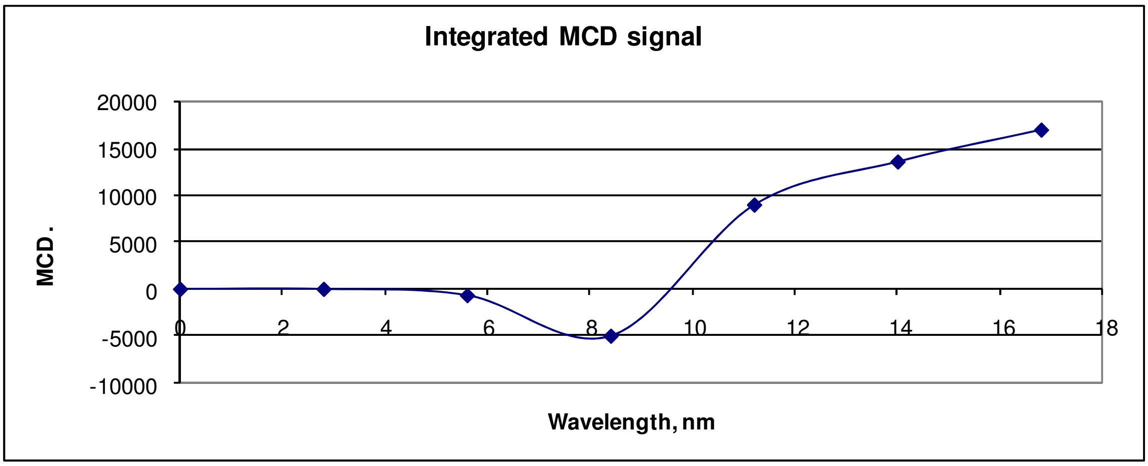

Fig. 2 Thickness dependence of integrated MCD signal of ultra thin Bi-substituted iron-garnet films.

3. Conclusion

Based on MCD measurements in visible and ultraviolet spectral regions we could be able to investigate the fine structure of transitional layer existing between $Gd_3Ga_5O_{12}$ (111) substrate and RIBS-sputtered iron-garnet film of nominal composition $Bi_{2.8}Y_{0.2}Fe_5O_{12}$. It was found that transitional layer consists of near 5 nm nonmagnetic at room temperature sublayer, 3.5 nm magnetic sublayer with negative sign of MCD where we expect sharp composition change from $(BiGdY)_3(FeGa)_5O_{12}$ with Curie temperature slightly above room temperature to composition possessed compensation point at room temperature, and 2.5 nm magnetic sublayer with positive sign of MCD where the composition changed from $(BiGdY)_3Fe_{3.75}Ga_{1.35}O_{12}$ to $Bi_{2.8}Y_{0.2}Fe_5O_{12}$ followed by main part of film with nominal composition $Bi_{2.8}Y_{0.2}Fe_5O_{12}$.

The compensation plane where the magnetic moments of tetrahedral and octahedral sublattices are equal by modulo but had opposite signs is expected to be near 8 nm from substrate. The composition of the film at this point may be near $Bi_{2.8}Y_{0.2}Fe_{3.7}Ga_{1.3}O_{12}$.

The observed fine structure of substrate-film transitional layer is very important if we consider the practical applications of ultra thin Bi-substituted iron-garnet layer for photonics applications such as magnetic photonic crystals. It was shown that real increase the value of Faraday rotation by MPC structure appeared essentially smaller that calculated one. The nonmagnetic and opposite sign Faraday rotation layers may be the main source of discrepancy observed.

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