Preparation of $\text{Bi}_2\text{Gd}_1\text{Fe}_5\text{O}_{12}$ magnetic garnet films showing Faraday rotation of 36.3 deg./ μm on glass substrates by metal organic decomposition method

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Abstract: We fabricated the $\text{Bi}_2\text{Gd}_1\text{Fe}_5\text{O}_{12}$ thin films on glass substrates with the $\text{Gd}_3\text{Fe}_5\text{O}_{12}$ buffer layer by the metal organic decomposition (MOD) method. We found an optimum thickness of the $\text{Gd}_3\text{Fe}_5\text{O}_{12}$ buffer layer and annealing temperature for crystallization giving the maximum Faraday rotation. The optimum sample showed Faraday rotation of as high as 36.3 deg./ μm at the wavelength $\lambda = 500$ nm, which is 23 times larger than the sample without the $\text{Gd}_3\text{Fe}_5\text{O}_{12}$ buffer layer, and as high as 90.1% of the single crystalline $\text{Bi}_2\text{Gd}_1\text{Fe}_5\text{O}_{12}$ thin films on an (111) SGGG single crystal substrate. These results are promising for applications in optical waveguide isolators and magneto-optic spatial light modulators.

Keywords: Faraday rotation, magnetic garnet, metal organic decomposition, crystallization process, photonic integrated circuits

Classification: Integrated optoelectronics

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1 Introduction

Bi-substituted rare-earth iron garnets (Bi:RIG) have large Faraday rotation (FR) with high transparency in the visible to near infrared region [1], which made them suitable for various applications. It was reported that with increasing the amount of Bi substitution for rare-earth element, FR of Bi:RIG becomes large [2]. Bi:RIG have been used for magneto-optical device elements in such as magnetoplasmonic structure [3, 4], optical isolators [5], circulators [6], and magnet photonic crystals (MPCs) used in magneto-optic spatial light modulators (MOSLMs) [7]. Among them, bismuth substituted gadolinium iron garnet (Bi:GdIG) is one of the ferromagnetic rare-earth iron garnets showing perpendicular magnetic anisotropy [8, 9]. There are several methods to prepare the Bi:GdIG thin films such as a laser ablation [10], RF magnetron sputtering [11], liquid phase epitaxy [12], etc. Metal organic decomposition (MOD) method is a promising one to prepare magnetic garnet film, because it is a simple fabrication method which is composed of spin coating of the MOD solutions (Bi_2O_3 , Y_2O_3 , Gd_2O_3 , Ga_2O_3 , and Fe_2O_3 carboxylates in acetic ester) and annealing, and guarantees high uniformity in chemical composition and purity combined with chemical stability [13]. So far, $\text{Bi}_x\text{Gd}_{3-x}\text{Fe}_5\text{O}_{12}$, $\text{Bi}_x\text{Y}_{3-x}\text{Fe}_5\text{O}_{12}$ (Bi:YIG) and $\text{Bi}_x\text{Y}_{3-x}\text{Ga}_y\text{Fe}_{5-y}\text{O}_{12}$ thin films have been fabricated on (111) oriented gadolinium gallium garnet (GGG) single crystal substrates [9, 10, 11, 12, 13, 14, 15], and glass substrates [16]. In order to apply Bi:GdIG or Bi:YIG thin films in Si/SiO₂ based waveguide optical isolators [17, 18, 19] and MOSLMs [7], it is required that Bi:GdIG thin films are prepared on glass substrates or SiO₂ thin films. Since the MOD method enables it to prepare Bi:GdIG/Bi:YIG thin films by spin-coating and annealing process, it is possible to prepare these magnetic garnet thin films on the specific area in a substrate with different levels, such as optical waveguides. This is a great advantage of the MOD method over conventional fabrication methods such as laser ablation and magnetron sputtering. However, it is not easy to fabricate Bi:GdIG thin films on glass substrates because of the differences in crystal structure and thermal expansion coefficient between Bi:GdIG/Bi:YIG and glass substrate [17]. It is important to obtain magnetic garnet thin films having large FR and high magneto optical activity. The fabrication of magnetic garnet such as Bi:YIG films was reported by using $\text{Nd}_2\text{Bi}_1\text{Fe}_4\text{Ga}_1\text{O}_{12}$ buffer layers on glass substrates by the MOD method, and FR of 13.8 deg./ μm at $\lambda = 520\text{ nm}$ was reported for the Bi:YIG films [16]. We prepared the $\text{Bi}_x\text{Gd}_{3-x}\text{Fe}_5\text{O}_{12}$ thin films with $x = 1, 2$, and 2.5 on glass substrates by the enhanced metal organic decomposition (EMOD) method [20], where the solutions of the Bi_2O_3 , Gd_2O_3 , and Fe_2O_3 carboxylates were prepared separately and mixed so that the Bi content x was controlled to 1, 2, and 2.5. We obtained FR of 27.5 deg./ μm at the wavelength $\lambda = 533\text{ nm}$ in $\text{Bi}_{2.5}\text{Gd}_{0.5}\text{Fe}_5\text{O}_{12}$ samples with $\text{Gd}_3\text{Fe}_5\text{O}_{12}$ buffer layer. We reported that the $\text{Gd}_3\text{Fe}_5\text{O}_{12}$ buffer layer is useful in order to realize $\text{Bi}_x\text{Gd}_{3-x}\text{Fe}_5\text{O}_{12}$ samples thin films with high Bi substitution $x = 2.5$ and FR comparable with that of a single crystal film on $(\text{GdCa})_3(\text{GaMgZr})_5\text{O}_{12}$ (SGGG) substrates.

However, the fabrication conditions of the $\text{Gd}_3\text{Fe}_5\text{O}_{12}$ buffer layer have not been fully optimized yet. Especially, the thickness of the $\text{Gd}_3\text{Fe}_5\text{O}_{12}$ buffer layer and crystallization temperature are important in order to apply Bi:GdIG and Bi:YIG

thin films to waveguide optical isolators on Si/glass substrates or SiO₂ films. When the buffer layer thickness is small, the crystallization of the Bi:GdIG and Bi:YIG thin films is not enough to show large FR. On the other hand, when the buffer layer is thick, magneto-optical contribution to the optical waveguide, and the transparency becomes small. Therefore, it is necessary to realize Bi:GdIG and Bi:YIG thin films showing large FR by using the buffer layer with minimum thickness. In this paper we report the fabrication of Bi₂Gd₁Fe₅O₁₂ thin films on glass substrates by the MOD method. We optimized the thickness of the Gd₃Fe₅O₁₂ buffer layer and annealing temperature for crystallization in order to maximize the FR of the Bi₂Gd₁Fe₅O₁₂ thin films on glass substrates. We discuss the crystallization process and relationship between the crystalline quality and FR among various preparation conditions for Gd₃Fe₅O₁₂ buffer layer.

2 Fabrications of Bi:GdIG thin films

First, we fabricated the Gd₃Fe₅O₁₂ thin films on 15 mm × 15 mm glass substrates by the MOD method in order to investigate the crystalline quality of the Gd₃Fe₅O₁₂ films as the buffer layer. We prepared the Gd₃Fe₅O₁₂ thin films by changing the spin-coating time in the range of 2, 3, 4, 6, and 8 at fixed final-annealing temperature (T_{FA}) of 650°C. Then we changed the annealing temperature in the range of 620, 650, 700, and 750°C with fixed spin-coating time of 3. Then we fabricated Bi₂Gd₁Fe₅O₁₂ thin film with the Gd₃Fe₅O₁₂ buffer layer. We also fabricated the Bi₂Gd₁Fe₅O₁₂ thin films directly on a glass substrate without buffer layer. The MOD liquids used in this experiment consist of solutions made from Bi₂O₃, Gd₂O₃, and Fe₂O₃ carboxylates in acetic ester with chemical composition ratio of Bi₂O₃:Gd₂O₃:Fe₂O₃ = 2:1:5 for Bi₂Gd₁Fe₅O₁₂ main layer, 0:3:5 for Gd₃Fe₅O₁₂ buffer layer. We fixed the fabrication conditions for the Bi₂Gd₁Fe₅O₁₂ main layer. The fabrication procedure was as follows. Two steps spin-coating process was done with 500 rpm for 10 s and 2000 rpm for 20 s, followed by drying on a hot plate at 120°C for 10 min. so that the solvent are dissolved. In order to decompose the organic materials and obtain the amorphous metal oxide films, the samples were annealed at 550°C for 10 min (pre-annealing). These conditions were fixed for all the samples. The Gd₃Fe₅O₁₂ buffer layers were then annealed at T_{FA} = 620–750°C for 2 hours (final annealing). We fixed the spin-coating time and final annealing conditions for Bi₂Gd₁Fe₅O₁₂ thin films to 6 and 620°C for 2 hours. For comparison, we prepared a Bi₂Gd₁Fe₅O₁₂ single crystal film without the buffer layer on a (111) SGGG substrate at annealing temperature of 620°C for 2 hours. All the samples were fabricated under air at atmospheric pressure. Table I shows the summary of the samples for this study.

Table I. The summary of the fabrication conditions for $\text{Gd}_3\text{Fe}_5\text{O}_{12}$ and $\text{Bi}_2\text{Gd}_1\text{Fe}_5\text{O}_{12}$ layers in this study.

Sample	Main Layer	Spin coating time	$T_{\text{FA}} [^\circ \text{C}]$	Substrate	Buffer layer
B'	$\text{Gd}_3\text{Fe}_5\text{O}_{12}$	2	650	glass	-
C'	$\text{Gd}_3\text{Fe}_5\text{O}_{12}$	3	650	glass	-
D'	$\text{Gd}_3\text{Fe}_5\text{O}_{12}$	4	650	glass	-
E'	$\text{Gd}_3\text{Fe}_5\text{O}_{12}$	6	650	glass	-
F'	$\text{Gd}_3\text{Fe}_5\text{O}_{12}$	8	650	glass	-
A	$\text{Bi}_2\text{Gd}_1\text{Fe}_5\text{O}_{12}$	6	620	glass	-
B	$\text{Bi}_2\text{Gd}_1\text{Fe}_5\text{O}_{12}$	6	620	glass	B'
C	$\text{Bi}_2\text{Gd}_1\text{Fe}_5\text{O}_{12}$	6	620	glass	C'
D	$\text{Bi}_2\text{Gd}_1\text{Fe}_5\text{O}_{12}$	6	620	glass	D'
E	$\text{Bi}_2\text{Gd}_1\text{Fe}_5\text{O}_{12}$	6	620	glass	E'
F	$\text{Bi}_2\text{Gd}_1\text{Fe}_5\text{O}_{12}$	6	620	glass	F'
G'	$\text{Gd}_3\text{Fe}_5\text{O}_{12}$	3	620	glass	-
H'	$\text{Gd}_3\text{Fe}_5\text{O}_{12}$	3	700	glass	-
I'	$\text{Gd}_3\text{Fe}_5\text{O}_{12}$	3	750	glass	-
G	$\text{Bi}_2\text{Gd}_1\text{Fe}_5\text{O}_{12}$	6	620	glass	G'
H	$\text{Bi}_2\text{Gd}_1\text{Fe}_5\text{O}_{12}$	6	620	glass	H'
I	$\text{Bi}_2\text{Gd}_1\text{Fe}_5\text{O}_{12}$	6	620	glass	I'
J	$\text{Bi}_2\text{Gd}_1\text{Fe}_5\text{O}_{12}$	6	620	SGGG	-

3 Characterizations

First we measured the optical reflectivity spectra of the $\text{Gd}_3\text{Fe}_5\text{O}_{12}$ thin films on glass substrates (B'–F') and $\text{Bi}_2\text{Gd}_1\text{Fe}_5\text{O}_{12}$ thin films without the $\text{Gd}_3\text{Fe}_5\text{O}_{12}$ buffer layer on a glass substrate (A) and SGGG substrate (J) in order to estimate the thickness of these films. The measurement wavelength range is from 250 to 2600 nm. The direction of the incident light was normal to the sample. Fig. 1 shows the optical reflectivity spectra of these samples. We fitted the measured optical reflectivity spectra by the calculated reflectivity spectra. We calculated the reflectivity spectra by considering the multiple reflections inside the films by interfaces between air/film and film/substrate. Detail of the estimation process was described in our previous paper [20]. The simulated reflectivity spectra are shown by dotted lines in Fig. 1. The thicknesses were estimated to 115 nm, and 105 nm for Sample A and J ($\text{Bi}_2\text{Gd}_1\text{Fe}_5\text{O}_{12}$ thin films without the $\text{Gd}_3\text{Fe}_5\text{O}_{12}$ buffer layer). The thicknesses are estimated to 133, 286, 320, 533, and 729 nm for Sample B'–F' respectively, and summarized in Fig. 2. The thickness obtained by single spin-coating process was estimated to 19.2 and 17.5 nm for Sample A and J where the MOD solution of $\text{Bi}_2\text{Gd}_1\text{Fe}_5\text{O}_{12}$ films was used.

On the other hand, the average thickness obtained by single spin-coating process was estimated to 84.4 nm for B'–F', where the MOD solution of the

Fig. 1. Optical reflectivity spectra (solid lines) of the $\text{Gd}_3\text{Fe}_5\text{O}_{12}$ thin films (B'–F') on glass substrates, $\text{Bi}_2\text{Gd}_1\text{Fe}_5\text{O}_{12}$ thin films without the $\text{Gd}_3\text{Fe}_5\text{O}_{12}$ buffer layer on glass substrate (A) and SGGG substrate (J). The fitted spectra are shown by dashed lines.

Fig. 2. Estimated thicknesses of the $\text{Gd}_3\text{Fe}_5\text{O}_{12}$ as a function of the spin-coating time.

$\text{Gd}_3\text{Fe}_5\text{O}_{12}$ was used. This is because viscosity of the MOD solution for the $\text{Gd}_3\text{Fe}_5\text{O}_{12}$ was higher than that for the $\text{Bi}_2\text{Gd}_1\text{Fe}_5\text{O}_{12}$ films. We measured the x-ray diffraction (XRD) of all the samples. Figs. 3 and 4 show the XRD of the $\text{Gd}_3\text{Fe}_5\text{O}_{12}$ thin films (B'–I') and $\text{Bi}_2\text{Gd}_1\text{Fe}_5\text{O}_{12}$ thin films (A–I). The symbols a, b, and c in Figs. 3, and 4 correspond to the diffraction angles from (420), (422), and (400) planes of $\text{Bi}_2\text{Gd}_1\text{Fe}_5\text{O}_{12}$ phases. The symbols d, and d' correspond to (420), and (422), planes of $\text{Gd}_3\text{Fe}_5\text{O}_{12}$ phase. The symbols e, f, and h correspond to (112) plane of Gd_2O_3 phase, (104) planes of $\beta\text{-Fe}_2\text{O}_3$ and $\alpha\text{-Fe}_2\text{O}_3$ phases.

These identifications are based on the powder diffraction file of international center for diffraction data (ICDD). It was reported that the lattice constant of $\text{Bi}_2\text{Gd}_1\text{Fe}_5\text{O}_{12}$ samples prepared by liquid phase epitaxy (LPE) was 1.2565 nm [21].

Fig. 3. X-ray diffraction of the $\text{Gd}_3\text{Fe}_5\text{O}_{12}$ thin films (Samples B'–I') on glass substrates.

Fig. 4. X-ray diffraction of the $\text{Bi}_2\text{Gd}_1\text{Fe}_5\text{O}_{12}$ thin films (Samples A–I) on glass substrates with and without the $\text{Gd}_3\text{Fe}_5\text{O}_{12}$ buffer layer.

We assumed the lattice constant of 1.2565 nm to identify the lattice spacing of the $\text{Bi}_2\text{Gd}_1\text{Fe}_5\text{O}_{12}$. The XRD of the $\text{Gd}_3\text{Fe}_5\text{O}_{12}$ thin films in Fig. 3 shows several peaks associated with (420) and (422) planes of $\text{Gd}_3\text{Fe}_5\text{O}_{12}$, (112) plane of Gd_2O_3 , (104)

plane of β -Fe₂O₃. We found that the Gd₃Fe₅O₁₂ phase are not fabricated and small amount of the Gd₂O₃ is observed in Sample B' with spin-coating times of 2. When the spin-coating times is 3 (C'), the Gd₃Fe₅O₁₂ phase are the most dominant among the samples B'–F' with different spin-coating time and fixed final-annealing temperature of 650°C. When the spin-coating time is larger than 4, the diffracted intensity ratio of the Gd₃Fe₅O₁₂ phase on the Gd₂O₃ phase became smaller. On the other hand, the samples H' and I' annealed at 700 and 750°C showed larger diffracted intensity ratio than that of C' and G' annealed at lower temperature of 650 and 620°C. Therefore optimum samples are H' and I'. From Fig. 4, the diffraction peak associated with Bi₂Gd₁Fe₅O₁₂ was the weakest in Sample A without the Gd₃Fe₅O₁₂ buffer layer among A–I except for B having the thinnest Gd₃Fe₅O₁₂ buffer layer. The diffraction peak associated with the Bi₂Gd₁Fe₅O₁₂ was not observed in B. This is because the amorphous Gd₃Fe₅O₁₂ layer did not work as a buffer layer as shown in B' in Fig. 3. The diffraction signals from the Bi₂Gd₁Fe₅O₁₂, Gd₂O₃, α -Fe₂O₃ and β -Fe₂O₃ were observed in Samples C–I. When the spin-coating time for the Gd₃Fe₅O₁₂ buffer layer was 3, the diffraction signal from Bi₂Gd₁Fe₅O₁₂ was the largest and signal from Gd₂O₃ was the smallest among samples with different spin-coating time of the Gd₃Fe₅O₁₂ buffer layer (B–F). The samples G showed the smallest signal from the Bi₂Gd₁Fe₅O₁₂ phase and largest signal from the Gd₂O₃, α -Fe₂O₃ and β -Fe₂O₃ phases among the samples C, G, H, and I with the same Gd₃Fe₅O₁₂ buffer layer thickness and different annealing temperature of 620–750°C. C, H, and I showed the larger diffraction signal from Bi₂Gd₁Fe₅O₁₂ among samples A–I. Please note that the diffraction signals from α -Fe₂O₃ and β -Fe₂O₃ were not observed in sample I. Therefore, sample I is the optimum condition to prepare Bi₂Gd₁Fe₅O₁₂ thin film on glass substrate.

Fig. 5 shows the XRD spectra of the Bi₂Gd₁Fe₅O₁₂ film on an SGGG single crystal substrate. The diffraction peaks from (444) and (888) planes are clearly observed and other peaks associated with polycrystalline or impurity phases were not observed. The lattice constant d was calculated to 1.256 nm, which agreed well

Fig. 5. X-ray diffraction spectra of the Bi₂Gd₁Fe₅O₁₂ thin film (J) on (111) SGGG substrate. Please note that the vertical axis is plotted in logarithmic scale.

with the reported lattice constant of $\text{Bi}_2\text{Gd}_1\text{Fe}_5\text{O}_{12}$ film [21].

Fig. 6 shows the optical transmittance spectra of Sample A–I on glass substrates and Sample J on an SGGG substrate. With increasing the $\text{Gd}_3\text{Fe}_5\text{O}_{12}$ buffer layer thickness, the transparency became lower in the wavelength region below $\lambda < 600$ nm, as shown in Fig. 6(a). Transparency was unchanged upon increasing the annealing temperature in $\lambda < 600$ nm, as shown in Fig. 6(b).

Fig. 7(a) and (b) show the FR spectra of all the $\text{Bi}_2\text{Gd}_1\text{Fe}_5\text{O}_{12}$ samples.

Fig. 6. Optical transmittance spectra of the $\text{Bi}_2\text{Gd}_1\text{Fe}_5\text{O}_{12}$ thin films with (a) different $\text{Gd}_3\text{Fe}_5\text{O}_{12}$ buffer layer thicknesses (A–F) and (b) different annealing temperature including Sample J on SGGG substrate.

Fig. 7(c), and (d) showed a summary of the maximum FR as a function of the spin-coating time for the $\text{Gd}_3\text{Fe}_5\text{O}_{12}$ buffer layer annealed at 650°C , and annealing temperature of the $\text{Gd}_3\text{Fe}_5\text{O}_{12}$ buffer layer. From Figs. 7(a) and (c), we found that optimum spin-coating time giving the largest FR was 3 (C) and the maximum FR decreased when the spin-coating time is larger than 4. From Figs. 7(b) and (d), we found that maximum FR increased with increasing the annealing temperature of the $\text{Gd}_3\text{Fe}_5\text{O}_{12}$ buffer layer. The optimum annealing temperature giving maximum FR is 750°C , and the maximum FR is 4.17 deg. (36.3 deg./ μm) at the wavelength $\lambda = 500$ nm, which is 23 times larger than that of FR of the sample without the $\text{Gd}_3\text{Fe}_5\text{O}_{12}$ buffer (Sample A), and 90.1% of the FR of single crystal $\text{Bi}_2\text{Gd}_1\text{Fe}_5\text{O}_{12}$ film on an SGGG substrate (4.23 deg. and 40.3 deg./ μm for Sample J).

Let us discuss the reason why the FR of the $\text{Bi}_2\text{Gd}_1\text{Fe}_5\text{O}_{12}$ films was changed by the spin-coating time (thickness) for the $\text{Gd}_3\text{Fe}_5\text{O}_{12}$ buffer layer. As we can see from the XRD characterizations of Figs. 3 and 4, when the spin-coating time is 2, the $\text{Gd}_3\text{Fe}_5\text{O}_{12}$ layer is amorphous, and does not work as the buffer layer and the $\text{Bi}_2\text{Gd}_1\text{Fe}_5\text{O}_{12}$ layer was not crystallized, leading to little FR. We found that when the spin-coating time is larger than 4, the (420) plane of the $\text{Gd}_3\text{Fe}_5\text{O}_{12}$ phase is decreased and the Gd_2O_3 phase becomes more dominant, leading to lower FR. The diffracted intensity ratio of the (420) plane of the $\text{Gd}_3\text{Fe}_5\text{O}_{12}$ phase on the other oxide phases (especially Gd_2O_3) in the buffer layer is very important for obtaining large FR in the $\text{Bi}_2\text{Gd}_1\text{Fe}_5\text{O}_{12}$ film on glass substrates. With increasing the spin-

coating time from 3 to 8, the ratio became smaller meaning that the amount of Gd_2O_3 phase increased when the buffer layer is too thick. Thick buffer layer reduces the optical transparency in the wavelength range showing maximum FR. Therefore, the optimum $\text{Gd}_3\text{Fe}_5\text{O}_{12}$ buffer layer thickness is 286 nm in this study for obtaining the $\text{Bi}_2\text{Gd}_1\text{Fe}_5\text{O}_{12}$ film on glass substrate giving the largest FR with minimum absorption by the buffer layer.

We also found that the $\text{Gd}_3\text{Fe}_5\text{O}_{12}$ layer is not crystallized and does not work as

Fig. 7. Faraday rotation spectra of the $\text{Bi}_2\text{Gd}_1\text{Fe}_5\text{O}_{12}$ thin films with (a) different $\text{Gd}_3\text{Fe}_5\text{O}_{12}$ buffer layer thicknesses (A–F) and (b) different annealing temperature including Sample J on SGGG substrate. Magnetic field of 10 kG was applied perpendicular to the sample plane. Maximum FR of Samples A–F and C, G–I are summarized in (c) and (d).

buffer layer when the annealing temperature is 620°C (G'), leading to smaller FR of the $\text{Bi}_2\text{Gd}_1\text{Fe}_5\text{O}_{12}$ layer (G) than that of the other samples (C, H, I) annealed at higher temperature. Sample I annealed at 750°C showed the largest FR among the samples (C, G–I) whose annealing temperature for the $\text{Gd}_3\text{Fe}_5\text{O}_{12}$ buffer layer is changed. In Sample I, the diffraction signal from (420) plane of the $\text{Bi}_2\text{Gd}_1\text{Fe}_5\text{O}_{12}$ phase is the largest and the signal from $\alpha\text{-Fe}_2\text{O}_3$ and $\beta\text{-Fe}_2\text{O}_3$ phase were not observed. Also, the diffracted intensity from the Gd_2O_3 phase is the same between Sample I' and I, meaning that the diffracted signal from the Gd_2O_3 phase is from the $\text{Gd}_3\text{Fe}_5\text{O}_{12}$ buffer layer (not the $\text{Bi}_2\text{Gd}_1\text{Fe}_5\text{O}_{12}$ layer). On the other hand, diffracted

signals from α -Fe₂O₃ and β -Fe₂O₃ phase were observed in Sample C, G, and H. α and β -Fe₂O₃ phases were suppressed by increasing the annealing temperature of the buffer layer. Also, growing of the Gd₂O₃ phase was suppressed in the Bi₂Gd₁-Fe₅O₁₂ layer whose buffer layer is annealed at 750°C (Sample I). Therefore, the optimum annealing temperature for the Gd₃Fe₅O₁₂ buffer layer is 750°C for obtaining the Bi₂Gd₁Fe₅O₁₂ film on glass substrate giving the largest FR and best crystalline quality, as shown in FR data of Fig. 7. Under the optimum condition, we obtained the largest FR of 36.3 deg./ μ m at the wavelength $\lambda = 500$ nm in the Bi₂Gd₁Fe₅O₁₂ thin film. The obtained FR is 1.3 time larger than that of our previous Bi_{2.5}Gd_{0.5}Fe₅O₁₂ thin film (27.5 deg./ μ m) by the EMOD method [20]. Optimized buffer layer thickness and annealing condition lead to larger FR in spite of smaller Bi substitution by 0.5 than that of our previous film [20].

4 Conclusions

We fabricated the Bi₂Gd₁Fe₅O₁₂ thin films with the Gd₃Fe₅O₁₂ buffer layer on glass substrates by the MOD method. Prior to the fabrication of the Bi₂Gd₁Fe₅O₁₂ thin films, we fabricated the single Gd₃Fe₅O₁₂ layers whose thicknesses were changed by the spin-coating times under various annealing temperatures. We measured the X-ray diffraction of the samples, and clarified the relationship among the Gd₃Fe₅O₁₂ layer thickness, annealing temperature, the crystalline orientation, and the amount of other oxide phases. Then we fabricated 115 nm-thick Bi₂Gd₁Fe₅O₁₂ thin films with the Gd₃Fe₅O₁₂ buffer layer whose thicknesses and annealing temperature were changed. We characterized the X-ray diffraction, and Faraday rotation spectra of the samples. The Bi₂Gd₁Fe₅O₁₂ thin films with 286 nm-thick Gd₃Fe₅O₁₂ buffer layer annealed at 750°C showed maximum Faraday rotation of 36.3 deg./ μ m at the wavelength $\lambda = 500$ nm. We investigated the influence of the preparation conditions of the buffer layer on the crystallization process, and discussed the relationship between the crystalline orientation of the Gd₃Fe₅O₁₂/Bi₂Gd₁Fe₅O₁₂ layers and the Faraday rotation. Appearance of (420) plane of the Bi₂Gd₁Fe₅O₁₂ phase, and disappearance of the other oxides such as Gd₂O₃, α -Fe₂O₃ and β -Fe₂O₃ phases are the key for obtaining larger Faraday rotation. The largest Faraday rotation of 36.3 deg./ μ m is 23 times larger than sample without the Gd₃Fe₅O₁₂ buffer layer, and as high as 90.1% of the single crystalline Bi₂Gd₁Fe₅O₁₂ thin films on an SGGG substrate (40.3 deg./ μ m). These findings are promising for application to optical waveguide devices such as optical isolators and circulators, and MOSLMs on glass substrates.

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