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Growth of magneto-optic Ce:YIG thin films on amorphous silica substrates

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Abstract

This paper presents a method for the growth of thin films of cerium substituted YIG (Ce:YIG) on an amorphous substrate. The Ce:YIG film was grown in two steps. The first step was the deposition of an amorphous film of $CeY_2Fe_5O_{12}$ on a SiO_2 substrate by RF-magnetron sputtering. The second step was crystallizing the film by raising its temperature to around 600°C in vacuum. A film of crysatllized Ce:YIG was obtained after this thermal treatment. For the thermal treatment process to work, a small chip of GGG plate was placed on the film. On the other hand, crystallization did not occur when the GGG chip was not placed on the film. The Faraday rotation θ_F was about 2300 deg/mm for light at a wavelength of 630 nm, and this was approximately the same value as for an epitaxial film of Ce:YIG on a GGG substrate. This method will be useful in the development of non-reciprocal planar light-wave circuits. © 2001 Elsevier Science Ltd.

Keywords: Films; Magnetic properties; Optical properties; Transition metal oxides

1. Introduction

Cerium-substituted yttrium-iron garnet ($Ce_xY_{3-x}Fe_5O_{12}$; Ce:YIG) is a promising material for use in high performance magneto-optic devices because of its high Faraday rotation coefficient.[1–3] The Faraday rotation increases with the amount of substituted cerium, x. The films that are of interest for use in non-reciprocal planar light wave circuits have x values above 1.[4,5] Ce:YIG has been fabricated on garnet substrates such as gadolinium-gallium garnet ($Gd_3Ga_5O_{12}$:GGG) by sputtering alone. However, the growth of Ce:YIG on substrates of various kinds is a pre-requisite to make non-reciprocal planar light wave circuits based on this material. This paper presents a new fabrication method consisted of two steps for fabricating Ce:YIG on amorphous silica substrates: The first step was deposition of an amorphous film by magnetron sputtering, and the second step was thermal treatment. During the thermal treatment, a small GGG chip had to be placed in contact with the film. The thermal treatment promoted crystallization of the film.

2. Conditions for epitaxial growth on GGG substrates

As part of our preparation for growing the CeYIG on SiO_2 substrates, we examined the conditions for epitaxial growth on GGG substrates by thermal treatment. Post-sputtering thermal treatment is indispensable to the fabrication of Ce:YIG films on silica, so we studied the conditions for the crystallization of such films on GGG substrates.

Although it was possible to obtain an epitaxial film of Ce:YIG on a GGG substrate by RF sputtering at high substrate temperature above 520°C as reported in the literature,[3,4] we prepared amorphous Ce:YIG film on GGG by magnetron sputtering at low substrate temperature. The film was then thermally treated to examine the conditions for crystallization. The substitution amount x was fixed to 1 throughout these experiments. A sintered plate of $CeY_2Fe_5O_{12}$ (Ce_1:YIG) was used as the sputtering target.

Epitaxial films were obtained with thermal treatment at temperatures above 640°C. Fig. 1 shows the X-ray

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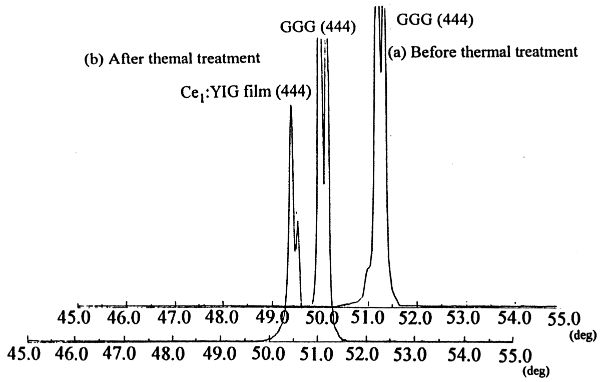

Fig. 1. X-ray diffraction pattern for an epitaxial film of Ce:YIG film on the GGG (111) substrate.

diffraction patterns before and after this thermal treatment. The thermal treatment obviously promotes crystallization. Table 1 shows experimental results in terms of crystallization. Thermal treatment in a vacuum at around 650°C was the best way to obtain epitaxy.

3. Preparation of Ce:YIG on SiO_2 substrates

With reference to the condition for growth on GGG substrates outlined above, conditions for the crystallization of Ce_1:YIG on silica substrates were investigated. Fig. 2 shows the fabrication process. Firstly, a film of amorphous Ce_1:YIG was deposited on a silica substrate by RF magnetron sputtering. As is shown later, the temperature of the substrate during sputtering is one important parameter. Next, thermal treatment was applied. During the thermal treatment, a small chip of GGG was in contact with the film's surface as shown in Fig. 3. The chip size was about 1 mm square.

Table 2 shows the experimental conditions. In deposition by sputtering, the substrate was kept at 250–500°C. Thermal treatment was at a temperature between 580 and 620°C. Experiments were carried out with and without contact with a chip of GGG to clarify its effect. Conditions for the crystallization of Ce_1:YIG on silica substrates were made clear through experiments with the variety of process parameter values listed in Table 2.

Table 1
Conditions for the crystallization of Ce:YIG on a GGG substrate

T_{treat}[a] (°C)	620	640	650	660	680	680
T_{sbst}[b] (°C)	560	570	580	585	585	605
Atmosphere	Vacuum			N_2		
Treatment time	1 h					
Crystallization[c]	×	△	○	△	○	×

[a] Thermal treatment temperature.
[b] Substrate temperature at film deposition.
[c] ×: Crystallization did not occur; △: partialz crystallization; ○: excellent crystallization.

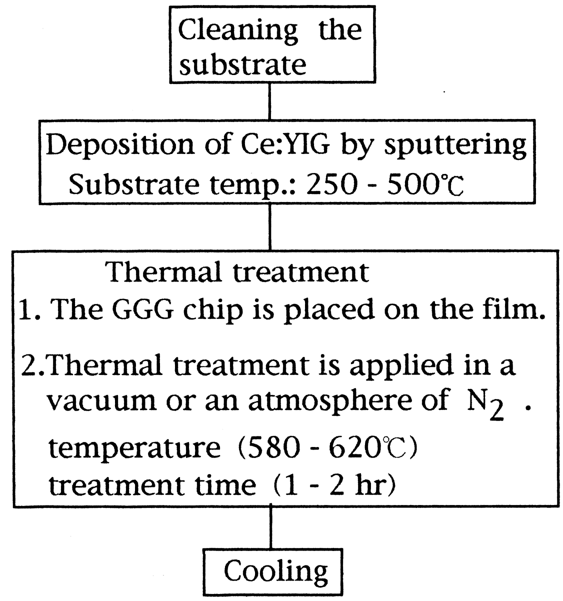

Fig. 2. Fabrication.

Table 3 shows the experimental results. Films of Ce_1:YIG only crystallized when they had been deposited at substrate temperatures of 250–300°C. However, films deposited with the substrate at above 350°C did not crystallize. The thermal treatment temperature that produced crystallization was around 600°C, both in a vacuum and in an atmosphere of nitrogen gas. On the other hand, crystallization did not occur when thermal treatment was applied without having the sample in contact with the chip of GGG.

Fig. 4 shows X-ray diffraction patterns. Fig. 4(a) is the diffraction pattern for a crystallized film as fabricated under condition set (1) listed in Table 3. Similar diffraction patterns were observed for condition sets (2) and (3).

Fig. 4(b) is the diffraction pattern for Ce_1:YIG powder and Fig. 4(c) is the pattern for a film treated without the presence of the GGG contact chip. Although the resulting film was poly-crystalline, thermal treatment of the samples while in contact with the chip of GGG was a useful way of fabricating films of Ce_1:YIG on silica substrates.

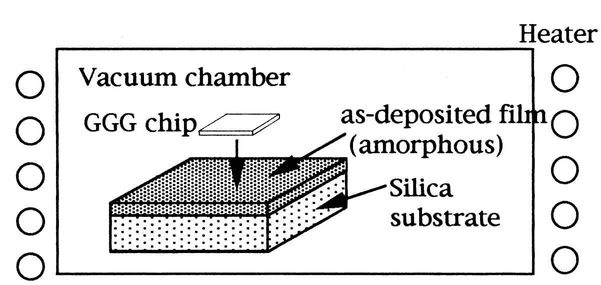

Fig. 3. Thermal treatment of the Ce:YIG film.

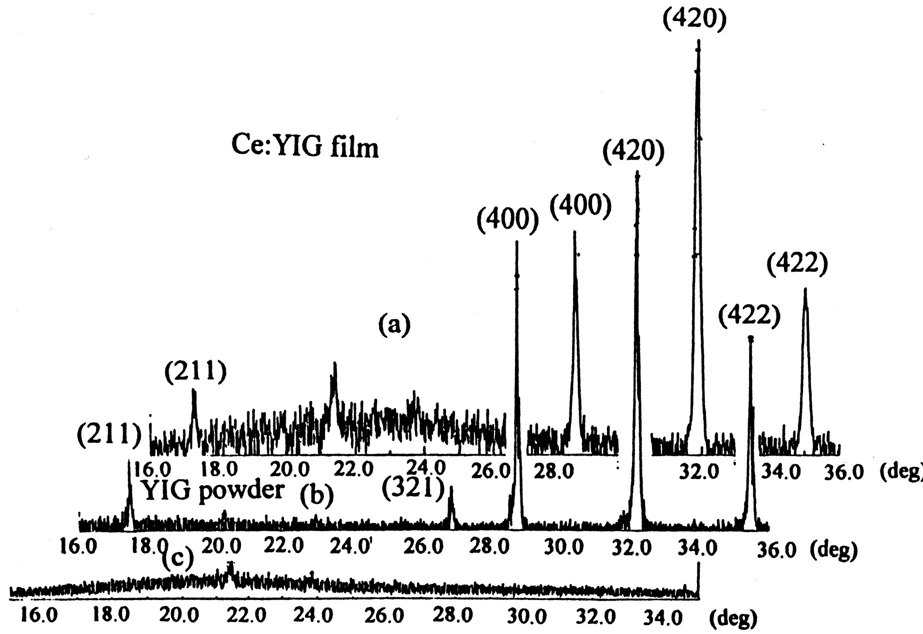

Fig. 4. X-ray diffraction pattern of a film of Ce:YIG on a SiO_2 substrate.

The role of the chip contact is not clear. Local temperature gradient, local stress and some other factors may cause the crystallization.

4. Faraday rotation characteristics

4.1. Dependence of Faraday on optical wave-length

The specific Faraday rotation, θ_F, (Faraday rotation in saturation region of magnetization) was measured at optical wavelengths of 0.63, 0.83, 1.15, 1.30 and 1.55 μm. Fig. 5 shows experimental results for two samples (Nos.1 and 2), both of which were prepared under condition set (2) of Table 3. The measured values are plotted as Δ and *x*, respectively, for samples Nos. 1 and 2. The solid lines in Fig. 5 are specific Faraday rotations for epitaxial Ce_1:YIG on GGG substrates. The specific Faraday rotation characteristics for the film on the SiO_2 substrate are obviously similar to those of the epitaxial film.

The curve for the film of Ce_1:YIG on silica is shifted to shorter wavelengths (blue shift). The reason for this blue shift is not yet clear, but it may be related to stress in the film. Compressive stress in the direction parallel to the film's surface is present in the epitaxial Ce:YIG film. This stress is caused by the lattice mismatch. Fig. 6 shows the dependence on wavelength of θ_F for epitaxial films of Ce_1:YIG prepared by RF sputtering. In Fig. 6, curves (a) and (b) respectively correspond to films grown on GGG and GCGMZG substrates. GCGMZG indicates GGG doped with Ca, Mg and Zr to increase its lattice constant. The lattice constants of GGG, GCGMZG, Ce_1:YIG and lattice mismatch values relative to the Ce_1:YIG are listed in Table 4. Fig. 6 and Table 4 appear to indicate that an increase in the lattice mismatch causes a red shift of the curve for wavelength

Table 2
Conditions of thermal treatment

T_{sbst} (°C)	250–500
T_{treat} (°C)	580–620
Atmosphere	Vacuum or N_2
Treatment time	1–2 h

Table 3
Treatment conditions for chip-contact method[a]

	(1)	(2)	(3)	(4)	(5)	(6)
T_{sbst} (°C)	250	300	300	350	400	500
T_{treat} (°C)	600	600		600~620		
Atmosphere	Vacuum		N_2			
Treatment time			1 h			
Crystallization	○	○	○	×	×	×

[a] Film thickness: about 300 nm; sample size: about 10 mm square.

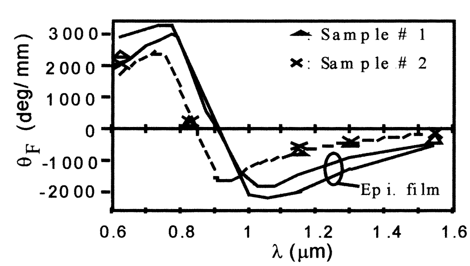

Fig. 5. Dependence of the specific Faraday rotation θ_F on wavelength.

dependence. Therefore, the blue shift suggests that the films of crystalline Ce_1:YIG on silica is stress-free.

4.2. Dependence of Faraday rotation on magnetic field strength

Fig. 7 shows the relation between the Faraday rotation to magnetic-field strength for the same wavelength of 0.63 μm to sample Nos. 1 and 2. In Fig. 7 Faraday rotation for an epitaxial film on a GGG (100) substrate is also plotted. Although the specific Faraday rotation and effect of magnetic field strength are slightly reduced for our samples as compared with an epitaxial film, the magneto-optic characteristics obtained are nonetheless of superior quality.

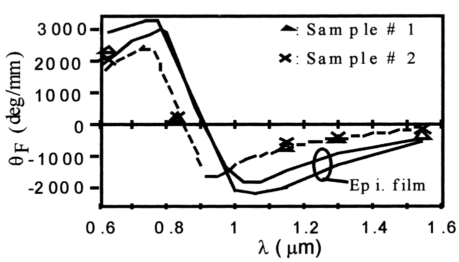

Fig. 6. Dependence of the θ_F of epitaxial films on wavelength.

Table 4
Lattice constants and lattice mismatches relative to Ce_1:YIG

Material	GGG	GCGMZG	Ce_1:YIG
Lattice const. (Å)	12.376	12.496	12.556
Mismatch%	1.45	0.48	–

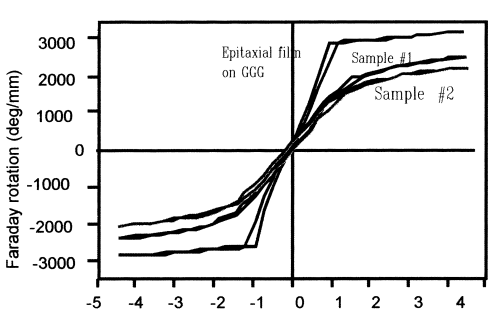

Fig. 7. Faraday rotation vs. magnetic field.

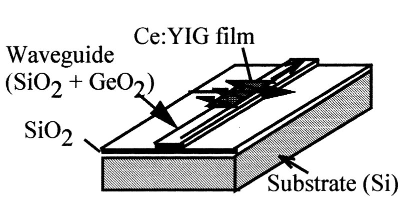

Fig. 8. Configuration of a waveguide-type optical isolator.

5. Applications

The Ce:YIG presented in this paper makes it possible to prepare high Faraday-rotation films on amorphous substrates. Such films are suitable for a variety of applications. Fig. 8 shows a configuration of a waveguide-type optical isolator on a planar light-wave circuit on a silicon substrate. A silica waveguide is formed on a silicon substrate. On part of this waveguide, a film of Ce:YIG is prepared. In this configuration, the forward light wave propagates along the waveguide, while the bac kward light leaks from the waveguide.[4,5] As optical attenuation is a very important factor in waveguides for light, optical absorption and scattering in the film of Ce:YIG must be investigated.

A compact magnetic/or current sensor with a high sensitivity will be possible using the Ce:YIG on silica.

6. Conclusion

A method for growing thin films of cerium substituted YIG on amorphous substrates as silica has been investigated. The Ce:YIG films were grown in two steps, deposition and crystallization. Thermal treatment while in contact with a GGG chip made it possible to crystallize the deposited Ce:YIG film. Ce:YIG with a substitution amount, x, of 1 ($Ce_1Y_2Fe_5O_{12}$), was easy to prepare. On the other hand, crystallization did not occur when the GGG chip was not placed on the film. In spite the size of the of GGG chip (about 1 mm^2), crystallization occurred over a large area (more than 1 cm^2). Specific Faraday rotation θ_F was about 2300 deg/mm for light at a wavelength of 630 nm. Wavelength characteristic of θ_F was slightly shifted to the blue side relative to the result for epitaxial film of the same material on GGG. The blue shift suggests that the films we obtained are stress free. This method is useful in the development of non-reciprocal planar light-wave circuits.

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