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Magneto-optical effect and ferromagnetic resonance of Bi–Fe garnet for high frequency electromagnetic sensor

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In order to develop a new probe sensor for high frequency electromagnetic field generated around integrated electric circuits, we have synthesized thermally nonequilibrium $Bi_3Fe_5O_{12}$ (BIG) and $Bi_3Fe_{5-x}Ga_xO_{12}$ [(BIGG), $x = 0.2$, 0.5, 1.0] films from metalorganic decomposition technique. The BIG materials are famous for the largest magneto-optical (MO) effect in visible light region. Ga substitutions are expected to increase the sensitivity of the MO effect to magnetic fields. For the preparation of the films, metalorganic solutions were spin coated on the garnet single-crystal substrates and then were annealed in the furnace. The optimized annealing temperature for BIG and BIGG is determined to be around 480 °C. The BIG film showed the largest Faraday rotation of approximately 6°/μm at 630 nm. The Ga substitution increases the change ratio of the Faraday rotation to the magnetic field from approximately 5 to 11×10^{-3} deg/μm Oe. The half width of the ferromagnetic resonance (FMR) line shape of the BIG was approximately 200 Oe. Due to the Ga substitution, the minimum half width became 28 Oe. The sharp resonance will be an advantage for MO imaging using FMR phenomena. © *2011 American Institute of Physics*.
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I. INTRODUCTION

The magneto-optical imaging (MOI) of the magnetic flux using Bi-substituted magnetic garnet film has been used for the characterization of high T_c superconductors since the investigations began at the end of 1980s.[1–3] The Faraday rotation of the magnetic garnet film makes possible visualization of magnetic flux. The observed image through the polarized optical microscope reflects the distribution of the magnetic flux penetrated in the superconductor. For the MOI technique, garnet films with in-plane magnetic anisotropy are widely used because magnetic domain aligned in the film plane does not disturb the spatial resolution due to magnetic domain wall width. We already have succeeded in preparing good quality magnetic film with in-plane anisotropy using $(BiLu)_3(FeGa)_5O_{12}$ system.[4]

Recent application of the MOI technique has been extended to the probe sensor of the high frequency magnetic field.[4–6] The frequency of the microwave in wireless communication or other electronic devices has reached the gigahertz region. In comparison to the metal loop coil, the probe sensor using the magneto-optical (MO) effect has great advantages because of the low invasiveness of the electromagnetic field and high speed response to the change of the magnetic field.[5] The problem is that the permeability of ferrite garnet decreases in the high frequency region due to the so-called Snoek's limit.[7] However, it was found that the ferromagnetic resonance (FMR) is effective in enhancing the MO effect in gigahertz frequency region. Induced magnetic moment also induces Faraday effect of the magnetic garnet. Thus, the MO measurement system has been available for detecting the magnetic field components of the gigahertz frequency electromagnetic field (see Ref. 4).

In order to improve the probe sensor with higher sensitivity of the magnetic field, $Bi_3Fe_5O_{12}$ (BIG) is an attractive material. Among the garnet materials, BIG has the largest Faraday effect in the visible and infrared light region. From the previous report about BIG, the magnetic field to saturate the magnetization H_s is approximately 2 kOe.[8] If the H_s become smaller, the change of the Faraday rotation to the magnetic field will increase and then the higher sensitivity of the MO effect to the magnetic field can be expected. In this paper, we report the MO properties of BIG and $Bi_3Fe_{5-x}Ga_xO_{12}$ [(BIGG), $x = 0.2$, 0.5, 1.0] films prepared by metalorganic decomposition (MOD) technique and also show the FMR properties. For the probe sensor of the gigahertz frequency electromagnetic field, it is important to characterize the FMR spectrum because the sharp magnetic resonance is necessary for high sensitive measurements.

II. EXPERIMENTS

The precursor BIG and BIGG films were prepared by spin coating of a metalorganic solution (molar ratio Bi:Fe:Ga = 3:5−x:x, Kojundo Chemical Lab. Co.) The total concentration of Bi and Fe calboxylate in the metalorganic solution was between 3% and 4%. The metalorganic solution was spin coated on $Gd_3Ga_5O_{12}$ (GGG) and substituted GGG (SGGG) single-crystal substrates (lattice parameter $a_s = 12.373$ and 12.497 Å, respectively) at 3000 rpm for 30 s. The substrates were 1 in. diameter and 0.5 mm thick.

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After drying at 100 °C for 30 min in an oven, the films were preannealed at 400 °C for 30 min in order to decompose the metalorganic solution. These processes were repeated 5–20 times. Then, the substrate was cut into approximately 5×5 mm^2 and the amorphous films were annealed for 3 h in the temperature range between 400 and 600 °C. All annealing treatments were achieved in an air atmosphere.

III. RESULTS AND DISCUSSIONS

The XRD spectra using Cu-*Ka* radiation of the ⟨111⟩-oriented BIGG ($x = 1.0$) film annealed between 450 and 550 °C are shown in Fig. 1. Note that no diffraction peaks from the films were observed for the films annealed below 450 and above 550 °C. The same results were observed at the BIG and BIGG ($x = 0.2$, 0.5) films. These results indicate that the BIG and BIGG garnet phases begin to grow above approximately 450 °C and disappear above 550 °C. The BIGG is considered to be a thermally nonequilibrium material as well as the BIG. The disappearance of the diffraction peak indicates the decomposition of the garnet above that temperature.

Figure 2 shows the Faraday rotation spectra of BIGG ($x = 1.0$) at the annealing temperatures between 450 and 550 °C. With decreasing the wavelength, the Faraday rotation increased and the largest Faraday rotation was observed around 530 nm. From these measurements, the optimum annealing temperature of the film was determined to be approximately 480 °C.

The Faraday hysteresis loops at 635 nm are shown in Fig. 3. The maximum Faraday rotation of the film annealed at 550 °C reached approximately 6°/μm for the case of BIG film. The MO effect of the BIG prepared by the MOD technique is slightly inferior to the BIG film prepared by vapor phase deposition,[8] however, the film apparently shows the largest performance of the Faraday effect in comparison to other magnetic garnet materials. By the substitution of Fe ions to Ga ions, the Faraday rotation was reduced by less than half of the BIG film and the coercive force was increased. As far as the Ga substitution ratios ($x = 0.2$, 0.5, and 1.0) are concerned, the reduction of the Faraday rotation seems to be too large. According to the analysis by Nakatsuka *et al.*, Ga ions are preferably substituted in tetragonal sites of garnet crystal up to $x = 1.6$.[9] The net magnetic moment comes from the tetragonal Fe ions. Thus, the preferable substitutions of tetragonal Fe ions may rapidly reduce the net magnetic moments of this material. Although remarkable reduction of Faraday rotation was observed in BIGG films, the Ga substitution increased the slope of the Faraday hysteresis loop from 5.1 to 10.9×10^{-3} deg/μm Oe. According to the surface image by the polarized microscope, no perpendicular magnetic domain in the film was observed and the magnetic easy axis probably still lies in the film plane for the case of BIGG ($x = 1.0$). The film with no perpendicular magnetic domain structure is suitable for the magnetic image sensor, because the perpendicular magnetic domain disturbs

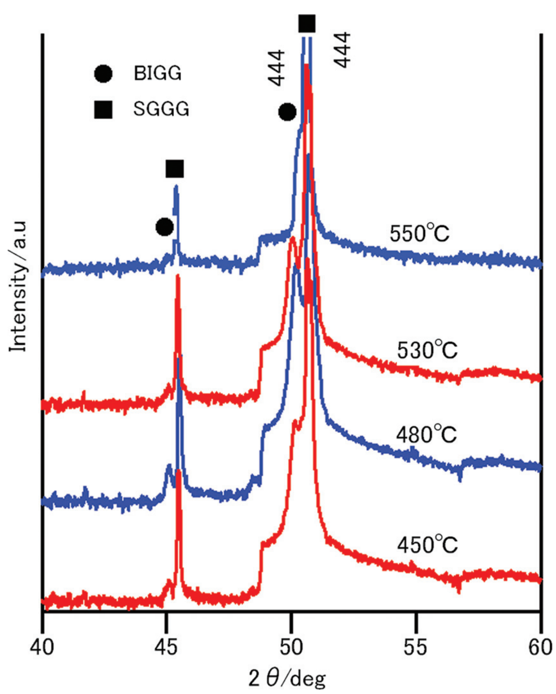

FIG. 1. (Color online) The XRD patterns of the BIGG(111) (x=1.0) films annealed at various temperatures. The diffraction peak appearing around 45° is 444 peak from the substrate due to the Cu $K\beta$ radiation which is not completely cut off.

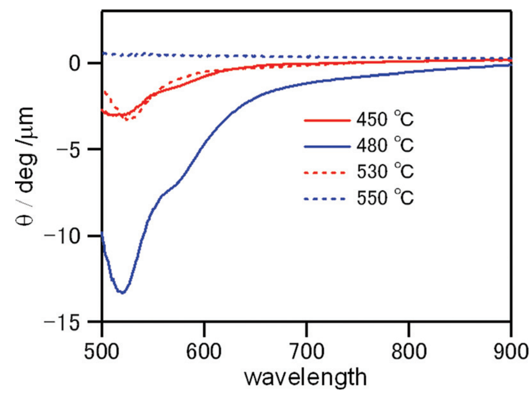

FIG. 2. (Color online) The Faraday rotation spectra of the BIGG(111) (x=1.0) films annealed at various temperatures in the magnetic field of 3 kOe.

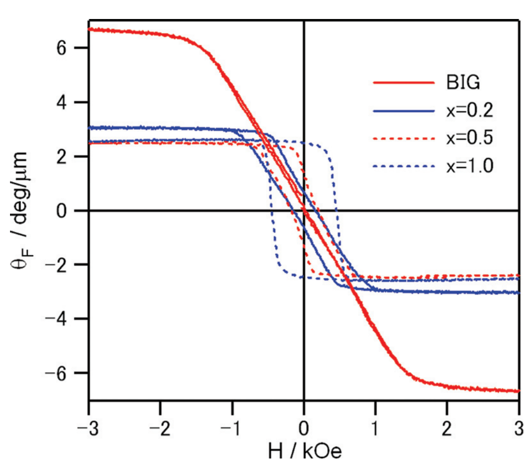

FIG. 3. (Color online) The Faraday hysteresis loops at 635 nm of BIG and BIGG (x=0.2, 0.5, and 1.0).

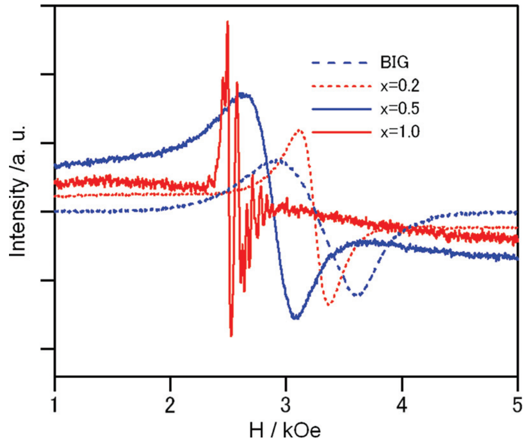

FIG. 4. (Color online) The FMR spectra of BIG and BIGG (x=0.2, 0.5, and 1.0) at 9 GHz.

the spatial resolution of the MO image. The existence of the coercive force is undesirable for the linear sensitivity to the magnetic field. The coercive force is well affected by the magnetic anisotropy. In this experiment, ⟨111⟩-oriented SGGG substrates were used because of the smaller lattice mismatch between the BIGG film and the substrate. The crystalline magnetic anisotropy of the magnetic garnet is parallel to the ⟨111⟩ direction, thus, the crystalline magnetic anisotropy is out of the BIGG film plane. In addition, the reduction of the magnetization tends to increase the coercive force.[10] One of the solutions of these problems is to use the ⟨110⟩-oriented substrate where ⟨111⟩ axis lies in the film plane, although these substrates are difficult to obtain at present. The optimization of the Ga substitution also will be necessary.

The FMR spectra of the BIG and BIGG films are shown in Fig. 4. The half width of FMR line shape of the BIG was approximately 200 Oe. This value is almost the same with the BIG prepared by the Pulsed Laser Deposition (PLD) technique.[11] In comparison to yttrium iron garnet, the width is much larger, although Bi is a nonmagnetic ion as well as Y ion. Basically, the enhancement of the MO effect by Bi substitutions in the iron garnet comes from the interaction between the d orbital of the Fe ion and the p orbital of the Bi ion. These interactions may affect the broadening of the width of the magnetic resonance spectrum. The BIGG films with $x = 0.1$ show the narrowest FMR spectrum and also the magnetostatic mode appeared in the spectrum. The width of the largest main peak was approximately 28 Oe. As the sharp FMR resonance is an advantage for the high frequency MO imaging using FMR phenomena,[4] Ga substitution can be expected for the high frequency electromagnetic sensor probe.

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[1]A. A. Polyanskii, V. K. Vlasko-Vlasov, M. V. Indenbom, and V. I. Nikitenko. Pis'ma v Zhurnal Tekhnicheskoi Fiziki. **15**, 1 (1989).
[2]Y. Yokoyama, Y. Suzuki, Y. Hasumi, H. Obara, T. Yosimi, Y. Kita, S. Kosaka, and S. Yoshida, Jpn. J. Appl. Phys. **30**, L1864 (1991).
[3]S. Gotoh, N. Koshizuka, M. Yoshida, M. Murakami, H. Fujimoto, and S. Tanaka, Supercond. Sci. Technol. **4**, S226 (1991).
[4]M. Takahashi, H. Ota, N. Adachi, and K. Arai, IEICE Tech. Rep. **106**, no. 579, EMCJ2006-129, pp. 77 (2007) (in Japanese).
[5]E. Yamazaki, H. Park, S. Wakana, M. Kishi, and M. Tsuchiya, Jpn. J. Appl. Phys. **41**, L864 (2002).
[6]H. Tamura, T. Tozuka, T. Nakaya, and O. Kamada, J. Magn. Soc. Jpn. **34**, 537 (2010).
[7]J. Smit and H. P. Wijn, *Ferrites* (Philips Technical Library, Eindhoven, 1959).
[8]N. Adachi, V. P. Denysenkov, S. I. Khartsev, A. M. Grishin, and T. Okuda, J. Appl. Phys. **88**, 2734 (2000).
[9]A. Nakatsuka, A. Yoshiasa, and S. Takeno, Acta Crystallogr., Sect. B: Struct. Sci. **B 51**, 735 (1995).
[10]S. Mito, J. Kim, K. H. Chung, K. Yamada, T. Kato, H. Takagi, P. B. Lim, and M. Inoue, J. Appl. Phys. **107**, 09A948 (2010).
[11]A. A. Jalali-Roudsar, V. P. Denysenkov, S. I. Khartsev, A. M. Grishin, N. Adachi, and T. Okuda, IEEE Trans. Magn. **37**, 2454 (2001).