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Magneto-optical properties of $Y_2BiFe_5O_{12}$/$Bi_2Sr_2CaCu_2O_{8+x}$/$SrTiO_3$ structures

Shuta Yufune, Tetsuya Kawata, Takayuki Ishibashi *, Katsuaki Sato

Department of Applied Physics, Tokyo University of Agriculture and Technology, 2-24-16 Naka-cho, Koganei, Tokyo 184-8588, Japan

Abstract

Deposition of magneto-optical film directly on superconducting layer has been studied in order to improve the spatial resolution and the magnetic sensitivity in a magneto-optical (MO) imaging of single vortices. Calculation of MO effect in $Y_2BiFe_5O_{12}$ (Bi:YIG)/Bi_2Sr_2-$CaCu_2O_{8+x}$ (BSCCO)/$SrTiO_3$ (STO) structure was carried out using the virtual optical constant method between 2 and 3 eV, showing possibility of enhancement of Kerr rotation up to approximately 4° for a thin Bi:YIG film of 200 nm in thickness. Preparation of the Bi:YIG/BSCCO/STO structures with an optimum layer thickness determined by the simulation was carried out by using the metal-organic decomposition (MOD) method. However only a small Kerr rotation was realized, suggesting degradation of magneto-optical effect due to out-diffusion of Bi.

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Keywords: MO microscope; MO effects; $Y_2BiFe_5O_{12}$; $Bi_2Sr_2CaCu_2O_{8+x}$; The virtual optical constant method

1. Introduction

Establishment of a technique for observation of single vortices of high-T_c superconductors (HTSC) is one of the most important issues not only for understanding the physics of HTSC but also for applications using vortices such as quantum computers and THz devices. For this purpose, number of techniques have been proposed, such as the scanning SQUID microscope [1], the scanning hole-probe microscope [2,3], the Lorentz electron microscope [4], the Bitter decoration technique [5], the magnetic force microscope (MFM) [6] and the magneto-optical (MO) visualization technique [7–9], among which the MO observation, as well as the Lorentz electron microscope, is promising for observation of vortices, taking into account a potentiality of a dynamic observation.

In the MO observation method, magnetic fluxes penetrating the superconductor are converted into optical images using an MO layer placed on superconductors. In this case a spatial resolution and a magnetic sensitivity are strongly dependent on the thickness of the MO layer as well as on the spacing between the MO layer and the HTSC sample. The thickness and the spacing should be less than 1 μm in order to get a sufficient resolution for observation of the individual vortices [7]. Generally speaking, realization of the small spacing is difficult due to the roughness of HTSC samples. Reduction of the film thickness is also difficult, since such thin MO layer does not give a sufficient magnetic sensitivity.

In order to reduce the spacing, we propose a direct deposition process of MO films on superconducting films. On the other hand, to obtain sufficient magneto-optical effect using MO films of several hundred nanometers in thickness, we propose a use of the multiple interference effect to enhance the MO effect.

In the first part of this paper we describe the simulation of MO Kerr rotation and ellipticity in the $Y_2BiFe_5O_{12}$ (Bi:YIG)/$Bi_2Sr_2CaCu_2O_{8+x}$ (BSCCO)/$SrTiO_3$ (STO) structures using the virtual optical constant method [10]. In the

* Corresponding author. Tel./fax: +81 42 388 7432.
E-mail address: bashi@cc.tuat.ac.jp (T. Ishibashi).

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next part, we also report on a fabrication of the Bi:YIG/BSCCO/STO structures by using the metal organic decomposition (MOD) technique [11,12] and in the last part we show the result of the magneto-optical measurement on the structures obtained.

2. Calculation of MO spectra

MO spectra of the Bi:YIG/BSCCO/STO structures were calculated by the virtual optical constant method [10] using dielectric functions of the Bi:YIG, the BSCCO, and the STO. In order to estimate Kerr rotation θ_K and Kerr ellipticity η_K of the multilayer, virtual optical constant $\widehat{N}^{\pm}$ of Bi:YIG/BSCCO/STO structures is calculated as follows. In the first step, virtual optical constant $\widehat{N}_1^{\pm}$ of the BSCCO/STO composite is obtained employing the complex refractive index $\widehat{n}_{\mathrm{BSCCO}}^{\pm}$ and the thickness d_{BSCCO} of BSCCO as well as the complex refractive index $\widehat{n}_{\mathrm{STO}}^{\pm}$ of STO by equations

$$\widehat{N}_1^{\pm} = n_{\mathrm{BSCCO}}^{\pm}\frac{1-\hat{r}_1^{\pm}\exp(-2i\phi_1^{\pm})}{1+\hat{r}_1^{\pm}\exp(-2i\phi_1^{\pm})}, \tag{1}$$

where $\hat{r}_1^{\pm}$ and $\phi_1^{\pm}$ are given by the following equation:

$$\hat{r}_1^{\pm} = \frac{\hat{n}_{\mathrm{BSCCO}}^{\pm}-\hat{n}_{\mathrm{STO}}^{\pm}}{\hat{n}_{\mathrm{BSCCO}}^{\pm}+\hat{n}_{\mathrm{STO}}^{\pm}}, \phi_1^{\pm} = \frac{2\pi\hat{n}_{\mathrm{BSCCO}}^{\pm}d_{\mathrm{BSCCO}}}{\lambda} \tag{2}$$

Here plus and minus signs correspond to the right and the left circularly polarizations, respectively. The $\widehat{N}_2^{\pm}$ is obtained using $\hat{n}_{\mathrm{Bi:YIG}}^{\pm}$ and $d_{\mathrm{Bi:YIG}}$ of the Bi:YIG layer, and the $\widehat{N}_1^{\pm}$ of the BSCCO/STO structure by equations

$$\widehat{N}_2^{\pm} = n_{\mathrm{Bi:YIG}}^{\pm}\frac{1-\hat{r}_2^{\pm}\exp(-2i\phi_2^{\pm})}{1+\hat{r}_2^{\pm}\exp(-2i\phi_2^{\pm})}, \tag{3}$$

$\hat{r}_2^{\pm}$ and $\phi_2^{\pm}$ are given by the following equation:

$$\hat{r}_2^{\pm} = \frac{\hat{n}_{\mathrm{Bi:YIG}}^{\pm}-\widehat{N}_1^{\pm}}{\hat{n}_{\mathrm{Bi:YIG}}^{\pm}+\widehat{N}_1^{\pm}}, \qquad \phi_2^{\pm} = \frac{2\pi\hat{n}^{\pm}{}_{\mathrm{Bi:YIG}}d_{\mathrm{Bi:YIG}}}{\lambda}. \tag{4}$$

Consequently, the Kerr rotation θ_K and the Kerr ellipticity η_K of the Bi:YIG/BSCCO/STO is obtained by equations

$$\theta_K = \mathrm{Re}\left(\frac{E^{XY}}{\widehat{N}'(1-\widehat{N}'^2)}\right), \tag{5}$$

$$\eta_K = \mathrm{Im}\left(\frac{E^{XY}}{\widehat{N}'(1-\widehat{N}'^2)}\right) \tag{6}$$

and

$$\widehat{N}' = \frac{\widehat{N}_2^{+}+\widehat{N}_2^{-}}{2}, E^{XY} = \frac{\widehat{N}_2^{+2}-\widehat{N}_2^{-2}}{2i}. \tag{7}$$

The spectra of diagonal elements of the dielectric tensor in BSCCO and STO used in this calculation have been obtained in our group. Dielectric functions of these materials for photon energies between 1 and 25 eV have been deduced using Kramers–Kronig analysis from reflectivity spectra measured at Synchrotron Laboratory of the University of Tokyo. Fig. 1 shows diagonal elements of the dielectric function obtained in a bulk single crystal of BSCCO grown by TFZ method. Solid and dashed lines denote the real and imaginary part of the dielectric function, respectively. In STO, measurements were carried out in a commercially available single crystal, the result of which was described elsewhere [13]. For diagonal and off-diagonal elements of the dielectric functions in a single crystal of Bi:YIG, we employed those reported by Wittekoek et al. [14].

Fig. 2(a) and (b) shows calculated spectra of Kerr rotation θ_K and Kerr ellipticity η_K of the Bi:YIG/BSCCO/STO structure between 2 and 3 eV. It is found that the values of θ_K and η_K are strongly dependent on the thickness of Bi:YIG, and that the θ_K can be enhanced to have a value as large as 4° for the thickness of 120 and 200 nm by multiple interference effects.

Fig. 3 shows the thickness-dependence of θ_K (solid line) and η_K (dashed line) calculated at photon energy of 2.35 eV. Periodical variation of MO effect on the thickness of Bi:YIG layer is observed both in θ_K and η_K. This result indicates that a large θ_K or η_K can be obtained by adjusting the thickness of Bi:YIG layer. Values of 4°–5° are expected to be sufficient for the purpose to visualize a single vortex.

3. Bi:YIG/BSCCO/STO structures by the metal-organic decomposition method

Bi:YIG/BSCCO/STO structures were prepared by the metal-organic decomposition (MOD) method. The BSCCO solution (SKBSCCO-008; Kojundo Chemical Lab. – Symetrix) was spin-coated on STO (001) substrates by two-step process using 1000 rpm for 5 s and 3000 rpm for 60 s. After the drying process on a hot plate at 120 °C for 2 min, films were annealed in O_2 or $O_2 + N_2$ (10:90) atmosphere at an annealing temperature between 870 and 885 °C for 2 h. Thickness of the films was estimated to be approximately 40 nm. The Bi:YIG layers were prepared as follows. The Bi:YIG solution (YBiFeO; Kojundo Chemical Lab.) was spin-coated on BSCCO layers by the two-step process using 1000 rpm for 5 s and 3000 rpm for

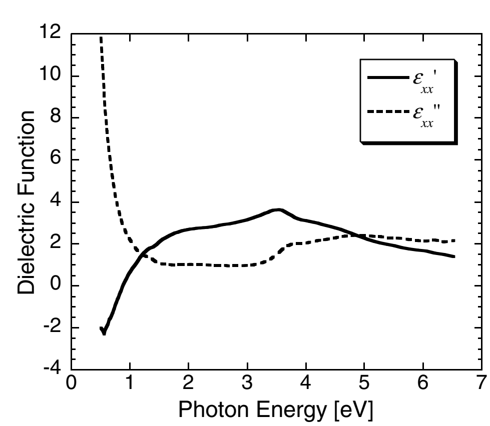

Fig. 1. Real and imaginary part of dielectric functions of BSCCO single crystals.

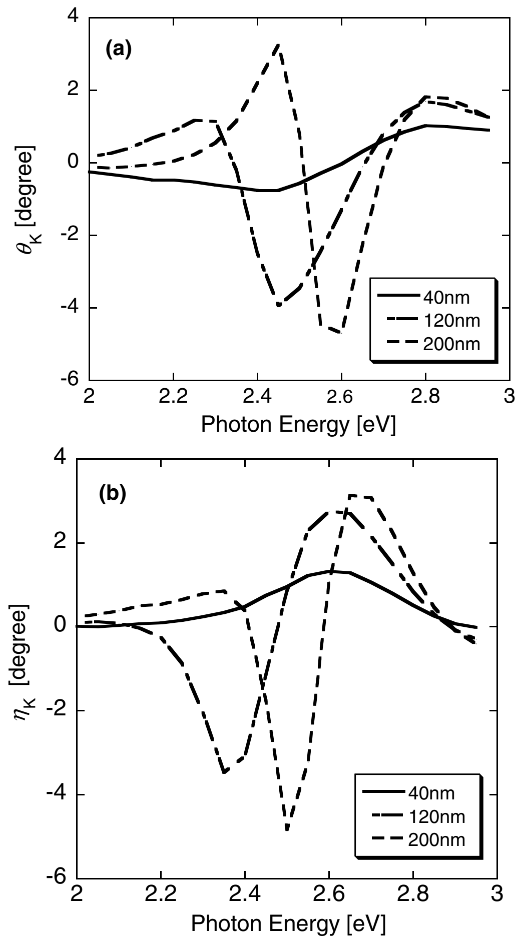

Fig. 2. Calculation of: (a) Kerr rotation θ_K and (b) Kerr ellipticity η_K for Bi:YIG/BSCCO/STO structures.

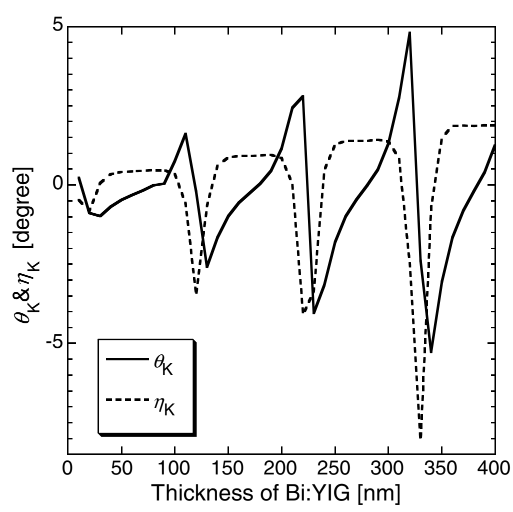

Fig. 3. Thickness dependence of θ_K and η_K for Bi:YIG/BSCCO/STO structures.

30 s, followed by the drying process on the hot plate at 90 °C for 2 min. In order to decompose organic materials and to obtain amorphous oxide films, samples were pre-annealed at 450 °C for 15 min. These processes, i.e., spin-coating, drying and pre-annealing, were repeated until an appropriate thickness value is achieved. The thickness of films employed in the present work was estimated to be approximately 200 nm. Finally, samples were annealed for crystallization of Bi:YIG layer at 650 °C for 2 h. The crystalline properties of these structures were measured by using the X-ray diffraction (XRD) apparatus (Philips X'Pert). Magnetic properties of these structures were analyzed by the vibrating sample magnetometer (VSM, Toei VSM-5) and a magneto-optical spectrometer.

Fig. 4 shows XRD patterns of the structures. The (0 0 *l*) diffraction peaks of BSCCO indicate that BSCCO films were successfully prepared. However, diffraction peaks of Bi:YIG were not observed, since the diffraction from polycrystalline Bi:YIG is relatively weak. In order to analyze Bi:YIG layer, *M–H* loops and MO spectra were investigated as shown in Figs. 5 and 6, respectively. Fig. 6 shows magneto-optical Kerr spectra of the Bi:YIG/BSCCO/STO structures obtained, in which the solid and dashed lines denote θ_K and η_K, respectively. The *M–H* loops showed that the easy axis of magnetization was in-plane. The MO spectra indicate that the Bi:YIG layer prepared on BSCCO/STO structure has the garnet structure. However, a periodic structure due to the multiple interference effects as we expected was not appeared on the MO spectra. We consider that the reason of the absence of the multiple interference effect is due to a roughness of the sample, which is caused by a rough surface of the BSCCO layer with a roughness of approximately 50 nm. Therefore, in order to improve the morphology of the Bi:YIG/BSCCO/STO structure, the BSCCO layer should be improved. An improvement of the morphology of the BSCCO will be described elsewhere [15]. On the other hand, the values of θ_K and η_K are rather smaller than those of bulk crystals. To discuss the degradation of MO properties, we can compare the MO spectra with those of bulk crystals, because no periodic structure appeared on the MO spectra as mentioned above. We consider that such small values of θ_K and η_K may be attributed to a reduction of Bi content in the Bi:YIG layer, because the spectra shown in Fig. 6 agree with that of YIG crystal without Bi substitution. It is con-

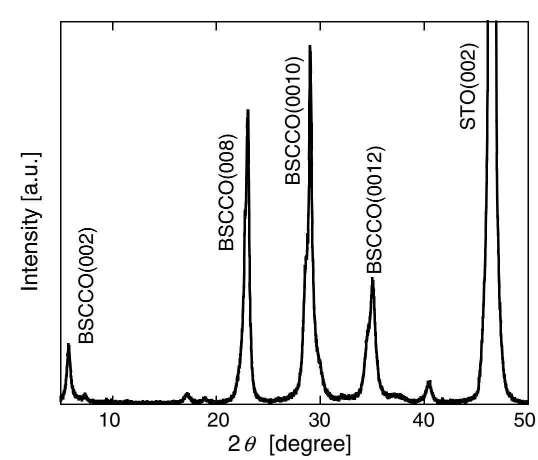

Fig. 4. XRD patterns of Bi:YIG/BSCCO/STO structures.

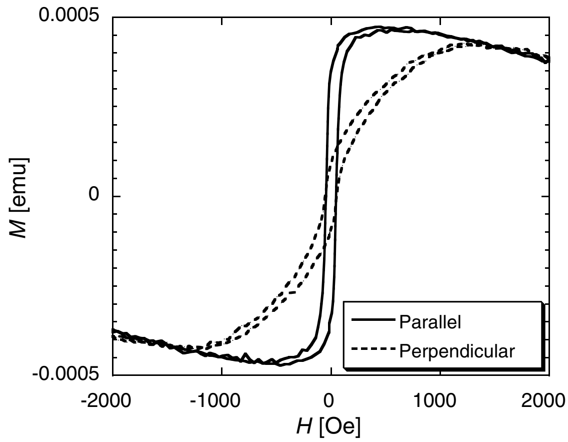

Fig. 5. *M–H* loops of Bi:YIG/BSCCO/STO structures.

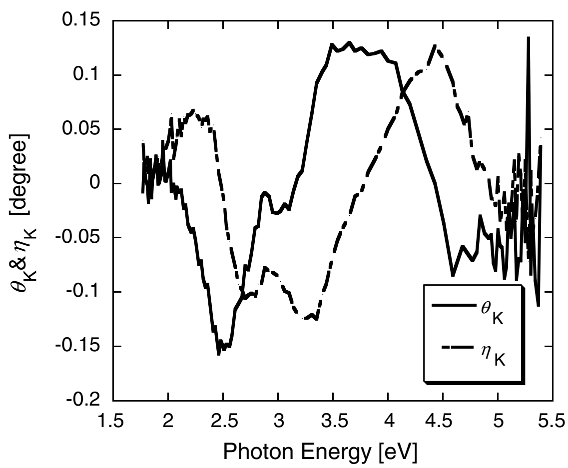

Fig. 6. MO Kerr spectra of Bi:YIG/BSCCO/STO structures.

sidered that a reduction of Bi was caused by a diffusion or an evaporation of Bi. However, the evaporation is not necessary to take into account, since the vapor pressure of Bi is sufficiently low at the annealing temperature of 650 °C with 1 atm. In fact, Bi:YIG films prepared on the gadolinium–gallium–garnet substrates at 650 °C showing large magneto-optical effects maintained a chemical composition ratio of Bi:YIG [11]. In order to get larger Kerr effect in the structure, insertion of an intermediate layer to prevent a diffusion of Bi atom may be effective.

4. Summary

Direct deposition of the MO film on the HTSC layer has been studied to improve the spatial resolution and the magnetic sensitivity in an MO imaging of the single vortex. MO Kerr spectra of Bi:YIG/BSCCO/STO substrate have been estimated by using the virtual optical constant method. It is found from the calculation that an enhancement of θ_K and η_K values to more than 4° is expected by optimizing the thickness of Bi:YIG layer. According to this estimation, Bi:YIG/BSCCO/STO structures were prepared using the MOD method. The XRD, *M–H* and MO spectra showed that Bi:YIG/BSCCO/STO structures have been successfully prepared. Nevertheless magneto-optical effect was much smaller than we expected. We tentatively attribute the poor MO effect to a loss of Bi in the Bi:YIG layer by a diffusion effect.

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