Monolithic Mach-Zehnder Optical Modulator Using Electro-Optic Material: (Ba,Sr)TiO_3 Film Sputter Deposited at Low Temperature on Silicon

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1. Introduction

With the progress of the switching speed of transistors, the performance of LSI is now limited by the signal transfer speed of the global interconnection. Therefore, the optical interconnection is attracting much attention as an interconnection which improves the performance of LSI [1]. We have proposed an optical interconnection system using optical switches made of electro-optic (EO) material [2], which are monolithically integrated on the metal interconnection layers as shown in Fig. 1. (Ba,Sr)TiO_3 (BST) is highly promising as an EO material because the BST film has been already used in the memory capacitors [3].

In this study, we have evaluated crystallinity and optical properties of the sputtered BST films [4][5]. Furthermore, we have, for the first time, succeeded in operation of monolithic Mach-Zhender interferometers (MZI) optical modulator on Si substrate using BST film sputter deposited at 450°C, and the performance of the fabricated MZI is evaluated [6][7].

2. Experimental

BST films were deposited by RF magnetron sputtering on Si (100) substrates with 1.0 μm thermal SiO_2. Sputtering conditions are shown in Table I. The crystallinity of BST films were analyzed by x-ray diffraction (XRD). BST waveguides for propagation loss measurement were fabricated by wet etching in HF. Then, we have developed a new structure in order to evaluate the propagation loss of the very high-loss (a few hundred dB/cm) BST film, where Si_3N_4 and BST waveguides are serially connected and the length of the BST region can be substantially shrunk. The MZI was fabricated using the BST/Si_3N_4 hybrid waveguides. The BST film used for the MZI was sputter deposited at 450°C which is an acceptable temperature for the process after metallization [8]. Details of fabrication of the MZI will be reported in ref. 7. Optical measurement system is shown in Fig. 2. He-Ne laser light (λ=633 nm) is introduced from the cleaved edge of the MZI.

3. Results and Discussion

3.1 Optical and structural properties of sputtered BST

The XRD spectra of the sputtered BST film on 1.0 μm SiO_2 layer are shown in Fig. 3. The peak intensity becomes larger as substrate temperature becomes higher. Figure 4 shows relationship between propagation loss and the XRD peak intensity of BST(200). This figure indicates that propagation loss rapidly increases with increasing the crystallinity of the polycrystalline BST film. Therefore, it is thought that the main cause of the propagation loss may be scattering at the interface of the polycrystalline grains. The output power of the Si_3N_4/BST hybrid waveguide versus BST waveguide length is shown in Fig. 5, where the BST was deposited at 450°C. As a result, the propagation loss of the BST waveguide is calculated to be 470 dB/cm.

3.2 Optical modulation properties of MZI using BST

Schematics of the fabricated MZI are shown in Fig. 6. As shown in Fig. 6(a), BST/Si_3N_4 hybrid waveguide are used for the MZI, and the BST waveguides are used only for phase shifter region of the MZI. Figure 7 shows optical response of the MZI when the voltage is applied to one arm of the MZI. The output intensity is changed by about 10 % at maximum when applied voltage V is 200 V (electric field E_{BST}=1.2×10^4 V/cm). Figure 8 shows voltage dependence of modulation and phase shift ($\Delta\phi$) which is given by

$$I = \frac{1+\cos(\Delta\phi)}{2}, \qquad (1)$$

where I is normalized output intensity of the MZI [9]. Linear relation of the V-$\Delta\phi$ suggests that the modulation is caused by an EO effect (Pockels effect). However, In Fig. 7, output intensity of the MZI is slowly changed even though the rectangular voltage waveform is applied. When the voltage is changed from 200 to 0 V (t=87 s), the output increases slowly. The time constant for this output increase is analyzed in Fig. 9, where two time constants of 6.3 s and 1.0 s are obtained. Figure 10 shows a time dependence of the measured current between Al electrode and Si substrate of the MZI when a rectangular voltage waveform is applied. The current decays slowly with time constants of 5.9 and 1.0 s which are very similar to the time constants of optical modulation (6.3 s and 1.0 s). Therefore, it is thought that the transient behavior of the optical modulation may be caused by the transient change of the electric field in BST layer owing to the dielectric relaxation of the BST [6]. Figure 11 shows the frequency dependence of the modulation. The modulation decreases with increase in frequency. This result indicates that the slow components of optical modulation can not follow the high operating frequency.

4. Conclusions

We have, for the first time, evaluated the optical properties of electro-optic material BST and succeeded in the operation of the MZI using low temperature (450°C) deposited BST film. A maximum modulation of ~10% was achieved at an electric field of 1.2×10^4 V/cm in the BST film. The modulation decreased with operating frequency due to the slow component of the response time. We expect that these disadvantages will be overcome by improving the device design and the crystal quality of the BST film.

References

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Table I Sputtering conditions

RF power	50 W
Base pressure	1.2×10^{-6} Pa
Sputtering gas	Ar = 44 sccm
	O_2 = 11 sccm
Pressure	2.0 Pa
Substrate temperature	23-700°C
Deposition rate	1 nm/min

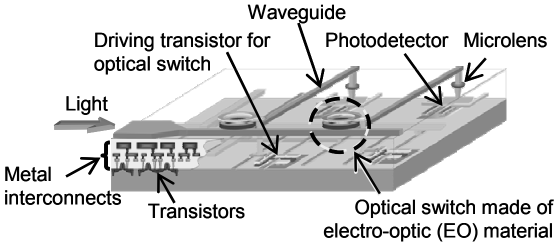

Fig. 1 Schematic of optical interconnection using optical switches made of electro-optic material.

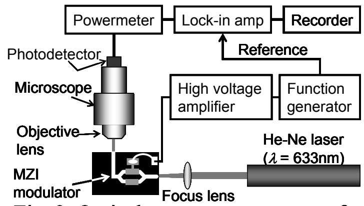

Fig. 2 Optical measurement system for MZI modulator.

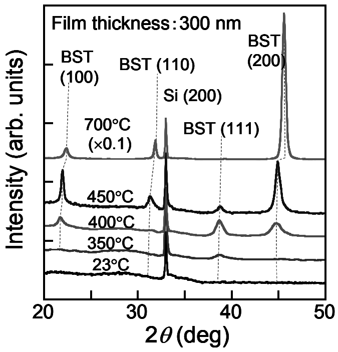

Fig. 3 XRD spectra of BST film sputtered on 1.0 μm SiO_2 layer at different temperatures.

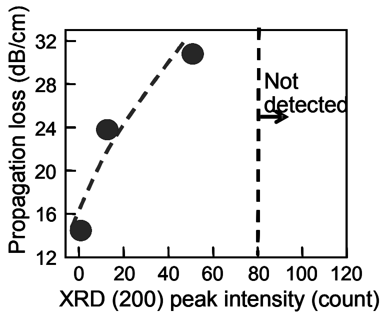

Fig. 4 Propagation loss of BST waveguide versus XRD peak intensity of BST(200). When XRD peak intensity of BST(200) is larger than 80 count and BST waveguide length is longer than 1 mm, output light is not observed.

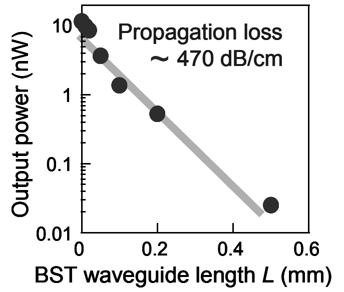

Fig. 5 Output intensity of BST/Si_3N_4 hybrid waveguide versus waveguide length of BST region.

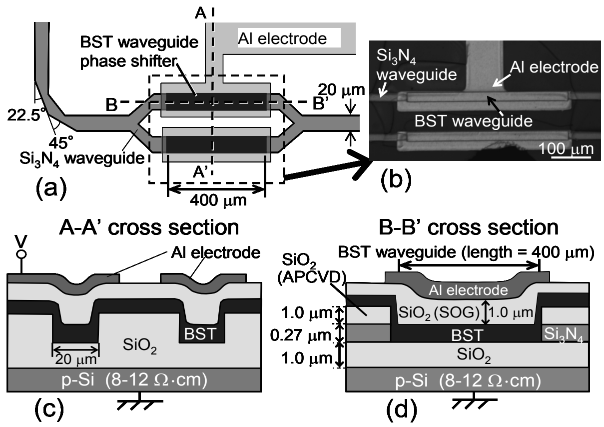

Fig. 6 (a) Schematic plan view and (b) photograph of the fabricated Mach-Zehnder interferometer, and cross-section along (c) A-A' and (d) B-B' in (a).

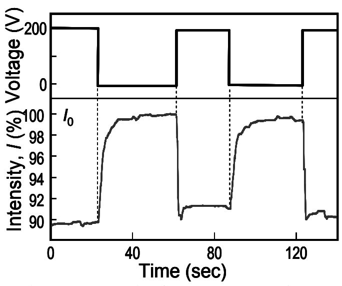

Fig. 7 Optical response of BST MZI modulator at a wavelength of 633 nm when a rectangular voltage was applied to one arm.

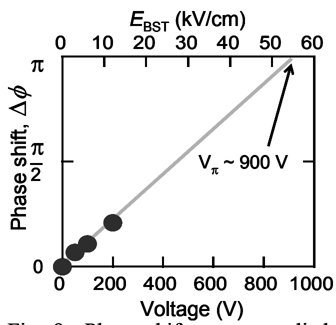

Fig. 8 Phase shift versus applied voltage of MZI. Drive voltage required for the phase shift π (V_π) = 900 V.

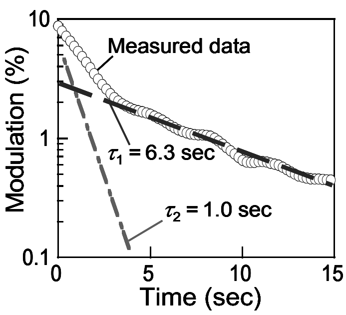

Fig. 9 Deconvolution of different time constants in time region between 87 and 102 s in Fig. 7.

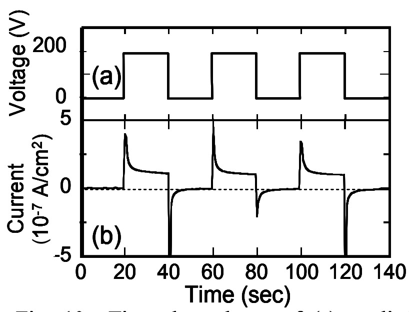

Fig. 10 Time dependence of (a) applied voltage and (b) measured current between Al electrode and Si substrate of MZI.

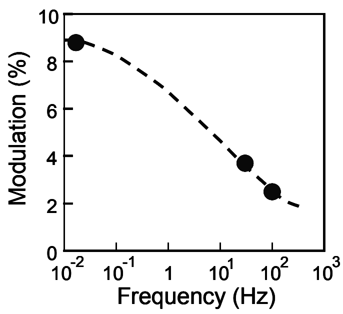

Fig. 11 Frequency dependence of optical modulation of BST MZI.