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Low Temperature Fabrication of Monolithic Mach-Zehnder Optical Modulator on Silicon using Sputtered (Ba,Sr)TiO$_3$ and Mechanism of Transient Response

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1. Introduction

Recently, optical interconnection in LSI has attracted much attention to improve performance of the LSI [1]. We have proposed optical interconnection using optical switches made of electro-optic (EO) material [2], which are monolithically integrated on the metallization layer. (Ba,Sr)TiO$_3$ (BST) is promising EO material for Si based process because it is used in the memory capacitor in the research stage [3]. Previously we have reported Mach-Zehnder interferometer (MZI) optical modulator made of BST film spin-coated on Si and annealed at 550°C [4].

In this study, we have employed sputter-deposited BST film and, for the first time, succeeded in lowering the MZI fabrication temperature to 450°C, which is a critical temperature for the process after metallization [5]. And also the performance of the fabricated MZI is evaluated.

2. Experimental

The fabricated monolithic MZI on Si is shown in Fig. 1, where Si$_3$N$_4$ and BST waveguides (20 μm wide and 0.26 μm thick) are serially connected to reduce the optical loss. The BST film was deposited by RF magnetron sputtering at 450°C. The sputtering conditions are listed in Table I. Details of fabrication of the Si$_3$N$_4$/BST hybrid waveguide were reported in Ref. 2. Measurement system is shown in Fig. 2. He-Ne laser light (λ=633 nm) is introduced from the cleaved edge.

3. Results and Discussions

3.1 Voltage dependence

Response of the MZI is shown in Fig. 3. The output intensity is changed by 8.8 % at maximum when applied voltage is 200 V (electric field, E_{BST}=1.2×10^4 V/cm). This result is better than that (~2%) of an MZI made of spin-coated and annealed (550°C) BST (E_{BST} = 1.3×10^4 V/cm) [4]. Figures 4 and 5 respectively show 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 output intensity of the MZI [6]. Linear relation in Fig. 5 suggests that the modulation is caused by an EO effect (Pockels effect).

3.2 Transient analysis and frequency dependence

In Fig. 3, when the voltage is switched from 0 to 200 V (t=60 s), the output quickly decreases and then slightly rises slowly with time constant of τ_0~2 s. On the other hand, when 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. 6, where two time constants of τ_1=6.3 s and τ_2=1.0 s are obtained. Figure 7 shows the frequency dependence of the modulation. The modulation decreases with increase in frequency. From the limitation of the response time of the powermeter, the maximum measured frequency is 100 Hz in this study. The reason for these phenomena is discussed in the following section.

3.3 Model of transient behavior and frequency dependence

The model of the transient behavior of the MZI is shown in Fig. 8, (a) cross section, (b) output intensity versus electric field (E_{BST}) (c) output intensity with time, and (d) polarization versus E_{BST}. In Fig. 8(b), E_{BST} dependence of output intensity is given by Eq. (1) because $\Delta\phi$ is proportional to E_{BST} (see Fig. 5). We assume that there are some movable ions in the BST film because it is not perfectly stoichiometric [7]. (1) At initial state (V=0, $0<t<t_1$), there is no electric field and output intensity is maximum. (2) When the voltage is applied (V>0, t=t_1), the electric filed is generated and polarized charges are quickly induced, resulting in quick decay in the output intensity. (3) After that, the movable ions slowly drift to the BST/SiO$_2$ interface by the electric field in the BST layer. These ions decrease the electric field in the BST layer. Therefore, the output intensity slowly increases to steady state. The time constant τ_0~2 s (discussed in section *3.2*) may correspond to that of this ion drift. (4) When the voltage is switched to 0 V (t=t_2), the external electric field is removed. However, some interface ions and polarized charges remain for a while (Fig. 8(d)) [8], which generate an electric field in the opposite direction in the BST. As a result, the output intensity does not quickly return to the initial maximum value but increases a little at t=t_2. (5) Then, output intensity slowly increases to the initial state along with diminishing the interface charges. The measured time constants τ_1=6.3 s and τ_2=1.0 s in section *3.2* may correspond to the time constants of these ion drift and polarization relaxation. These slow response components lead to the large frequency dependence shown in Fig. 7.

The heating effect is negligible because the leak current is very small due to the thick SiO$_2$ cladding layer.

4. Conclusions

We have, for the first time, succeeded in operation of the MZI modulator made of BST deposited at 450°C on Si, and modulation of 8.8% is observed. The transient response and frequency dependence of the MZI were investigated, and a model of the transient behavior was proposed based on the movable ions and slow polarization relaxation time. Improvement of the BST film quality is essential to improve the performance. The operation voltage will be reduced by a suitable device design.

Acknowledgments

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References

[1] I. Hayashi, Jpn. J. Appl. Phys. **32** (1993) 266.
[2] M. Suzuki *et al*., Jpn. J. Appl. Phys. **45** (2006) 3488.
[3] H. Yamaguchi *et al*., *Ext. Abst. IEEE IEDM* (1996) 675.
[4] Z. M. Xu *et al*, Appl. Phys. Lett. **88** (2006) 161107.
[5] M. Salib *et al*., *1st Int. Conf. Group IV Photonics* (2004) PLE1.
[6] H. Nishijima *et al*., *Optical Integrated Circuits,* McGraw-Hill, (1989) 286.
[7] T. Kikkawa *et al*., Appl. Phys. Lett. **81** (2002) 2821.
[8] N. Abt, *Proc. 3rd Int. Symp. Integr. Ferroelectrics* (1991) 376.
[9] Y. Kato *et al*., Oyobuturi **67** (1998) 1239 [in Japanese].

Table I Sputtering condition.

RF power	50 W
Base pressure	1.2×10^{-6} Pa
Sputtering gas	Ar : O_2 = 4 : 1
Pressure	2.0 Pa
Substrate temperature	450°C
Deposition rate	1.0 nm/min

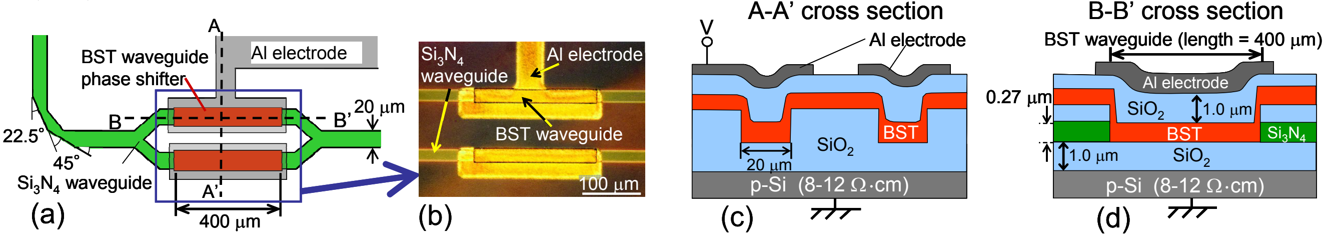

Fig. 1. (a) Schematic plan view, (b) photograph of the fabricated Mach-Zehnder Interferometer (MZI), and cross-section along (c) A-A' and (d) B-B' of Fig. 1(a). Because the optical loss of the BST waveguide is very large (470 dB/cm) [2], the Si_3N_4/BST hybrid structure is used.

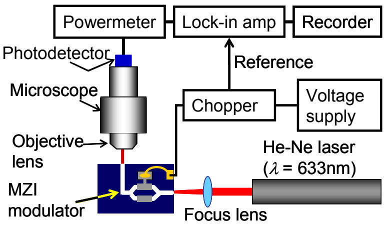

Fig. 2. Optical measurement system for MZI. For DC measurement, powermeter is directly connected to the recorder.

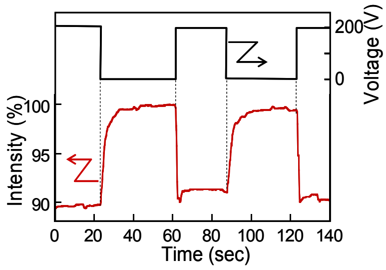

Fig. 3. Optical response of the BST MZI modulator when rectangular shape voltage is applied.

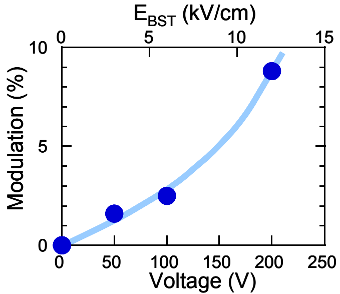

Fig. 4. Optical modulation versus applied voltage of the MZI.

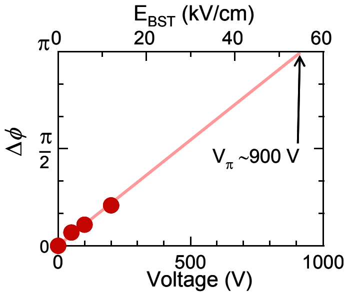

Fig. 5. Phase shift versus applied voltage of the MZI.

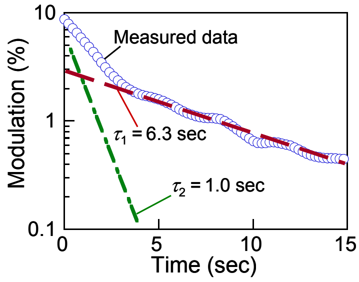

Fig. 6. Deconvolution of different time constants in the time region between 87 s and 102 s in Fig. 3.

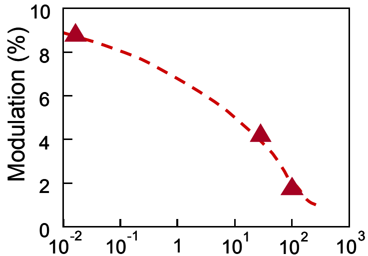

Fig. 7. Frequency dependence of optical modulation of MZI.

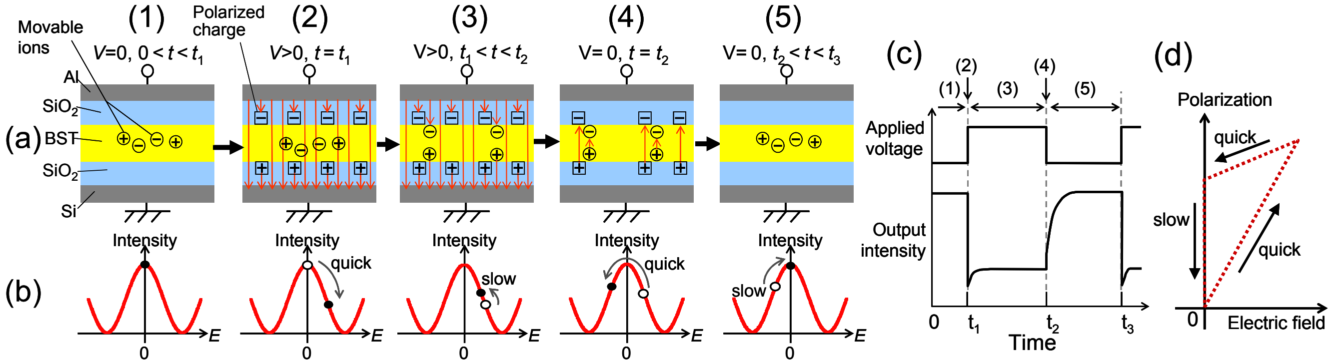

Fig. 8. Model of transient behavior of MZI. (a) Cross-section of the MZI, where arrows indicate electric field. (b) Output intensity versus electric filed in BST. (c) Optical response based on the proposed model. (d) Polarization versus electric filed in the BST. The BST film used in this study is $(Ba_{0.34},Sr_{0.4})TiO_3$, which is not ferroelectric [9].