Structural and Optical Properties of Electro-Optic Material: Sputtered $(Ba,Sr)TiO_3$

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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 interconnection. Therefore, the optical interconnection is attracting much attention as an interconnection which improves the performance of Si LSI. We have so for proposed the optical interconnection shown in Fig. 1. This system monolithically integrates the optical switches using the micro-ring resonator made of electro-optic (EO) materials (Fig. 2)[1]. Therefore, the numbers of light emitting devices on the LSI chip can be decreased. $(Ba,Sr)TiO_3$ (BST) is highly promising as an EO material because BST is ferroelectric substance and also the BST films have been already used in the memory capacitor. However, there is little report on optical properties of the BST film.

In this paper, we have evaluated structural and optical properties of the sputtered BST films. As the result, we newly found that there is strong relationship between crystallinity and optical loss.

2. Experimental

BST films were simultaneously deposited by RF magnetron sputtering on Si (100) substrates with 1.0 μm thermal SiO_2 and quartz wafers. Sputtering parameters are shown in Table I. The optical transmission of BST films on quartz substrate has been studied using a double beam spectrophotometer. The structural property of BST films were analyzed by X-ray diffraction (XRD). Waveguides using BST film on SiO_2 layer was fabricated by lithography and wet etching in buffered HF. The light propagation loss was measured by using He-Ne laser (λ=633 nm).

3. Result and Discussion

The optical transmission spectra of BST films sputtered on quartz substrates at different substrate temperature are shown in Fig. 3. From this result, the refractive index is calculated by the method reported by R. Swanepoel as shown in Fig. 4 [2]. The reflective index is necessary to design the ring resonator optical switch. The XRD spectra, peak intensity and full width at half maximum (FWHM) of the sputtered BST film on 1.0 μm SiO_2 layer are shown in Figs. 5 and 6. Figure 5 shows substrate temperature dependence and Fig. 6 shows film thickness dependence, respectively. Grain size G was calculated by using following equation

$$G = 0.94\lambda/(B \cdot \cos\theta) \qquad (1)$$

where λ is wavelength of X-ray, B is FWHM and θ is diffraction angle. In Fig. 5, the peak intensity and the grain size become lager as substrate temperature become higher. Additionally, the BST(200) peak is much lager than other peaks at 700°C. In Fig. 6 the peak intensity and grain size become larger as the BST film becomes thicker. As the film thickness increases, especially (100) and (200) orientation peaks selectively increase whereas (110) and (111) peaks saturate. The grain size calculated from FWHM is increased as the film becomes thick in the range 7-20 nm. Figure 7 shows the output power versus the length of the BST waveguide. Propagation loss of waveguide is ranging from -14 dB/cm to -31 dB/cm. Figure 8 shows relationship between propagation loss and the XRD peak intensity of BST(200). This figure indicates that propagation loss decreases with increasing the XRD peak intensity.

The models of propagation loss are shown in Fig. 9. The BST film is polycrystalline, therefore the light is scattered by grains as shown in Fig. 9(a). The XRD peak intensity increases with grain density. Therefore, increase in the propagation loss (Fig. 8) may be due to the light scattering by grains. On the other hand, the grain size increases with increase in XRD peak intensity (Figs. 5 and 6). The increase in grain size may reduce the scattering probability of the light, resulting in reduction of optical loss. However, in the experiment, the optical loss increases with increasing the grain size (Figs. 5 and 6). This means that the contribution of the increase in grain density may overcome the effect of the enlargement of the grain size. Furthermore, surface roughness is also thought to be one of the origins of the optical loss (Fig. 9(b)).

4. Conclusions

We have, for the first time, evaluated the optical properties of elect-optic material BST. It is newly found that when the crystallinity of BST film becomes better, the optical loss increases. This phenomenon can be explained by the increase in the grain density. In order to reduce the grain density and enlarge the grain seize, the laser annealing may be effective.

Acknowledgement

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References

[1] Y. Tanushi *et al.*, 1st int. Conf. on Group IV Photonics, WB3 (Hong Kong, 2004).
[2] R. Swanepoel, J. Phys. E **16**, 1214 (1983).

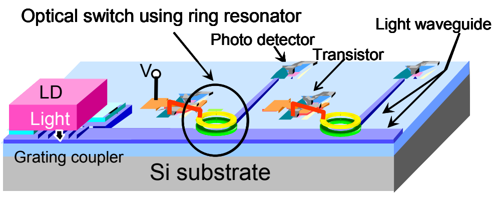

Fig. 1 Schematic of optical interconnection using ring resonator optical switches.

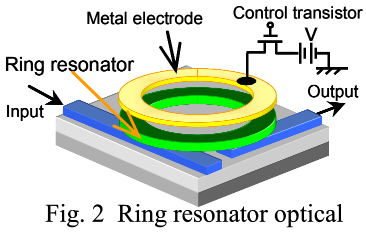

Fig. 2 Ring resonator optical switch made of EO materials

Table I sputtering parameter.

RF power	50 W
Base pressure	1.2×10^{-6} Pa
Sputtering gas ratio	$Ar : O_2 = 4 : 1$
Pressure	2.0 Pa
Substrate temperature	23-700°C
Sputtering rate	1 nm/min

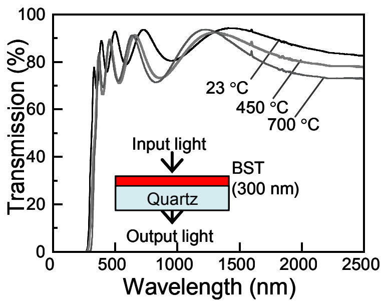

Fig. 3 Optical transmission spectra of BST films sputtered on quartz substrates at different temperatures.

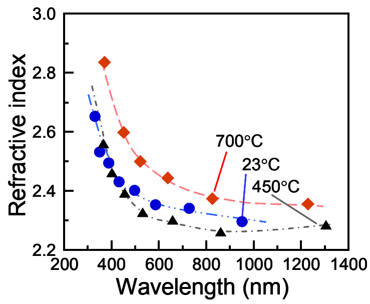

Fig. 4 Refractive index of BST films sputtered on quartz substrates calculated from optical transmission spectra .

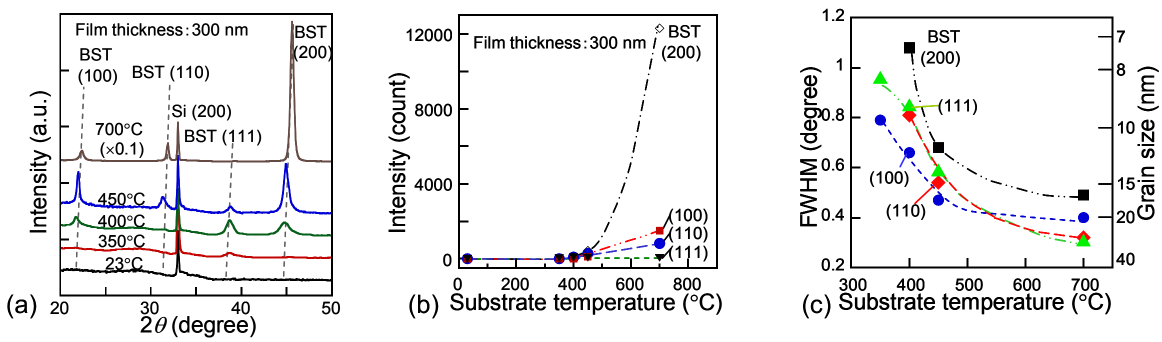

Fig. 5 (a)XRD spectra , (b)peak intensity, (c)grain size and FWHM of BST film sputtered on 1.0 μm SiO_2 layer at different temperatures.

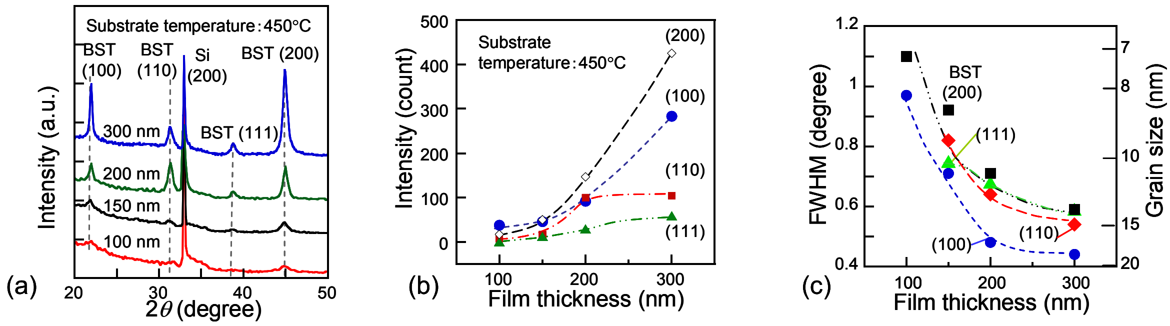

Fig. 6 (a)XRD spectra , (b)peak intensity, (c)grain size and FWHM of BST film sputtered on SiO_2 of varied thickness.

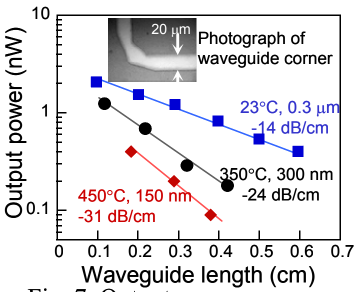

Fig. 7 Output power versus waveguide length. (λ=633 nm)

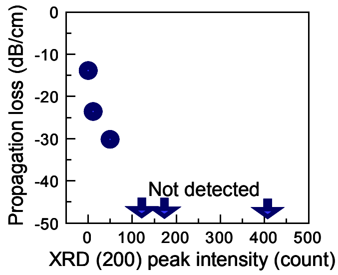

Fig. 8 Propagation loss versus XRD peak of BST(200).

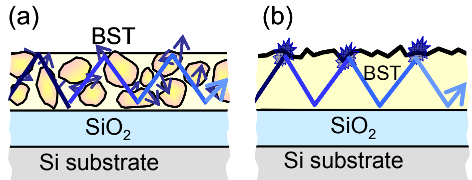

Fig. 9 Model of light propagation loss, (a)grain scattering model, and (b)surface scattering model.

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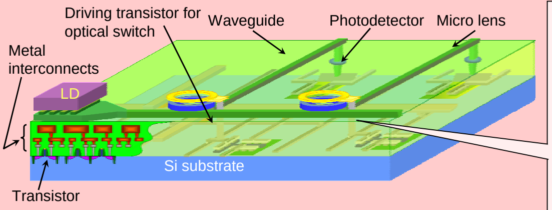
Introduction

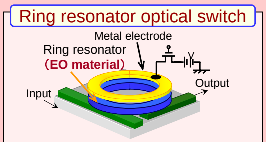
Target

LSI with optical global interconnection instead of metal interconnection



- Optical waveguides are monolithically integrated on LSI top layer.
- Optical signals are controlled by optical switches not by LD or LED.
- Ring resonator optical switch is made of electro-optic (EO) material.

Ring resonator optical switch



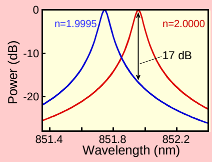
Resonant wavelength light is coming out.

Shift of resonant wavelength

$$\Delta\lambda = 2\pi R \cdot \Delta n_{eff} = 2\pi R \cdot \left(-\frac{1}{2} n^3 r E\right)$$

r : EO coefficient, R : ring radius, n: refractive index, E: electric field.

Simulation result



Waveguide width 2 μm
Ring radius 12 μm
Gap width 0.1 μm

Gain=17dB at Δn_{eff} =5x10^{-4}

Why BST?

- High EO coefficient
- BST have been already used as an dielectric film of the memory capacitors.

Object

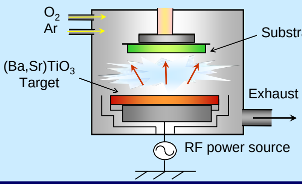
Evaluation of sputtered BST

Structural properties
- Crystallinity and orientation
- Surface roughness

Optical properties
- refractive index
- propagation loss

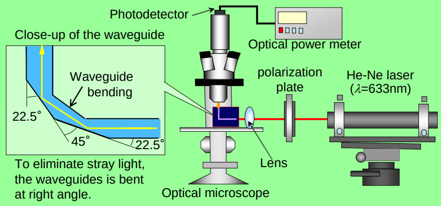
Experimental

Sputtering



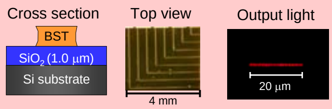
Parameter

RF power	50 W
Base pressure	1.2×10^{-6} Pa
Sputtering gas ratio	Ar : O_2 = 4 : 1
Pressure	2.0 Pa
Substrate temperature	23-700°C
Sputtering rate	1 nm/min



To eliminate stray light, the waveguides is bent at right angle.

Fabricated waveguide

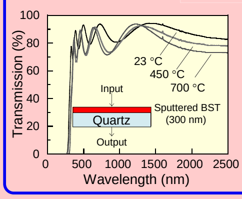


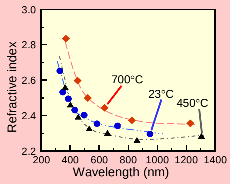
Photolithography and wet etching in HF

Results and discussion

Optical properties

Optical transmission measurement



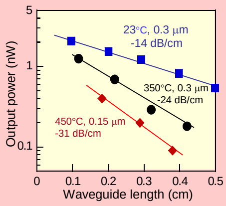


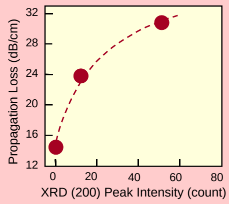
Refractive index calculation

$$n(\lambda) = \frac{m\lambda}{2d}$$

n : Refractive index, λ : Wavelength, d : Film thickness, m = 1,2,3・・・・

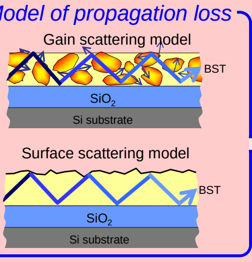
Propagation characteristics of BST Waveguides



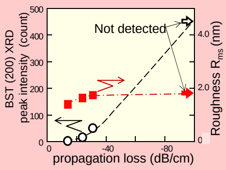


The propagation loss rapidly decreases with increasing the XRD peak intensity.

Model of propagation loss



Surface roughness dependence

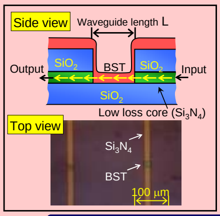


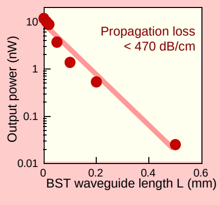
Grain scatter model is more reasonable.

Evaluation for high loss waveguide

Newly developed waveguide structure for high loss core material

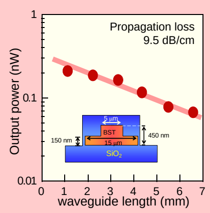
Two kinds of core material are serially contacted in horizontal direction.





High loss waveguide can be evaluated.

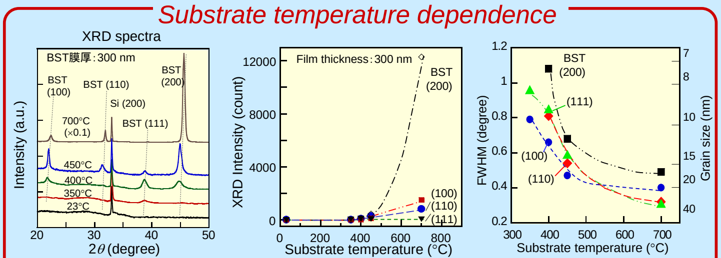
Ever lowest loss waveguide



Structural properties

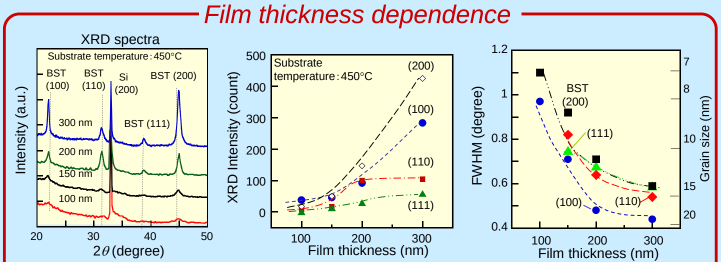
Crystallinity and orientation of sputtered BST film were measured by X-ray diffraction (XRD)

Substrate temperature dependence



- The peak intensity and the grain size become lager as substrate temperature become higher.
- The BST(200) peak is much lager than other peaks at 700°C.

Film thickness dependence



- The peak intensity and grain size become larger as the BST film becomes thicker.
- As the film thickness increases, (100) and (200) orientation peaks selectively increase whereas (110) and (111) orientation peaks saturate.

Summary

- Structural and optical properties of sputtered BST film are evaluated
- When the crystallinity of BST film becomes better, the optical loss increases.
- This phenomenon may be explained by the polycrystalline nature of BST.
- High loss waveguide can be measured propagation loss by combining Si_3N_4 and BST.