I-1-4

Extended Abstracts of the 2009 International Conference on Solid State Devices and Materials, Sendai, 2009, pp202-203

Reducing Operation Voltage of Silicon-Ring Optical Modulator Using High-*k* Cladding Layer

Yoshiteru Amemiya, Mizue Nishida, Hao Ding, Masataka Fukuyama, and Shin Yokoyama

Research Institute for Nanodevice and Bio Systems, Hiroshima University
1-4-2 Kagamiyama, Higashihiroshima, Hiroshima 739-8527, Japan
Phone: +81-82-424-6265, FAX: +81-82-424-3499, E-mail: yokoyama-shin@hiroshima-u.ac.jp

1. Introduction

Signal delay and power consumption in metal interconnection are serious problems to limit performance of large scale integrated circuits (LSIs). Optical interconnection is one of the promising methods to overcome this problem. Optical modulator is a key device for the optical interconnection. We have investigated the electric-field drive Si ring optical modulator [1], where the carrier concentration in Si ring resonator is controlled by applied voltage and resonance wavelength is changed. However, the operation voltage is still too high (> 1000 V) [2], because the cladding layers consist of SiO_2 whose dielectric constant (3.9) is much lower than Si (11.9). In this study, to reduce the operation voltage, $(Ba,Sr)TiO_3$ (BST) film, which is high–*k* dielectric film (dielectric constant of ~400), is used for thecladding layer (Fig. 1).

2. Experimental

The ring resonators shown in Figs. 1 and 2 were fabricated by the following process. By electron-beam lithography and reactive ion etching, silicon-on-insulator wafer was patterned and Si ring resonators were fabricated. Next, the 150 nm thick patterned Pt electrodes were made by lift-off process, where Pt electrodes are used for seed layer of lateral epitaxy of BST film. Then the 350 nm thick BST cladding layer was deposited by RF magnetron sputtering. After the contact holes are formed by buffered HF acid solution, 500 °C N_2 annealing was carried out to crystallize the BST film. The optical measurement setup is shown in Fig. 3. The light source is infrared tunable semiconductor laser. The optical intensity of output light is detected by the InGaAs detector.

3. Results and Discussion

3.1 Dielectric constant of BST and operation voltage

Operation voltage versus dielectric constant of cladding layer is simulated by using Poisson's equation and optical simulator with finite difference method, and the result is shown in Fig. 4. The operation voltage increases with increasing the dielectric constant of the cladding layer. Figure 5 shows the sample structure to evaluate lateral epitaxy of BST, where the BST film deposited on the patterned Pt film is laterally crystallized after annealing. Figure 6 shows the anneal temperature dependence of the dielectric constant of BST film. The lateral epitaxy method results in the crystallization at lower anneal temperature (450°C) compared with other anneal methods and the maximum dielectric constant of 170 is obtained. For this dielectric constant (170) and quality factor of $5x10^4$, the operation voltage less than 10 V is possible (see Fig. 4).

3.2 Performance of optical modulator with BST clad

Figure 7 shows the resonance characteristics of the fabricated Si ring modulator with BST clad. The resonance characteristics are changed by applying voltage as shown in Fig. 8. The peak intensity is decreased by the light absorption and the resonance wavelength is shortened both by due to the carriers induced in Si. The voltage dependence of these characteristics is summarized in Fig. 9. An example of optical modulation by the applied voltage is shown in Fig. 10, where the input light wavelength is fixed at 1498.9 nm (resonance peak at 0 V). The 75% modulation is obtained at 125 V. In the previous device with SiO_2 clad, the operation voltage was 1000 V for the 60% modulation. Therefore, less than 1/8 reduction of the operation voltage is achieved as shown in Fig. 11. Figure 12 shows calculated quality factor of ring resonator versus propagation loss of BST clad as a parameter of coupling constant between ring and input/output waveguides. For our deposition method, the propagation loss of the crystallized BST is reported to be 250-470 dB/cm [3] and the quality factor is estimated to be 4000-8000 (the measured value 6700 is reasonable). To obtain the quality factor larger than $5x10^4$ (necessary for operation voltage < 10 V), the loss of cladding layer must be less than 28 dB/cm. These target values are achievable when the high quality $Pb(Zr,Ti)O_3$ (PZT) film (the dielectric constant is almost same as BST) with low optical loss (22 dB/cm) formed by aerosol deposition method [4] is used for the cladding layer.

4. Conclusion

We have achieved to reduce the operation voltage of the Si ring modulator to < 1/8 by employing $(Ba,Sr)TiO_3$ film as the cladding layer compared with SiO_2 clad. Also it is estimated that the operation voltage less than 10 V will be achievable when the light propagation loss of the cladding layer is improved to less than 28 dB/cm and the quality factor larger than $5x10^4$ (both are realistic).

Acknowledgements

This work was supported in part by a Grant-in-Aid for Scientific Research (B) (No. 17360166) from the Ministry of Education, Culture, Sports, Science and Technology of Japan.

References

[1] Y. Amemiya *et al*., to be published in Opt. Rev. **16** (2009).
[2] Y. Amemiya *et al*., Ext. Abst. (69th Autumn Meet. 2008) Jpn. Soc. of Appl. Phys., 2p-ZN-7 [in Japanese].
[3] M. Suzuki *et al*., Jpn. J. Appl. Phys. **45**, 3488 (2006).
[4] M. Nakada *et al*., J. Crys. Growth **275**, 1275 (2005).

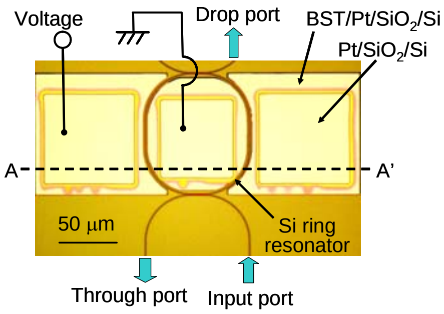

Fig. 1 Typical example of optical micrograph of fabricated Si ring modulator.

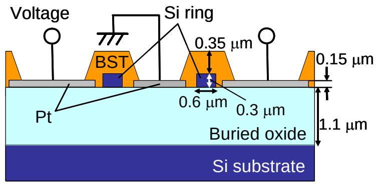

Fig. 2 A-A' cross sectional schematic structure of Si ring optical modulator.

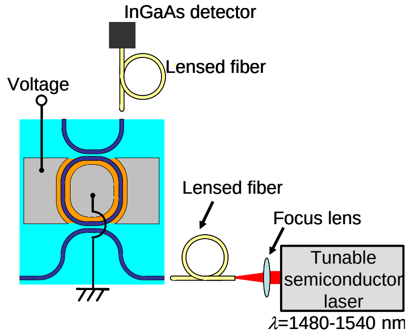

Fig. 3 Measurement setup for characterization of Si ring optical modulator.

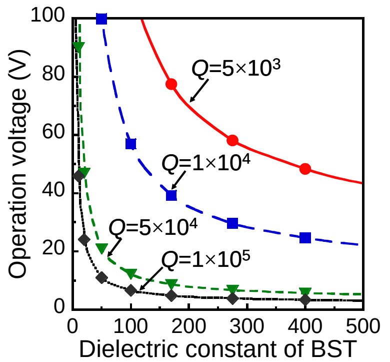

Fig. 4 Calculated operation voltage at 90 % (10 dB) modulation versus dielectric constant of cladding layer.

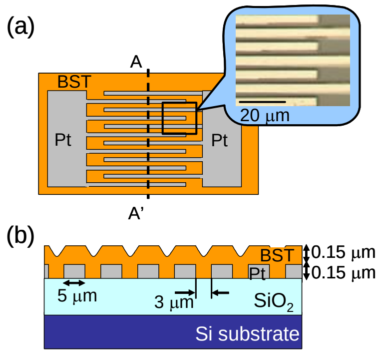

Fig. 5 (a) Schematic plan view and optical micrograph, and (b) A-A' cross section of (a) for lateral-epitaxy sample.

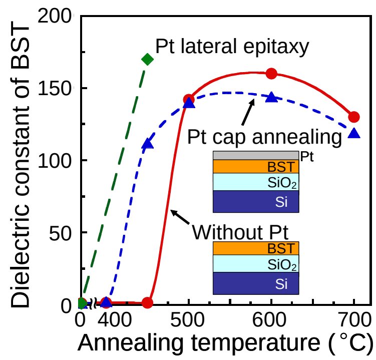

Fig. 6 Annealing temperature dependence of dielectric constant of BST films for three kinds of methods.

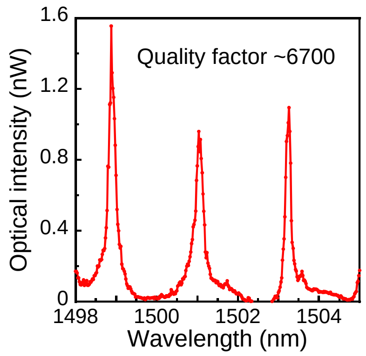

Fig. 7 Resonance characteristics of the fabricated optical modulator with BST clad. The quality factor is about 6700.

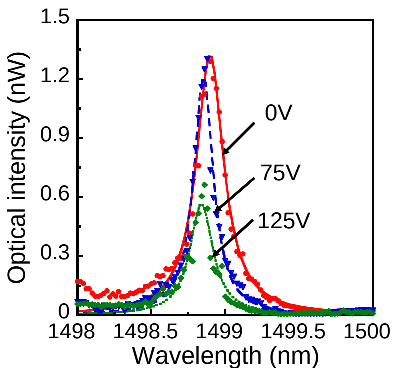

Fig. 8 Resonance characteristics as a parameter of applied voltage.

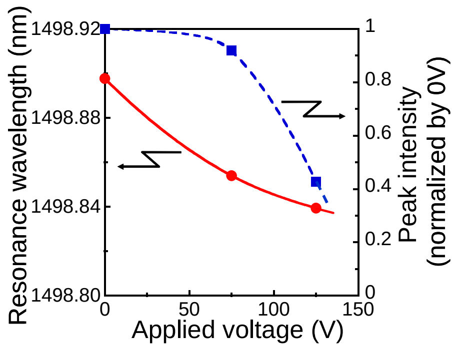

Fig. 9 Applied voltage dependence of resonance wavelength and peak intensity.

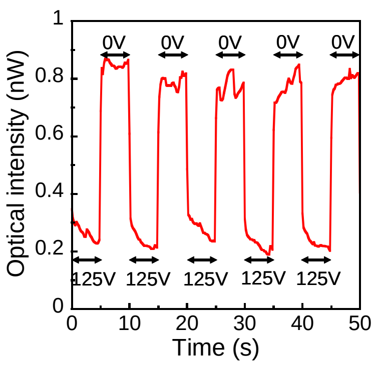

Fig. 10 Optical output intensity at applied voltages of 125 V and 0 V. Modulation is ~75 %.

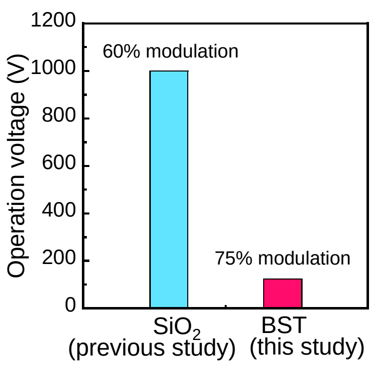

Fig. 11 Operation voltages at 60 % modulation for SiO_2 clad and 75 % modulation for BST clad.

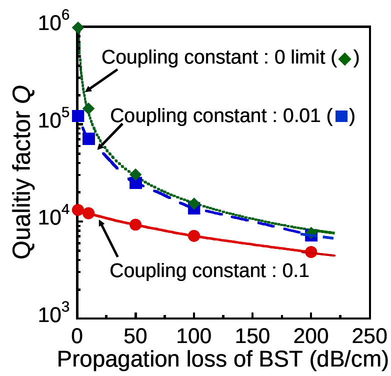

Fig. 12 Calculated quality factor of ring resonator with BST clad vs propagation loss as a parameter of coupling constant.