Status of Research on Optical Interconnection in LSI

Shin Yokoyama

Research Center for Nanodevices and Systems, Hiroshima University
1-4-2, Kagamiyama, Higashi-Hiroshima, Hiroshima, 739-8527, Japan
Phone: +81-82-424-6266, FAX: +81-82-424-3499, E-mail: yokoyama@sxsys.hiroshima-u.ac.jp

1. Introduction

In the state-of-the-art LSI, the signal delay in the global metal interconnection limits the processing speed of the LSI. In order to overcome this problem we are studying optical interconnection in LSI. Our research target is to realize the compact ring-resonator optical switches using electro-optic (EO) and magneto-optic (MO) materials or Si, which can be monolithically integrated in LSI (Figs. 1-3). In order to realize the optically interconnected LSI as shown in Fig. 1, we are studying wide range of researches from optical switches to photodetectors.[1-5]

2. Optical switches using electro-optic material

Concerning the operation speed, we have found from the simulation that the speed of the ring resonator switches using EO materials is limited by the resonation time[6] and is more than 40 GHz (Fig. 4), which is faster about one order of magnitude than Si optical modulator switch.[7] Also the size of the ring resonator switch is very small compared with the Mach Zehnder modulator and is suitable for integration in LSI.

In monolithic fabrication of the optical switches using EO materials on LSI, it is important to realize the small optical loss and high electro-optic constant. Figure 6 shows the relation between optical loss and crystallinity evaluated by the (200) x-ray diffraction peak of the $(Ba,Sr)TiO_3$ (BST) film deposited by RF sputtering and metal organic decomposition (MOD). The MOD film has smaller optical loss and higher crystallinity than sputtered film. In order to evaluate the electro-optic constant of the BST film, we have fabricated Mach Zehnder (MZ) interferometer as shown in Fig. 7 by using sputtered and MOD BST films. And we have, for the first time, succeeded in observing the optical modulation in BST MZ modulator as shown in Fig. 8. The instability of the input He-Ne laser power and noise is smaller than the modulation amplitude (Fig. 9). The electro-optic constant calculated from the result in Fig. 8 is γ=0.45 pm/V which is about 1/100 of the single crystal $LiNbO_3$. Although the modulation efficiency observed in this study is very small, it is meaningful that the operation of the optical modulation using monolithically integrated device is demonstrated.

3. Optical switches using Si ring resonator

We are also studying the optical switches using Si ring resonator. Qianfan Xu *et al.* reported the operation of the Si ring resonator switches operating at 1.5 Gb/s.[8] We employed the stack type structure, in which the coupling efficiency between the ring and the waveguide is more precisely controlled than the plane type ring resonators (Fig. 9).

4. Optical switches using magneto-optic material

We have proposed the ring resonator optical switches using magneto-optic (MO) materials. The structure is shown in Fig. 3. From the simulation we have found that the resonance peak splits to double peaks by applying the magnetic field (Fig. 10). The switching gain more than 10 dB can be obtained when Bi substituted $Y_3Fe_5O_{12}$ film is used. The interesting finding is that the polarizer is not necessary although the usual magneto-optic devices needs the polarizer. Now we are studying the Bi substituted $Y_3Fe_5O_{12}$ film deposition by means of RF sputtering.

5. Integration of photodetectors

Integration of high-speed photodetectors is necessary to realize the LSI with optical interconnection. When the EO material is used, it is acceptable to use the visible light. Then Si photodetectors are available. But for the MO materials or Si light modulators, the infrared light is necessary, then the SiGe photodetectors are necessary. We have designed and fabricated Si *pin* photodetectors as shown in Fig. 11 with cooperation with Prof. Miura in this COE group. Although the simulated operation speed is in the order of 10 GHz, the fabricated device exhibited the slower speed of 300 MHz. The reason of the slow speed may be the degraded *p/i* or *i/n* junctions. We are now trying to clear the reason.

Conclusions

We have, for the first time, demonstrated the light modulation by using the BST MZ interferometer monolithically integrated on Si substrate. The status of the research on other optical devices such as stack type Si ring resonator switches, ring MO resonator switches and integrated Si *pin* photodetectors are described.

References

[1] Y. Tanushi *et al.*, Abst. Int. Conf. on Solid State Devices and Materials (SSDM2005). [2] M. Suzuki *et al.*, ibid. [3] Zhimou Xu *et al.*, ibid. [4] T. Tabei *et al.*, ibid. [5] S. Yokoyama and T. Kakite, ibid.
[6] Y. Tanushi *et al.*, 1st Internat. Conf. on Group IV Photonics (Hong Kong, China, Sept. 29-Oct. 1, 2004) WB3.
[7] A. Lim *et al.*, NATURE, **427**, Feb. 12, 2004, 615.
[8] Qianfan Xu *et al.*, NATURE, **435**, May 19, 2005, 325.

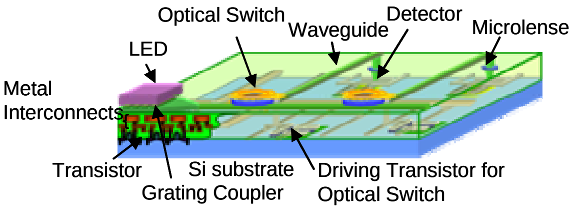


Fig. 1 LSI with optical interconnection, which operates at >10 GHz and is the target of this research.

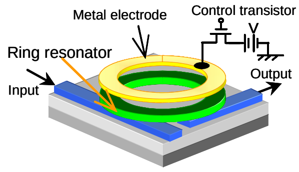


Fig. 2 Ring resonator type optical switch using electro-optic material.

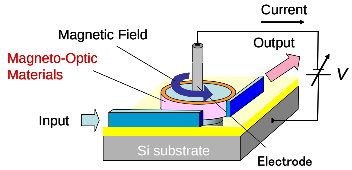


Fig. 3 Optical switch using ring resonator and magneto-optic material.

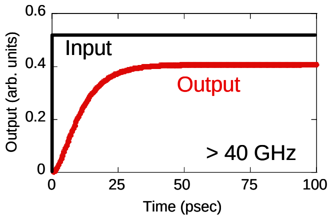


Fig. 4 Simulated switching characteristics of the ring resonator switch using electro-optic material ($LiNbO_3$).

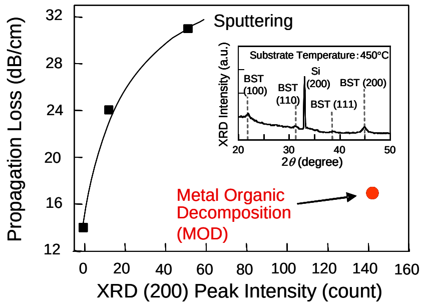


Fig. 6 Relation between optical loss and crystallinity of $(Ba,Sr)TiO_3$ (BST) films fabricated by sputtering and metal organic decomposition (MOD).

(a)

(b)

(c)

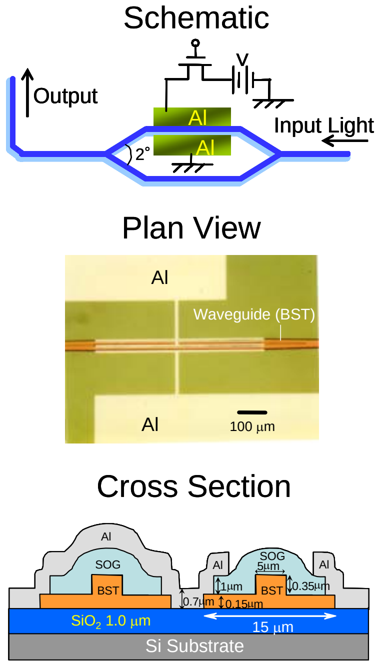
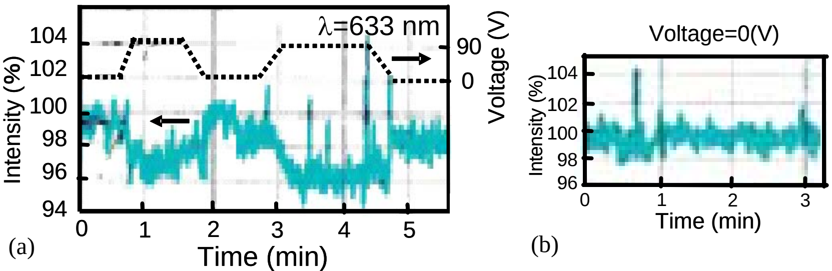


Fig. 7 Fabricated Mach Zehnder interferometer, (a) schematic, (b) optical micrograph, and (c) cross section.



(a) (b)

Fig. 8 Observed optical modulation characteristics of the fabricated Mach Zehnder interferometer using MOD BST film, (a) effect of the applied bias voltage, and (b) stability of the output light intensity when bias voltage=0 V. The change in the output intensity, when 90 V of bias voltage is applied, is larger than the noise and instability of the input laser power.

(a)

(b)

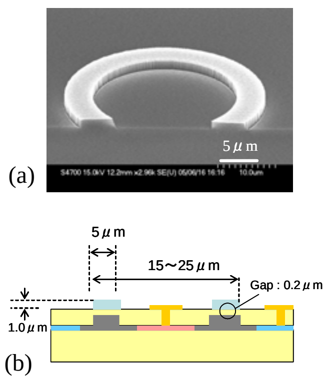


Fig. 9 Stack type Si ring resonator switch which is under fabrication, (a) scanning electron microscope (SEM) picture and (b) cross section.

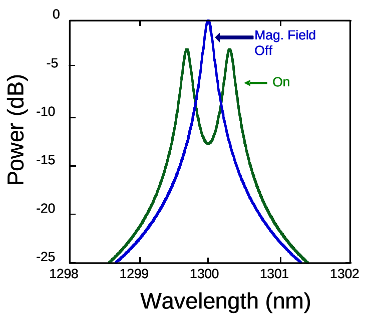


Fig. 10 Resonance characteristics of the ring resonator using MO material (Bi substituted $Y_3Fe_5O_{12}$) without polarizer. The resonance peak splits to double peaks by applying magnetic field.

(a)

(b)

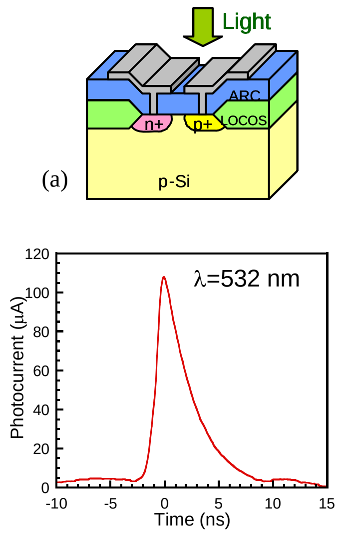


Fig. 11 (a) Structure of the fabricated *pin* photodetector and (b) response characteristics.

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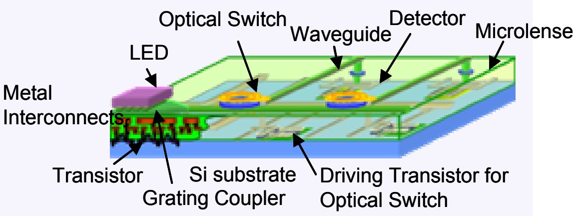
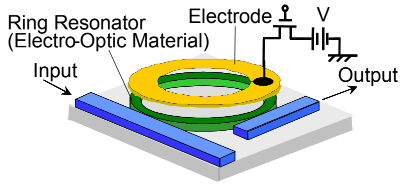
1. Target System: Optically Interconnected LSI

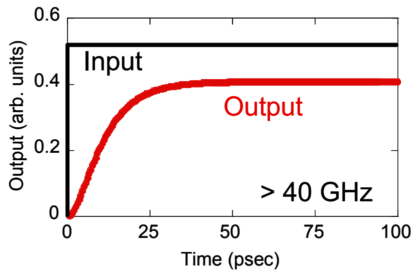


2. Optical Switch using Ring Resonator with Electro-Optic Material

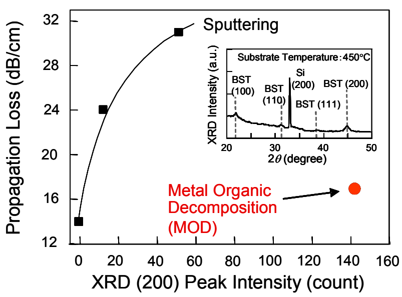


- Monolithically Integrated on Si LSI.
- Compact (a few tens of μm)
- High speed (∼100 GHz)

Simulated Switching Speed



Propagation Loss vs Crystal Structure of $(Ba,Sr)TiO_3$

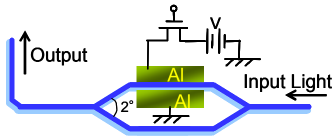


High crystallinity results in largege loss.
MOD film is better than sputtered one.

Mach Zehnder Optical Switch

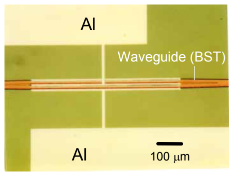
Schematic

(a)



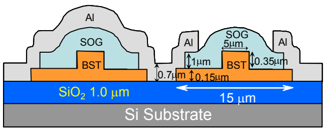
Plan View

(b)

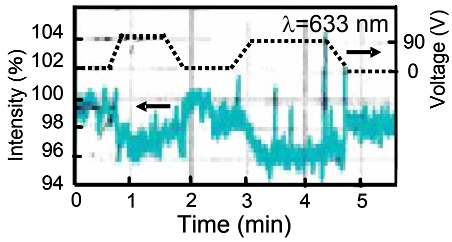


Cross Section

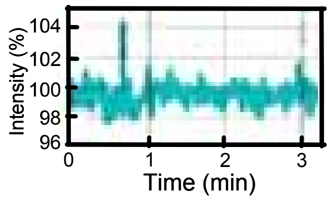
(c)



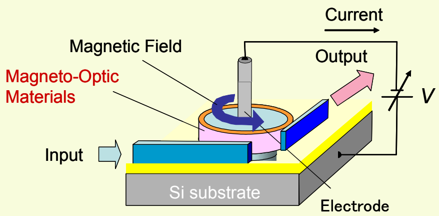
First Demonstration of Operation of EO Devices Monolithically Integrated on Si



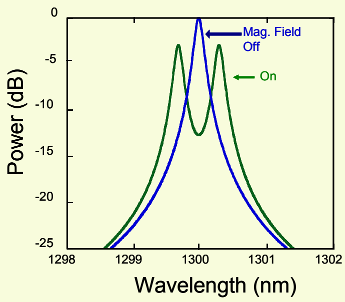
Voltage=0(V)



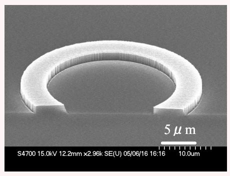
3. Optical Switch using Ring Resonator with Magneto-Optic Material

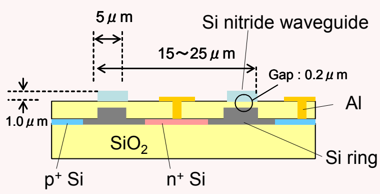


Simulated resonance characteristics using MO material (Bi substituted $Y_3Fe_5O_{12}$) without polarizer.
The merit of this ring switch is that the polarizer is not necessary.

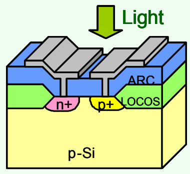


4. Optical Switch using Si Ring Resonator (stack type)

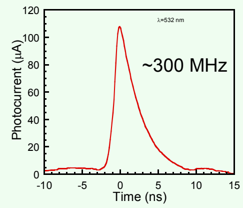




5. Si *pin* Photodetectors



Example of pulse response of fabricated detector (~300 MHz).



6. Summary

Following three kinds of ring resonator optical switches are under developing.
1) Electro-optic (EO) type
2) Magneto-optic (MO) type
3) Si type
We have, for the first time, succeeded in demonstrating optical switch operation of EO device (Mach Zehnder Interferometer) monolithically integrated on Si.
High-seed Si *pin* photodetectors are also studied and now being improved.