Extended Abstracts of the 2010 International Conference on Solid State Devices and Materials, Tokyo, 2010, pp1076-1077

# Design and Simulation of Silicon Ring Optical Modulator with p/n Junctions along Circumference

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## 1. Introduction

Global metal interconnection limits the performance of large scale integrated circuits (LSIs) because of its signal delay and power consumption. Our target is optical interconnection in LSI, which is one of the promising methods toward the further high performance LSI. Optical modulator is a key device and we have investigated the electric-field drive Si ring optical modulator using metal-oxide-semiconductor (MOS) type Si ring resonator [1], where the carrier concentration in Si ring resonator is controlled by applied electric-field and optical modulation is achieved.

For the optical interconnection in LSI, the low operation voltage of optical modulator is necessary with shrinking the transistor size. In order to improve the performance, we propose the optical modulator with p/n junctions along the circumference of the ring resonator as shown in Fig. 1. At no voltage, Si ring resonator consists of p- and n-type neutral regions, and short depletion regions. By applying reverse bias, the depletion regions expand and total refractive index is changed, and the optical modulation is achieved. When whole ring regions are depleted, which is most ideal case, the highest optical modulation is expected.

In contrast, the previously reported Si ring optical modulator as shown in Fig. 2 uses the p/n junction crossing the ring whose width is only 0.3 μm [2]. When the junction boundary is in the core region and carrier concentration is higher than $2\times10^{17}$ cm$^{-3}$, the high operation voltage of ~10 V is required to expand the total initial depletion region [which is sum of p- and n-type depletion regions, ~90 nm (see Fig. 3)] to the whole core width. This problem can be solved for our proposed structure (now under patent application), because widths of p- and n-type region, $W_p$ and $W_n$, are determined arbitrary. The detailed structure of the proposed Si ring optical modulator with p/n junctions is shown in Figs. 4 and 5.

## 2. Simulation Setup

For the simple simulation, the p/n junction is treated as the abrupt junction and the rectangular approximation of the space charge distribution is used and high dose region is separated from the core region enough to ignore the optical loss by the electrodes. There exist three different refractive index regions, (1) neutral p-type, (2) neutral n-type, and (3) depletion regions. In taking the refractive index change by free carrier into the consideration [3], the effective refractive indices of Si rib waveguides in three different regions are simulated by the finite difference method (Apollo Photonic Solutions Suite). The optical modulation is calculated by using these simulated refractive indices.

## 3. Results and Discussion

The simulated effective refractive index of Si waveguide with each carrier concentration is shown in Fig. 6, where the width, central rib height and thickness of the high dose region are 0.35 μm, 0.3 μm and 0.05 μm, respectively (see Fig. 5).

Optical modulation is calculated using quality factor $Q$, assuming the resonance spectrum is expressed by the Lorentzian function. The relation between the quality factor $Q$ and the propagation loss is shown by Fig. 7, where the circumference length of the ring resonator is 125 μm, i.e., the radius of 20 μm. When coupling constant between the ring and input waveguide is zero limit, the quality factor does not depend on the circumference length, and is given by

$$Q \sim \frac{2\pi n_{\mathrm{eff}}}{\alpha\lambda_{\mathrm{res}}}$$

where $\alpha$, $\lambda_{\mathrm{res}}$ and $n_{\mathrm{eff}}$ are carrier absorption coefficient, resonance wavelength and effective refractive index, respectively [4]. In this condition, the optical modulation can be calculated by only the simulated result in Fig. 6. Figure 8(a) shows thus calculated result at 1 V, where the widths of p- and n-type regions, $W_p$ and $W_n$, are 2 times of the depletion width at 1 V, $W_D$(1V). In this case, all Si ring regions are depleted and the highest modulation is obtained at 1 V. The modulation > 95% seems to be possible for higher carrier concentration > $5\times10^{18}$ cm$^{-3}$ even if the propagation loss is > 100 dB/cm. However, it is not realistic because the width of p- and n-type region is less than 32 nm (see Fig. 3).

For more realistic case that the widths of p- and n-type regions, $W_p$ and $W_n$, are set to be 150 nm, the calculated result is shown in Fig. 8(b). To obtain a modulation larger than 95%, propagation loss less than 5 dB/cm is necessary for $1\times10^{17}$-$5\times10^{17}$ cm$^{-3}$ carrier concentration. For $1\times10^{18}$ cm$^{-3}$, near 90 % modulation is possible when the propagation loss is less than 2 dB/cm. Since the 2 dB/cm waveguide loss is a reported realistic value [5], 90% modulation is possible for $1\times10^{17}$-$1\times10^{18}$ cm$^{-3}$ carrier concentration. For $5\times10^{18}$ cm$^{-3}$, free carrier absorption limits the optical modulation and the modulation cannot exceed 60%.

## 4. Conclusion

We have proposed the Si ring optical modulator where p/n junctions are arranged along circumference of the ring resonator. The modulation at 1 V is simulated as a parameter of the propagation loss of Si waveguide. To obtain ~ 90% modulation at 1 V for $1\times10^{17}$-$1\times10^{18}$ cm$^{-3}$ carrier concentration, the propagation loss < 2 dB/cm is necessary, where the width of p/n region is 150 nm. Moreover, modulation > 95% is obtained when carrier concentration is $1\times10^{17}$-$5\times10^{17}$ cm$^{-3}$ and the propagation loss is < 5 dB/cm.

## Acknowledgements

This work was supported in part by a Grant-in-Aid for Scientific Research (B) (No. 17360166) and "Interdisciplinary Research on Integration of Semiconductor and Biotechnology at Hiroshima University" based on "Creation of Innovation Centers for Advanced Interdisciplinary Research Areas", Special Coordination Funds for Promoting Science and Technology, all from the Ministry of Education, Culture, Sports, Science and Technology of Japan.

## References

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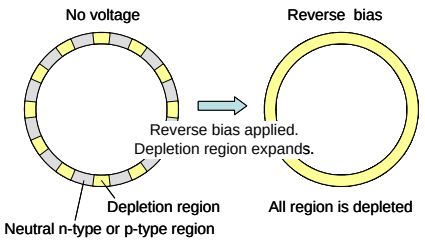


Fig. 1 Change of depletion region by the reverse bias. Refractive index of the depletion region is higher than that of the neutral region.

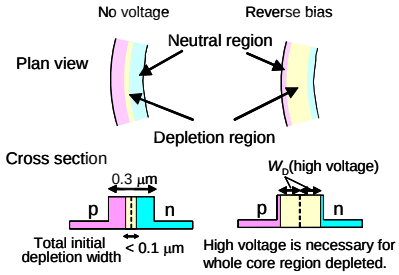


Fig. 2 Problem of the previous optical modulator using p/n junction crossing the core region.

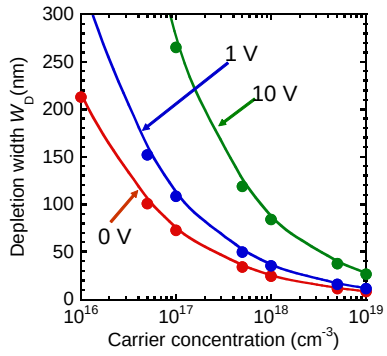


Fig. 3 Depletion width at 0, 1 and 10 V for each carrier concentration where carrier concentration in p- and n-type Si are same as each other.

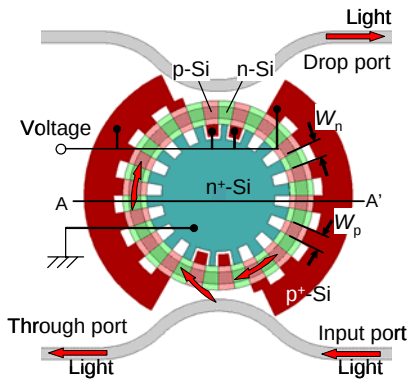


Fig. 4 Detailed structure of the proposed Si ring optical modulator with p/n junctions.

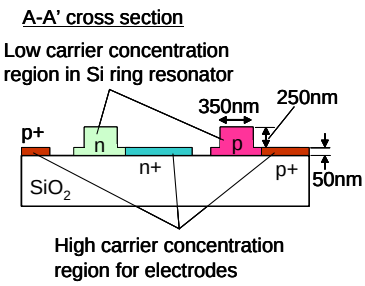


Fig. 5 A-A' cross sectional schematic structure of Si ring optical modulator shown in Fig. 4.

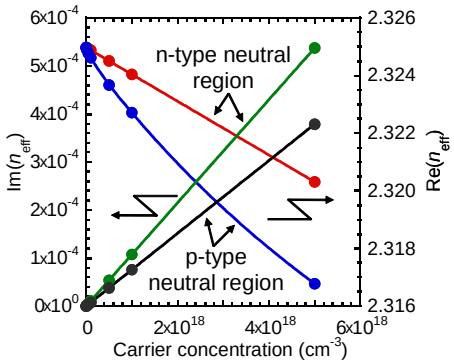


Fig. 6 Simulated effective refractive index for different carrier concentration.

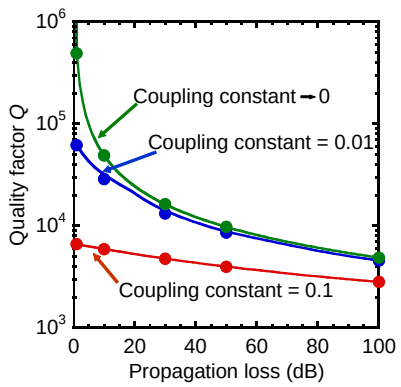


Fig. 7 Calculated quality factor of ring resonator versus propagation loss as a parameter of coupling constant.

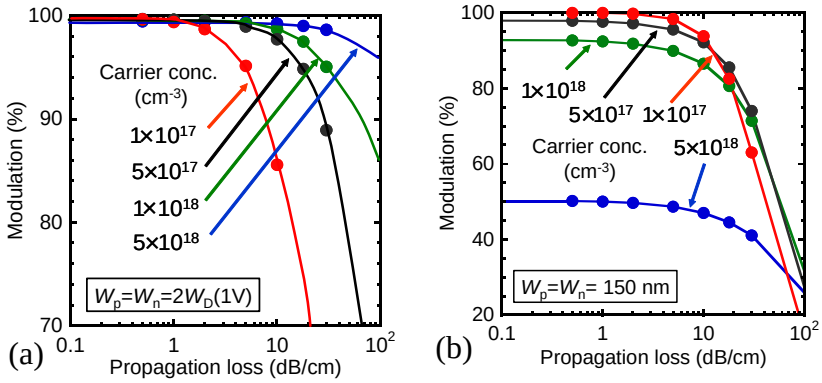


Fig. 8 Propagation loss dependence of optical modulation as a parameter of carrier concentration of p- and n-type regions at the width of p- and n-type regions being (a) 2 times of the depletion width at 1 V, $W_D$(1V), and (b) 150 nm.