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Low-operation Voltage and High-speed Silicon Ring Optical Modulator with p/n Junctions along Waveguide

Yoshiteru Amemiya, Ryuichi Furutani, 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

Optical interconnection in LSI is one of the promising methods toward the further high performance LSI, because of the advantages, high-speed signal transmission and low power consumption. We have investigating optical modulator, which is a key device of optical interconnection [1, 2]. The low operation voltage of optical modulator is necessary with shrinking the transistor size. For the reduction of the operation voltage, we propose the optical modulator with p/n junctions along the ring waveguide as shown in Fig. 1. Si ring resonator consists of p- and n-type neutral regions and depletion regions. The length of depletion regions in Si ring resonator is controlled by reverse bias, and optical modulation is achieved. The advantage of our proposal modulator is arbitrary determination of lengths of p- and n-type region, l_p and l_n, so that the modulation is high at low applied voltage. In this paper, we evaluate the modulation and switching speed of this modulator by simulation. The preliminary experimental performance of the fabricated device is also reported.

2. Experimental

The optical modulator shown in Fig. 1 was fabricated by using silicon-on-insulator wafer. Firstly, the patterns of waveguides and ring resonator were made by electron-beam lithography and reactive ion etching (Fig. 2). Next, p- and n-type regions were formed by electron-beam lithography and ion-implantation. The SiO_2 upper cladding layer was deposited by atmospheric pressure chemical vapor deposition. Finally, Al electrodes were fabricated after contact hole wet etching. The optical measurement setup consists of the infrared tunable semiconductor laser and the InGaAs detector.

3. Results and Discussion

3.1 Simulated modulation and switching speed

Optical modulation is calculated using the simulated effective refractive index of waveguide and quality factor Q which is related to the propagation loss by carrier absorption. The simulated device structure is as follows: the width, central rib height and thickness of the slab layer are 0.35 μm, 0.3 μm and 0.05 μm, respectively (Fig. 3). Total switching speed is decided by *RC* delay and lifetime of light circulating in ring resonator (cavity photon lifetime) which is related to Q. *RC* delay is calculated by capacitance of p/n junctions and resistance of low carrier concentration regions (see Fig. 3). Figure 4 shows carrier concentration dependence of simulated modulation at 1 V and switching speed. Here each length of p- or n-type region (sum of neutral and depletion regions) is four times of the length of depletion region at 1 V (l_D(1V)). In this case, half of Si ring regions are depleted. Moreover, for realistic condition, modulation is calculated by including realistic propagation loss 2 dB/cm [3] except for carrier absorption loss. It is found that carrier concentration ~$1x10^{18}$ cm^{-3} results in best condition, where modulation is over 90 % and switching speed is ~ 12 GHz. At high carrier concentration, the *RC* delay is neck for switching speed. In order to obtain the further high speed modulation, lengths of p- and n-type regions are expanded and series resistance connected to the p/n junction (indicated by in Fig. 3) is reduced. Figure 5 shows simulated modulation and switching speed as a function of length of p-type and n-type regions at fixed carrier concentration of $1x10^{18}$ cm^{-3}. Over 30 GHz is obtained at length, ~ 0.4 μm, but modulation is about 50%. Table I is summary of performances of our proposal modulator compared with other researcher's modulator. The most advantage of our device is low operation voltage (1 V), much lower than other works [4].

3.2 Preliminary experimental performance of fabricated device

We have checked p/n junction by measuring capacitance of test pattern, because depletion regions are important in our device. The capacitance of ring resonator is too small to measure. So, the test pattern is designed as comb shape in order to increase the measured capacitance, where the shape of the comb is shown in the inset of Fig. 6. Measured capacitance is small compared with theoretical value. Possible reasons are (1) depletion of the waveguide circumference due to the positive charge in the SiO_2 layer and (2) measurement error due to the series resistance shown by in Fig. 3. Figure 7 shows resonance spectrum and red shift of resonance wavelength by applying voltage is certainly confirmed. The quality factor is about 3000. Optical modulation of fabricated modulator at fixed wavelength (1291.3 nm) is shown in Fig. 8, where carrier concentration is $5x10^{18}$ cm^{-3} and lengths of p-type and n-type regions are 0.5 μm. At reverse bias, 6 V, modulation of 25% is obtained. Small quality factor and resonance wavelength are reasons for small modulation compared with simulation. Quality factor can be improved when the following structure parameters are optimized: coupling coefficient between ring resonator and input/output waveguide and waveguide loss except for carrier absorption loss. We have fabricated the device with higher quality factor in other paper [5]. Wavelength shift is improved by increasing ion-implantation dose (see Fig. 6).

4. Conclusion

We have evaluated the modulation and switching speed of the Si ring optical modulator where p/n junctions are arranged along waveguide of the ring resonator. At low voltage, 1V, over 30 GHz and 50% modulation are obtained. In other researcher's paper, 20 GHz and 50% (3 dB) modulation is achieved at 6.5 V (peak-to-peak) combined with 3.5 V (DC offset) [4]. In the fabricated device, we have achieved 25% modulation at 6 V. Even though modulation of the preliminary fabricated device is small, it can be improved because the simulated performance is excellent.

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References

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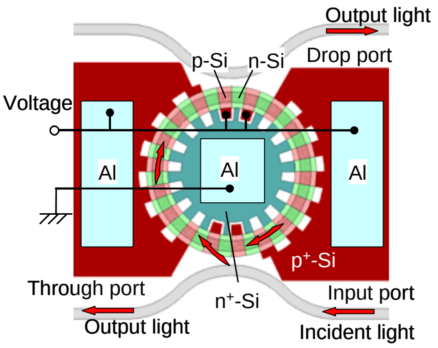

Fig. 1 Schematic structure of the proposed Si ring optical modulator with p/n junctions.

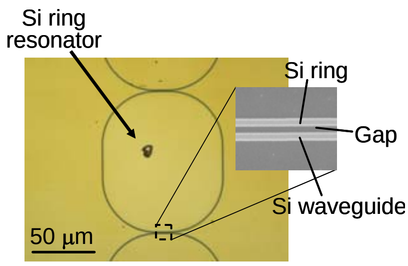

Fig. 2 Optical micrograph of fabricated device after Si-etching.

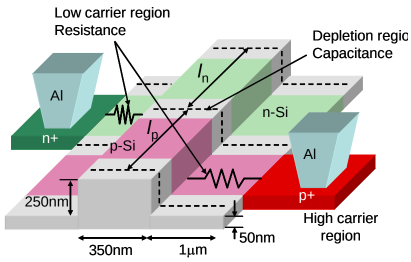

Fig. 3 Bird view of proposal device. Capacitance is formed at p/n junction and resistance is large at low carrier concentration regions.

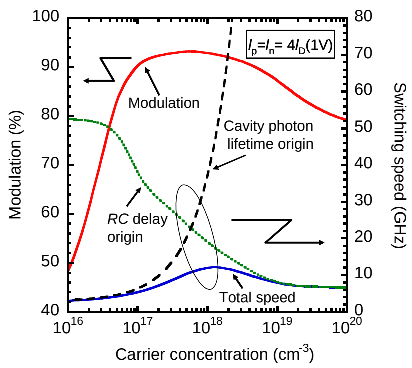

Fig. 4 Carrier concentration dependence of simulated modulation and switching speed at 1 V.

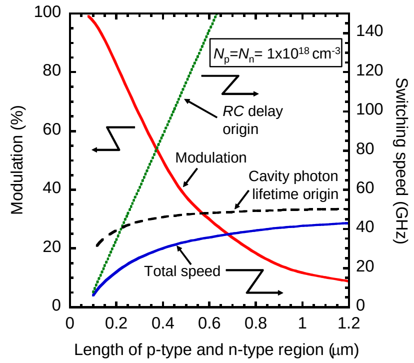

Fig. 5 Simulated modulation and switching speed at 1 V for different length of p-type and n-type regions where carrier concentration is $1x10^{18}$ cm^{-3}.

Table I. Summary of performance of optical modulator.

	Size (Structure)	Operation voltage	Modulation	Speed (GHz)
A. Liu *et al.* [4]	3mm (MZI)	6.5 V	50 %	20
Our work	~100μm (Ring)	1V	50 %	30

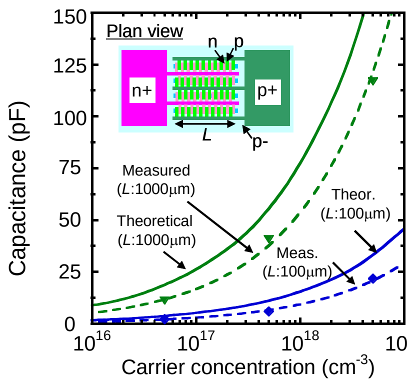

Fig. 6 Carrier concentration versus measured and theoretical capacitance of test pattern at 0 V. Measurement frequency is 10 kHz.

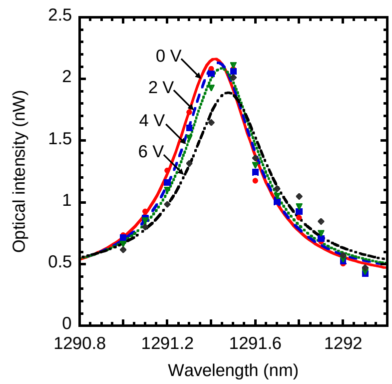

Fig. 7 Optical intensity near resonance wavelength for different applied voltage.

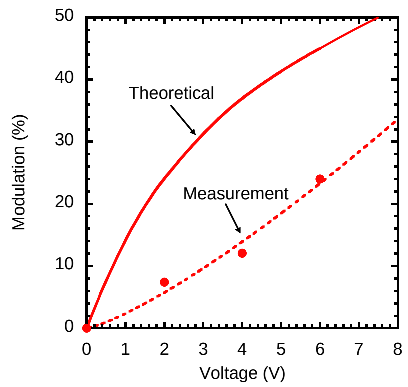

Fig. 8 Voltage dependence of optical modulation at fixed wavelength of 1291.3 nm.