Influence of doping position on the extinction ratio of Mach–Zehnder-interference based silicon optical modulators*

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Abstract: The extinction ratio (ER) of a Mach–Zehnder-interference (MZI) based silicon optical modulator can be strongly influenced by carrier absorption. Moreover, different doping positions can induce different distributions of injected carriers, leading to different ERs. This effect has been experimentally investigated based on the devices fabricated on silicon-on-insulator (SOI) by using a 0.18 μm CMOS process. Our experiments indicate that a device with a doping position of about 0.5 μm away from the edge of the rib waveguide has optimal ER.

Key words: silicon photonics; modulator; carrier dispersion effect; carrier absorption; doping position

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1. Introduction

Silicon photonics has recently attracted wide attention because it offers an opportunity for low-cost optoelectronic solutions for applications ranging from telecommunications down to chip-to-chip interconnects[1]. Various silicon photonic devices, such as silicon modulators[2–4], silicon switches[5, 6], silicon photo-detectors[7, 8] and silicon lasers[9, 10], have been demonstrated. The free carrier dispersion (FCD) effect[11], which is remarkable in silicon, is one of the key electro-optic effects used to implement silicon optical modulators and switches. However, the performances of these silicon photonic devices can be influenced by self heating[12] and carrier absorption[13]. Furthermore, structural parameters such as D, which is defined as the distance between the edge of the heavily doped region and the edge of the waveguide, also influence the performance of silicon photonic devices.

It is known that the absorption loss due to the overlap of the optical mode and the optically absorbing heavily doped regions and electrodes can be supremely reduced if D is more than 1.5 μm[14]. However things are far from simple. The doping position can also influence the electric and thermic characteristics of the p–i–n diode. In contrast with the case that a larger D has less absorption loss, a smaller D is more helpful for heat dissipation[15] and modulation speed. Moreover, different D have different injected currents and carrier distributions. This will finally lead to different ERs and different modulation efficiencies. In this paper, we focus on the influence of carrier absorption and doping position to the ER of MZI based silicon modulators supported by theory and our recent experimental results.

2. Device structure and transmission characteristic

With advantages of high modulation efficiency and a compact structure, a p–i–n diode is always employed as the electrical structure to inject carriers under forward bias[16]. The structure of the MZI based silicon optical modulator used in our analyses and experiments is shown in Fig. 1. The MZI configuration includes two 1 × 2 couplers and two phase shifters with the p–i–n diode. The 1 × 2 coupler with a splitting ratio of 50 : 50 is a 1 × 2 multimode interferometer (MMI). The length of the p–i–n diode based phase shifter is 1500 μm. Taking into account the 340-nm-thick top silicon layer of the SOI, the 400-nm-wide single mode rib waveguide is implemented by etching 260 nm of the top silicon layer with an 80-nm-thick silicon slab. The concentrations of the heavily doped regions (p^+ and n^+) are both 1×10^{19} cm^{-3} and the concentration of the p-type intrinsic silicon is 1×10^{15} cm^{-3}. D is the distance between the edge of the heavily doped region and the edge of

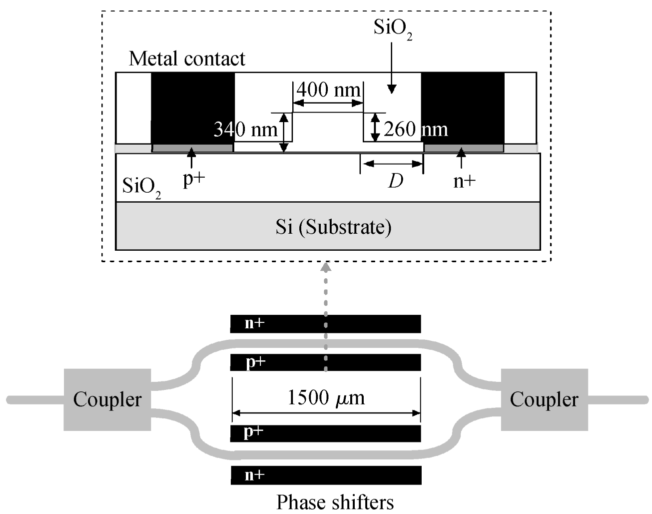

Fig. 1. Schematic of the MZI based silicon optical modulator with a p–i–n diode embedded in the phase shifters.

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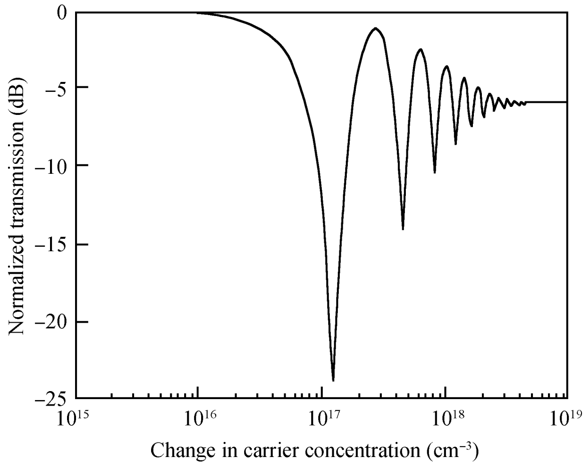

Fig. 2. Numerically simulated transmission characteristic of the MZI based silicon modulator with a p–i–n diode.

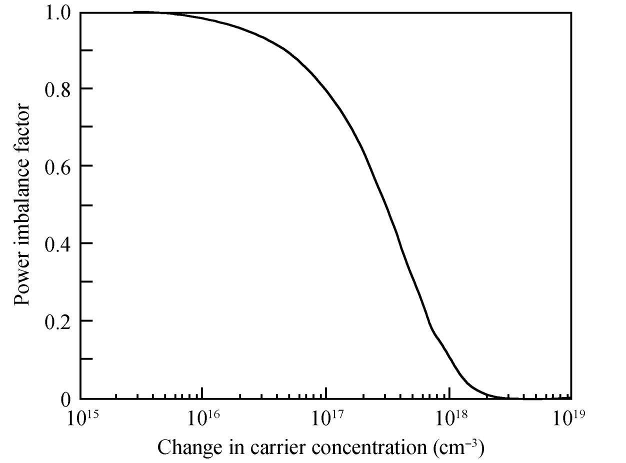

Fig. 3. Power imbalance factor versus change in carrier concentration.

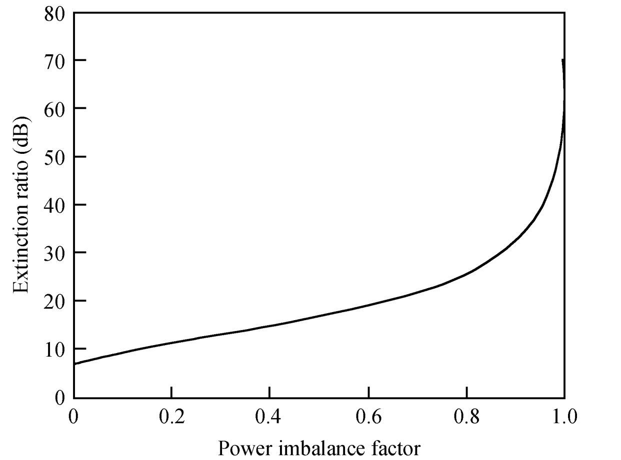

Fig. 4. Possible extinction ratio under the condition of unbalanced interference of two beams.

the waveguide, as previously defined. Metal is deposited on the heavily doped regions and etched to obtain electrodes.

Only one of the two phase shifters is modulated when the modulator is working. Phase modulation is achieved by injecting carriers to the p–i–n diode embedded in the phase shifter and then converted into intensity modulation by the MZI structure. According to the FCD effect and the interference theory of the MZI structure, we obtain the output optical power (P_{out}) as

$$P_{\text{out}} = \frac{A^2}{4}[\exp(-\alpha_0 L) + \exp[-(\alpha_0 + \Delta\alpha)L] + 2\exp\{-[\alpha_0 + (\alpha_0 + \Delta\alpha)]L/2\}\cos\Delta\Phi], \quad (1)$$

where A is the amplitude of the input light; α_0 is the intrinsic absorption coefficient of the silicon waveguide phase shifter; $\Delta\alpha$ is the absorption coefficient variation due to the carrier injection; $\Delta\Phi$ is the phase shift introduced by the carrier injection; and L is the length of the waveguide phase shifter.

According to Eq. (1), numerically simulated transmission characteristic of the modulator is shown in Fig. 2. Phase shift in the modulated phase shifter is always accompanied by the absorption coefficient variation, while the phase and the power of the light passing through the unmodulated phase shifter are invariable. Therefore the transmission is convergent. The valley values increase while the peak values decrease with the injected carriers, until most of the optical power passing through the modulated phase shifter is absorbed, achieving 6 dB modulation.

Due to the free carrier absorption in the modulated phase shifter, there exists a power imbalance between the two phase shifters. The power imbalance factor r can be calculated as

$$r = \frac{I_1}{I_2} = \exp(-\Delta\alpha L), \quad (2)$$

where I_1 and I_2 are the optical powers passing through the modulated phase shifter and the unmodulated phase shifter, respectively. According to Eq. (1), the on-state output power P_{on} and the off-state output power P_{off} can be derived. Finally, the most ideal ER of MZI based devices can be obtained as

$$\text{ER} = 10\lg\frac{P_{\text{on}}}{P_{\text{off}}} = 20\lg\frac{2}{1-\sqrt{r}}. \quad (3)$$

Equation (2) indicates that r decreases with the change in carrier concentration ΔN, as shown in Fig. 3. r reduces from $\sim$1 to $\sim$0 when ΔN increases from 10^{15} to 10^{19} cm^{-3}. When the injected carrier concentration is very low (ΔN close to 10^{15} cm^{-3}), the carrier absorption in the modulated phase shifter is so little that the powers passing the two phase shifters are perfectly balanced ($r \approx 1$). When the injected carrier concentration is very high (ΔN close to 10^{19} cm^{-3}), most of the power in the modulated phase shifter is absorbed by carriers, thus the powers between the two phase shifters are completely unbalanced ($r \approx 0$).

Figure 4 schematically shows the relation between ER and r, as described by Eq. (3). It presents an intuitive estimation of the ER under the condition of unbalanced interference. If the influence of the carrier absorption is low, as previously mentioned $r \approx 1$ in Fig. 3, the ER will be as high as more than 70 dB, as shown in Fig. 4. In order to obtain a device with ER beyond 25 dB, r should be more than 0.8. If the power imbalance between the phase shifters is serious, typically with $r <$ 0.6, the most ideal ER can never exceed 20 dB. For the worst condition $r = 0$, corresponding to ΔN close to 10^{19} cm^{-3} in

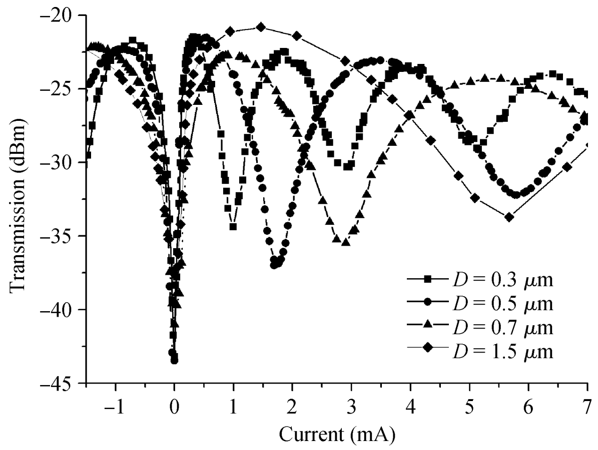

Fig. 5. Transmission characteristics of devices with different doping positions.

Figs. 1 and 3, the ER is 6 dB. Under this condition, the power passing through the modulated phase shifter is almost totally absorbed and the power passing through unmodulated shifter is half transmitted.

3. Experimental results and discussions

MZI based silicon modulators with structures as illustrated in Fig. 1 were fabricated on SOI by 0.18 μm CMOS process. The only difference in design is that these modulators have different doping positions. All devices were simultaneously fabricated on the same SOI wafer, so the device fabrication variations should be identical. Considering that the initial phases of these modulators may be different, we measured two transmission characteristic curves for every modulator by separately modulating each phase shifter. In addition, the experimental curves are processed by moving the minimum transmission points to 0 mA. The final results are shown in Fig. 5. The peak values reduce and the valley values increase when currents increase, coinciding with the previous simulation result of the transmission characteristic. Moreover, the highest ER is about 22 dB, also agreeing with the previous analysis of the ER.

It is seen from Fig. 5 that the transmission characteristic is influenced by doping positions. It is known that the modulation efficiency is higher if the heavily doped regions are placed closer to the center of the waveguide[16]. The device with $D = 0.3$ μm has an obvious current injection effect, but it also has strong absorption to optical power, so its ER is not that high. For device with $D = 1.5$ μm, its absorption to optical power is weak, and its modulation efficiency is low due to the small overlap between the injected carriers and the optical mode. Therefore both the current injection effect and the ER decrease. When $D = 0.5$ μm, the ER of the device is the highest in all experimented devices. These experimental results imply that the heavily doped region has an optimal position of about 0.5 μm away from the edge of the rib waveguide, with which the device has optimal ER. Thus when designing a MZI based silicon modulator with the p–i–n diode, we should trade off the doping position among the heavily doped regions' absorption to optical power, the heat dissipation, the modulation speed and the influence of the doping position to the ER.

4. Conclusion

In conclusion, we have discussed the influence of carrier absorption and doping position on the ER of MZI based silicon modulators with a p–i–n diode embedded in the phase shifter. Different doping positions have different injected currents and carriers, and correspondingly having different ERs. Our experimental results imply that the heavily doped region has an optimal position for ER, which is about 0.5 μm away from the edge of the rib waveguide. Thus, considering the absorption of heavily doped regions, the heat dissipation, the modulation speed and the influence of doping position to ER, there exists a tradeoff to the doping position.

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