Analysis of the thermo-optic effect in lateral-carrier-injection SOI ridge waveguide devices*

Zhao Jiate(赵佳特), Zhao Yong(赵勇), Wang Wanjun(王皖君), Hao Yinlei(郝寅雷), Zhou Qiang(周强), Yang Jianyi(杨建义), Wang Minghua(王明华), and Jiang Xiaoqing(江晓清)†

(Department of Information Science and Electronic Engineering, Zhejiang University, Hangzhou 310027, China)

Abstract: The thermo-optic effect in the lateral-carrier-injection pin junction SOI ridge waveguide is analyzed according to the thermal field equation. Numerical analysis and experimental results show that the thermo-optic effect caused by carrier injection is significant in such devices, especially for small structure ones. For a device with a 1000 μm modulation length, the refractive index rise introduced by heat accounts for 1/8 of the total effect under normal working conditions. A proposal of adjusting the electrode position to cool the devices to diminish the thermal-optic effect is put forward.

Key words: plasma dispersion effect; SOI waveguide device; thermo-optic effect; silicon photonics
DOI: 10.1088/1674-4926/31/6/064009 **PACC:** 7820N; 4280L

1. Introduction

In optical networks and optoelectronic hybrid integration, waveguide devices of various functions are of great importance. Nowadays, many kinds of waveguide devices are proposed, including MZI optical switch and modulator, total internal reflection optical switch, directional coupler, FP resonator, micro-ring, etc. The devices are mainly made of SOI, Si/Ge, compound semiconductor, $LiNbO_3$ and polymer. The main physics effects used are the thermal-optic effect, electro-optic effect, plasma dispersion effect, acousto-optic effect, quantum effect, etc. Silicon CMOS technology which is very mature and steady, is widely used in microelectronics fields, so it is reasonable to anticipate that photonic devices based on silicon CMOS can also have an extremely large space for development. The benefits include low cost, process stability and maturity, high suitability for large-scale industrial production and ease of optoelectronic hybrid integration. Because there is no first-order electro-optic effect in silicon and the response speed of the thermo-optic effect is too slow, silicon based CMOS electro-optic switches usually use the plasma dispersion effect[1−3]. The basic structure of these devices always includes a pin junction or pn junction. It is the injected carrier which changes the silicon refractive index that makes the electro-optic devices achieve the desired functions[4].

Because carrier injection SOI waveguide devices usually need relatively large injection current, it will inevitably produce a certain temperature rise. However, because the thermo-optic effect in silicon is positive, the refractive index change caused by the temperature rise will weaken the refractive index decrease introduced by the carrier dispersion effect. So, if the temperature rise is too high, it will seriously affect the device performance, and even make the device not work. For this reason, it is very important to investigate the thermo-optic effect in SOI waveguide devices. An analysis of the thermo-optic effect in SOI waveguide devices is given in Ref. [5], which is based on the top injection structure 2 × 2 electro-optic switch proposed in Ref. [6], as shown in Fig. 1. The analytical result shows that, for a produced π phase shift, the temperature rise of the device is only about 0.1 K, which means the ratio of refractive index change caused by the plasma dispersion effect and the thermo-optic effect is 41.7. So, for devices with a modulation length shorter than 500 μm, the thermo-optic effect is negligible. A similar analytical method is given in Ref. [7]. Nevertheless, devices with structures like Fig. 2 are actually different from the top injection structure devices in Ref. [6] because of the electrode position which is important for thermal analysis, as will be described below. So the analytical method in Ref. [5] is not suitable for the structure in Fig. 2 and there is still no paper which gives a detailed analysis of the lateral-carrier-injection pin junction SOI ridge waveguide.

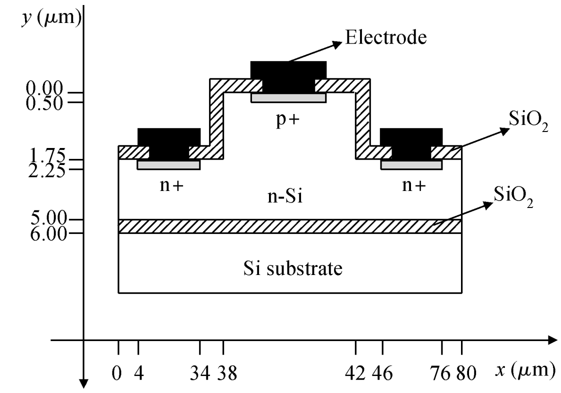
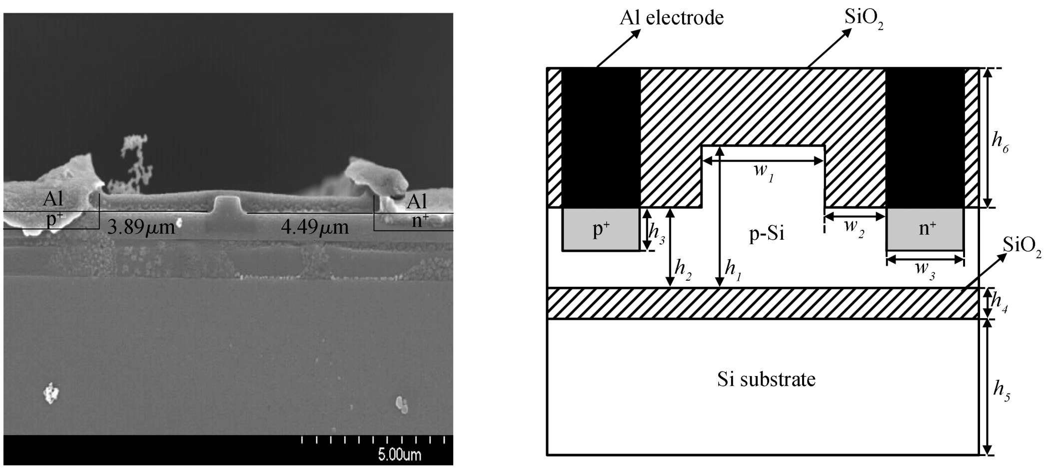


Fig. 1. Cross-sectional view of a top injection pin junction ridge waveguide device.

* Project supported by the Natural Basic Research Program of China (No. 2007CB613405), the National Natural Science Foundation of China (No. 60777015), the Science & Technology Program of Zhejiang Province, China (No. 2007C21022), and the Opened Fund of State Key Laboratory on Integrated Optoelectronics, China.

† Corresponding author. Email: iseejxq@zju.edu.cn

Received 31 December 2009, revised manuscript received 26 January 2010



(a) (b)

Fig. 2. Cross-sectional view of a lateral injection pin junction ridge waveguide device. (a) SEM of the cross section of the device. (b) Sketch map of the sectional size of the device. The typical size of the device of our experiment is: ridge width $w_1 = 1$ μm, ridge height $h_1 = 0.98$ μm, slab height $h_2 = 0.42$ μm, covering SiO_2 layer thickness $h_6 = 0.6$ μm, intermediate SiO_2 layer thickness $h_4 = 1$ μm, Si substrate thickness $h_5 = 650$ μm, doping concentration of the p+ and n+ region: 10^{19}cm^{-3}, doping depth $h_3 = 0.3$ μm, width $w_3 = 4$ μm, distance between the ridge margin and the heavily doped region $w_2 = 1.5$ μm, the core of the waveguide is a lightly doped p region with a doping concentration of 10^{17}cm^{-3}[4].

2. Thermo-optic effect phenomenon observed in lateral-carrier-injection SOI waveguide devices

An important feature of the top injection structure device analyzed in Ref. [5] is that it has its electrode and p^+ region at the top region. However, the strong absorption of the electrode and the p^+ region will make the modulation arm unbalanced, especially in small cross-section devices. For this reason, this structure is not frequently used in small cross-section devices. We prefer the lateral-carrier-injection pin junction structure[4], as shown in Fig. 2.

For the lateral injection structure, we found in the experiment that the temperature rise was much higher than the top injection structure reported in Ref. [5]. Figure 3 shows the measured data of an MZ optical modulator of this structure with a device length of 2000 μm. It is not difficult to find in the figure that the current increase between the second on-state and the second off-state is 10 mA bigger than the one between the first on-state and the first off-state, along with a reduced extinction ratio. The reason for the decrease of the extinction ratio is the carrier absorption which causes the light in the two arms to be unbalanced. Apart from the nonlinearity of the injected carrier density and the current, another important reason for the current margin broadening is the thermo-optic effect caused by the temperature rise when we inject current into the device. As previously mentioned, the refractive index change introduced by heat and by carrier injection is a mutual offset process. Under the influence of the thermo-optic effect, we will need more injected carriers to switch to the off-state, which means a larger current. Meanwhile, we also found that when the current was relatively large (120 mA), the device could not return to the initial state immediately when we cut off the current, the substrate heating significantly. This is because the thermo-optic effect and the slow reply process corresponds to a slow cooling process.

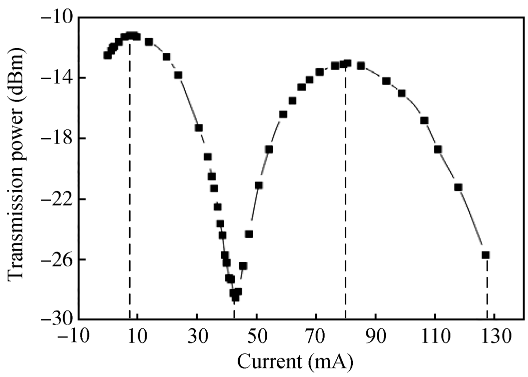


Fig. 3. Measured output port data of the lateral injection structure MZ optical modulator. The modulator length is 2000 μm.

The main reason that there exists such an apparent discrepancy between the analysis of Ref. [5] and the experiment result measured in our lab is that the device structure determines the temperature rise. The analytical method in Ref. [5] does not fit the lateral injection structure for the following reason.

Reference [5] analyzes the problem by using the equation:

$$P = VI = \frac{\Delta T w L k_{\mathrm{si}}}{H}, \tag{1}$$

where w, L correspond to the ridge width and the length of the modulation region respectively, H is the thickness of the Si layer, and k_{si} is the silicon thermal conductivity coefficient. Actually, this method takes the upper surface temperature equal to the room temperature as a default condition, and it obtains the device temperature rise by calculating the temperature difference between the upper and lower surface of the Si ridge. This method fits well for the structure in Fig. 1 because the upper surface of the ridge in this structure contacts the metal electrode whose thermal conductivity coefficient is

Table 1. Results of the numerical calculation.

Voltage (V)	Current (mA)	Electronic concentration (10^{17}cm^{-3})	Hole concentration (10^{17}cm^{-3})	Refractive index decrease introduced by carrier plasma dispersion effect	Temperature rise	Refractive index increase caused by temperature rise
1.28	1167	14	14	4.02×10^{-3}	17.1	3.18×10^{-3}
1.23	792	11	11	3.27×10^{-3}	11.2	2.08×10^{-3}
1.18	510	8.7	8.7	2.68×10^{-3}	6.9	1.28×10^{-3}
1.13	317	6.4	6.4	2.03×10^{-3}	4.2	7.81×10^{-4}
1.06	133	3.9	3.9	1.35×10^{-3}	1.6	2.98×10^{-4}
1.04	99	3.3	3.3	1.17×10^{-3}	1.2	2.23×10^{-4}
0.99	48	2.1	2.1	8.0×10^{-4}	0.56	1.04×10^{-4}
0.94	20	1.3	1.3	5.3×10^{-4}	0.22	4.09×10^{-5}
0.90	7	0.76	0.77	3.4×10^{-4}	0.07	1.30×10^{-5}

big, which means we could approximately treat the temperature of the upper surface of the ridge as room temperature. But, for the structure in Fig. 2, we could not treat the temperature of the upper or lower surface of the ridge as room temperature because the surfaces contact SiO_2 instead of metal, and SiO_2 is a poor conductor of heat. So, the method in Ref. [5] cannot be used for structure 2.

3. Analysis of the thermo-optic effect

To get the thermal distribution field in structure 2, we use a numerical method whose calculating process obeys the equation:

$$\rho c \frac{\partial T}{\partial t} - \mathrm{div}(k\,\mathrm{grad}(T)) = Q + h(T_{\mathrm{ext}} - T), \qquad (2)$$

where ρ is material density, c is the material heat capacity, T is the temperature, k is the thermal conductivity coefficient, h is the convection heat transfer coefficient, Q is the heat source power per unit volume and T_{ext} is the external temperature. Since our analysis focuses on the steady-state thermal field, we take $\frac{\partial T}{\partial t} = 0$.

Before we calculate the thermal field, we simulate the device to get the voltage and current feature and the corresponding injected carrier concentration by LaserMod from Rsoft. Then, we can obtain the corresponding refractive index decrease by using Eq. (3).

$$\Delta n = \Delta n_{\mathrm{e}} + \Delta n_{\mathrm{h}}$$
$$= -\left[8.8 \times 10^{-22} \times \Delta N_{\mathrm{e}} + 8.5 \times 10^{-18} \times (\Delta N_{\mathrm{h}})^{0.8}\right]. \qquad (3)$$

Because the resistance of the semiconductor area is much greater than the electrode and in the lateral injection structure the current is mainly confined in the area between the p^+ and n^+ region, we can approximate the power $P = UI$ as all heating evenly in the area between the p^+ and n^+ region. Then we can treat the heat source power per unit volume Q as UI/S, where S is equal to the area of the region between p^+ and n^+. It has to be pointed that, because the thickness of the Si substrate is much greater than the intermediate SiO_2 layer and the Si slab, if considered in the numerical calculation, it will make the process vast. So the influence of the Si substrate on the heat conduction is not considered. Instead, we take room temperature (300 K) for the temperature at the bottom of the intermediate SiO_2 layer. We think that the air conducts and transfers heat well, which means the surface temperature of the whole device is 300 K. After substituting the thermal conductivity coefficient of Si, SiO_2 and Al electrode, we can numerically calculate the thermal field of the device. The results are shown in Table 1.

The refractive index increase in the table is the temperature rise multiplied by the thermo-optic effect coefficient 1.86×10^{-4} K^{-1}. We can obtain the following figure from the table above.

The modulation length of an interferometric device determines the required injected carrier concentration in working conditions, which also determines the working current. Since the actual devices in our experiments (2000 μm long) are twice as long as the analytical model in our numerical calculation (1000 μm long), the result we observed in our experiment is still relatively slight. Thinking of a device 1000 μm long, a refractive index decrease of 7.75×10^{-4} is necessary for every π phase shift in the 1550 nm wavelength. Numerical calculation results show that the working current is about 40 mA. It is obvious that for the 1000 μm long device, no matter in the working condition or in the super large injection current (1167 mA, which is of course too large for the device) or even when the pin junction is just on (20 mA), the influence of the thermo-optic effect is always non-negligible. The ratio of the refractive index changes introduced by the plasma dispersion effect and the thermo-optic effect varies from 10 to 4/3 and is 8 : 1 under working conditions. On increasing the current slightly, the ratio falls rapidly to 4 : 1 for 133 mA, when the thermo-optic effect is very significant.

Otherwise, it is not difficult to find in Fig. 4 that the refractive index decrease is no bigger than 1.5×10^{-3}, which means that if no special and effective cooling method is applied, the carrier injection structure interferometric devices whose modulation arms are shorter than 500 μm will have very poor performance.

From the model analyzed above we can find that an important but inevitable reason that the device suffers a large temperature rise is that there exist SiO_2 layers on both the top and the bottom of the Si slab, which cut off the heat conduction. So actually, the numerical calculation results are still smaller than real devices because when we are creating the analysis model we assume that the air transfers and conducts heat perfectly and ignore the influence of the Si substrate. However, these factors are considerable because the Si substrate is 600 times thicker than the intermediate SiO_2 layer while the thermal conductivity

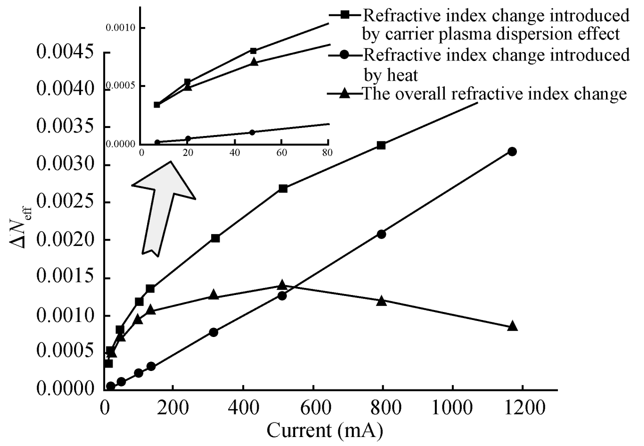


Fig. 4. Comparison of the refractive index changes introduced by the plasma dispersion effect and by the thermo-optic effect under different currents.

of Si is only 100 times bigger than SiO_2, which makes the heat insulation effect of the Si substrate much greater than a thin SiO_2 layer. That is to say, the influence of the thermo-optic effect is more serious in the actual device.

4. Influence of the electrode position

In the process of analyzing, we found that, because of the good thermal conductivity feature of the metal electrode, the electrode influenced the temperature rise significantly. To investigate the influence of the electrode on the temperature rise, we consider two very extreme conditions. Condition 1 assumes that the electrodes conduct heat perfectly, which means the temperature of the lower surface of the electrode (ohmic contact) is room temperature (300 K). This is the default setting of some microelectronic simulation software. The result shows almost no temperature rise. Condition 2 assumes that the electrodes conduct no additional heat, which means that the heat conductivity coefficient of the electrode is set to equal SiO_2. The result shows that under 133 mA injected current, the temperature rise is 4.5 K which is twice as big when we set the actual Al heat conductivity coefficient (240 W/(m·K)) to the electrode. Apparently, these two assumptions are too extreme and impractical. But we can still be inspired by this. For the purposes of diminishing the thermo-optic effect, we can fabricate the electrodes as close as possible to the ridge. Of course, this approach is not endless and it is restricted by the light field because the closer the electrodes are, the more absorption the device suffers.

Figure 5 shows the light field distribution of the lateral injection structure device. Clearly, the light field distributes to the area 0.7 μm away from the ridge, which means that the electrode can be made as close as 0.7 μm away from the ridge. Finally, we analyze the influence of the position of the electrode on the thermo-optic effect. Under 133 mA current, we obtain the following figure, Fig. 6.

It can be seen that the electrode position affects the temperature rise. If the light absorption limit allows it, fabrication of the electrode closer to the ridge will cool the device and reduce the influence of the thermo-optic effect. When the distance between the electrode and ridge is 0, or we put the electrode right

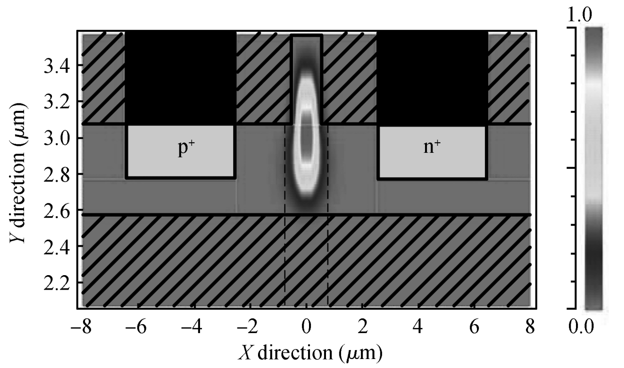


Fig. 5. Light field distribution at the injection region of the lateral injection SOI waveguide device.

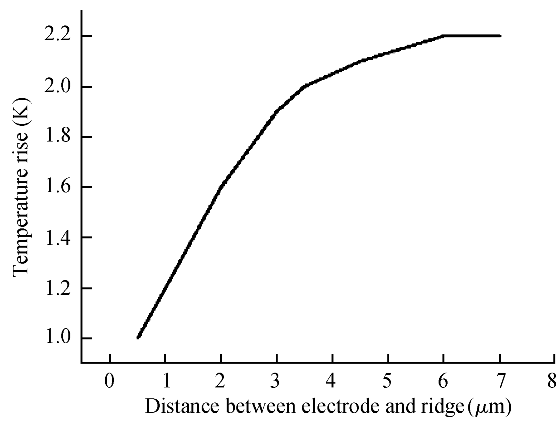


Fig. 6. Relationship between the temperature rise and the distance between electrode and ridge.

at the top of the rig, which is the case in Ref. [5], the cooling effect of the electrode will make the temperature rise very slight. When the distance increases to bigger than 7 μm, the cooling effect of the electrode is no more significant and the temperature rise will not become worse for any more increase of the distance.

5. Conclusions

The thermo-optic effect in carrier injection pin junction SOI optical devices is significant. But the top injection structure device's temperature rise is negligible because of the cooling of the top metal electrode. However, the lateral injection structure suffers a relatively serious temperature rise for its poor cooling condition. For a device with a 1000 μm modulation length, the refractive index change caused by heat accounts for 1/8 of the total effect under normal working conditions. The maximum refractive index decrease is less than 1.5×10^{-3}, so if no special and effective cooling method is applied, the performance of the interferometrice devices whose modulation arms are shorter than 500 μm cannot be improved easily, except using the reverse depletion-based structure. Finally, we analyzed the influence of the electrode position on the thermal field, based on which we proposed that choosing an optimized electrode position can effectively improve the performance of the pin junction SOI optical switch.

References

[1] Sorf R A, Lorenzo J P. All silicon active and passive guided-wave components for λ = 1.3 and λ = 1.6 μm. IEEE J Quantum Electron, 1986, 22(6): 873

[2] Lorenzo J P, Sorf R A. 1.3 μm electro-optic silicon switch. Appl Phys Lett, 1987, 51(1): 6

[3] Sorf R A, Bennett B R. Electrooptical effects in silicon. IEEE J Quantum Electron, 1987, 23(1): 123

[4] Zhao Yong, Jiang Xiaoqing. Fabrication of silicon photonic devices by utilizing industrial CMOS technology. Proc SPIE, 2009, 7516: 751606

[5] Yan Qingfen, Yu Jinzhong. Analysis of the thermo-optic effect in SOI optical switch. Journal of Optoelectronics · Laser, 2003, 14(1): 1

[6] Zhao C Z, Liu Y L, Li G Z, et al. Investigation of silicon electro-optical waveguide intensity modulator at 1.3–1.6 μm. Chinese Journal of Semiconductors, 1996, 17(4): 279 (in Chinese)

[7] Jackson S M, Hewitt P D, Reed G T, et al. A novel optical phase modulator design suitable for phased arrays. J Lightwave Technol, 1998, 16(11): 2016

[8] Marris-Morini D, Vivien L, Rasigade G, et al. Recent progress in high-speed silicon based optical modulators. IEEE Proceeding, 2009, 97(7): 1199