Extended Abstracts of the 2013 International Conference on Solid State Devices and Materials, Fukuoka, 2013, pp1004-1005

Mach-Zehnder Interferometer Optical Modulator with Cascaded P/N Junctions

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1. Introduction

Silicon industry is reaching its limit in size, device integration and complexity, as the physical limitations of metallic interconnects. Existing metallic interconnect technology facing a severe challenges due to ever-increasing bandwidth demand for next generation high performance computing. The solution may be silicon photonics, a technology that employs silicon as an optical material, and has been driven by recent technological advances. Electro-optic modulator based on silicon photonics is an essential component for low cost optoelectronic circuits. Light modulation in silicon, the challenging aspects is to change the refractive index, because of silicon does not show any Pockel's effect [1]. The electro-optic effects in silicon, induced by the free carrier plasma effect. Many researchers have been proposed several configurations to alter the refractive index of silicon. The configurations are generally classified by the following ways [1] a) carrier injection mode b) MOS capacitor and c) carrier depletion mode. Among the various types of silicon modulators, the carrier injection modulators have advantages due to its compactness [2,3]. However, carrier injection-based silicon modulators suffer from long free carrier life time in silicon on insulator (SOI).

In this paper, we demonstrate MZI modulator with cascaded p/n junctions which are arranged as shown in Fig. 1 along the arms of modulator and operated at forward biased mode. MZI optical modulator under carrier injection mode offers highest modulation efficiency than carrier depletion mode device. We investigate that carrier depletion mode device needs more voltage to achieve same amount of modulation like carrier injection mode device.

Output

2. Simulation method

To simulate the modulator operation, the key performance parameters is the modulation efficiency i.e how much input light can modulate as well as how fast with minimum driving power. Our investigation focuses on the effects of carrier concentration near the junction under forward bias condition. The free carrier injection to a silicon waveguide strongly affects its optical properties. Traditionally, the change of refractive index and the absorption are induced by the presence of free-charge carriers**.** The simulated results show that modulation efficiency is very small below built in potential due to small free carrier concentration near the junction. During our simulation we have used modulator arm length of 5 mm, where p and n has the same width of 0.3 μm. Figure 2 shows the schematic 3D view of modulator arm.

3. Fabrication process

The MZI optical modulator shown in Fig. 3 was fabricated on "silicon-on-insulator"(SOI) wafer. An oxidation layer of 100 nm is formed on the SOI wafer. The SiO_2 layer is then patterned to waveguide form using hard-mask of etching of top silicon layer. After that, p- and n-type regions are formed by electron-beam lithography and ion-implantation. The impurities for p and n regions are "boron" and "phosphorus" respectively. The SiO_2 layer is deposited by atmospheric pressure chemical vapor deposition (APCVD) and this layer acts as an insulator as well as upper cladding layer. After that contact holes are formed by silicon dioxide etching. Finally, Al electrodes are fabricated after contact hole wet etching, by the DC magnetron sputtering and H_2+N_2 annealing is carried out. Optical micrograph of our fabricated device is shown in Fig. 4

4. Optical switching behavior

The transient responses for rectangular shape voltage are different depending on applied voltage. Figure 5 is showing the transient responses at V_F= 4.5 V and 4.9 V. The change of optical intensity is directly proportional to $\cos^2\theta/2$ as shown in Fig. 6, where θ is the phase difference of two arms at no voltage and applied voltage condition. We assume the operating point "a" at zero applied voltage. The initial phase difference is caused by small unbalance between two arms. We also assumed the thermal effect due to Joule heat generation by forward current. It should be noted that direction of phase shift is opposite between carrier injection (refractive index is reduced) and thermal effect (refractive index is increased). When applied voltage is small (V_F=4.4) the carrier injection effect is relatively small and operation point moves to point "b", after that it is followed by thermal effects which enhance the output intensity, that phenomenon is shown in Fig. 6(a). On the other hand at V_F=4.9 the current exponentially increased because both free carrier injections and thermal effects has increased, due to those effects the phase shift reaches to the next ascent of the $\cos^2\theta/2$ curve. In this situation the output intensity is once increased by carrier injection and then decreased by thermal effect, which reproduces a result shown in Fig. 6(b). It is also reasonably understood that when the bias voltage is returned to zero, both condition (V_F=4.4 and 4.9) has the same behavior.

Figure 7 shows the simulated (□) and experimental (x) optical modulation as a function of applied voltage. At low voltages less than 1 V the simulated modulation is rather high whereas the experimental one was too small to measure. Also at high voltages larger (>1 V) the experimental modulation is smaller than the simulated one. The reason is not clear but the possible reason is that the current intensity at the center of the waveguide is not strong but flows at the fringes due to the surface defects caused by dry etching.

5. Conclusion

We have proposed and fabricated new type of MZI modulators with cascaded p/n junctions along the waveguide. They have shown high modulation efficiency almost 100% at forward bias of 4.4 V. But the simulation results showed the lower operation voltages less than 1 V. We will continue to improve the performance of the proposed devices.

References

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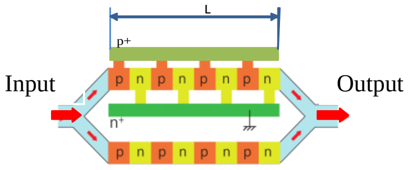

Fig. 1 Structure of Si MZI optical modulator with cascaded p/n junctions.

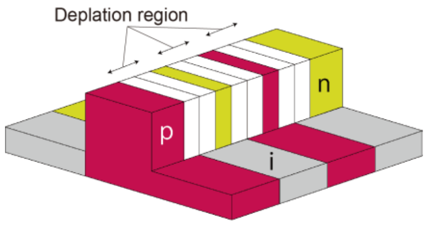

Fig. 2 Three dimensional view of Mach-Zehnder optical modulator's arm.

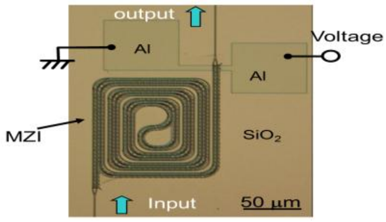

Fig. 4 Optical micrograph of the fabricated MZI (arm length is 3 mm).

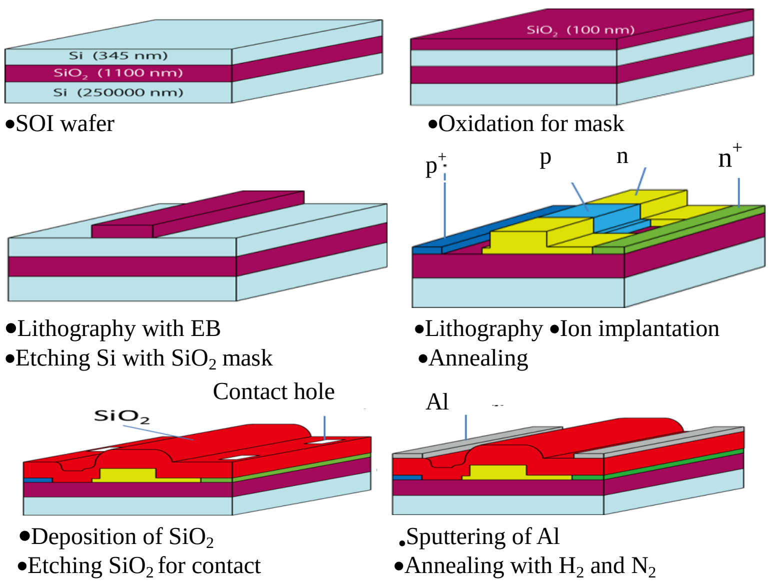

Fig. 3 Fabrication process.

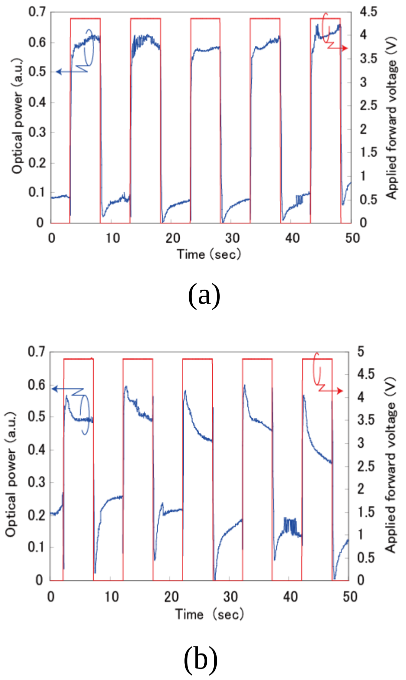

Fig. 5 Transient response at (a) V_F=4.4 V (b) V_F=4.9 V.

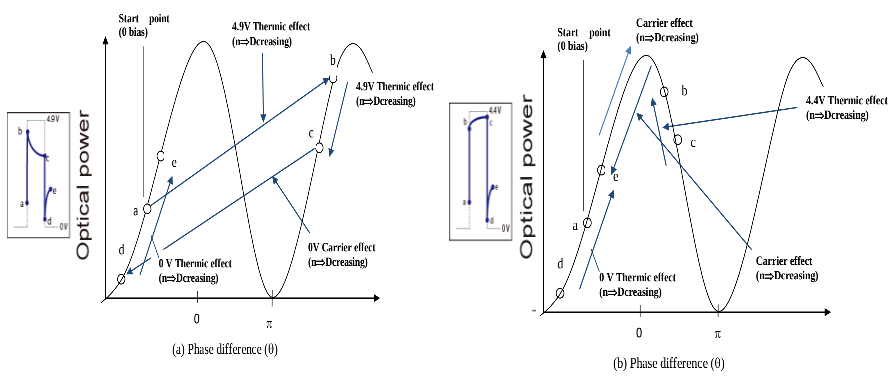

Fig. 6 Phase shift model for explaining the experimental results.

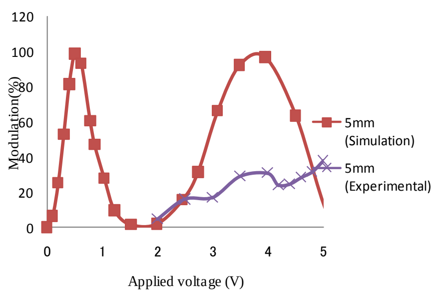

Fig. 7 Modulation versus applied voltage. The length of p and n regions is 0.3 μm and N_A=N_D=5.0x10^{18} cm^{-3}.