VARIOUS DOPING CONCENTRATION EFFECT ON SILICON-ON-INSULATOR (SOI) PHASE MODULATOR

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Various Doping Concentration Effect on Silicon-on-Insulator (SOI) Phase Modulator

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Abstract — **This paper reports the effect of doping concentration to the electrical characteristic performance of the phase modulator in the carrier injection mode at wavelength 1.55μm. The phase modulator device has been integrated in the silicon-on-insulator (SOI) rib waveguide with the p-i-n diode structure. The electrical device performance is predicted using the 2-D semiconductor package SILVACO (CAD) software under DC operation. The least doping concentration of p+ and n+ region produces the least change of refractive index of the modulator. Meanwhile, results show that by increasing the doping concentrations, the value of Iπ decreases. This means that the phase modulator performance is better with increased doping concentrations.**

Index Terms—**Phase modulator, Silicon-on-Insulator, carrier injection, refractive index change.**

I. INTRODUCTION

RECENTLY, silicon-on-insulator (SOI) has been widely used as a photonic substrate in many research studies due to its unique characteristic [1]. Furthermore, the matured process of silicon in microelectronic fabrication process is the reason why SOI are the most chosen for many photonic devices such as the modulator [1,2]. The phase modulator is one of the basic components for the more complex photonic integrated circuits. It is developed based on free carrier plasma dispersion effect in the waveguide. The phase shift can be obtained by inducing more free carrier in the optical guiding region with the purpose to change the refractive index value [3]. Although there are many studies on the design of the phase modulator had been done before, the most challenging tasks is to design the more efficient, high speed and low loss phase modulator. In this paper, we propose a design of p-i-n diode structure phase modulator with a specific dimension based on rib waveguide formed from SOI materials and operating at important optical communications wavelengths of 1.55 μm [3, 4]. Soref and Bennet [7] quantified the changes they had identified from the research for the refractive index and in the absorption coefficients. The following equations are widely used in order to evaluate changes due to injection or depletion of carriers in silicon and hence are utilized in this report:

At $\lambda_0 = 1.55$ μm:

$$\Delta n = \Delta n_e + \Delta n_h = -[8.8 \times 10^{-22}\, \Delta N_e + 8.5 \times 10^{-18} (\Delta N_h)^{0.8}] \quad (1)$$

At $\lambda_0 = 1.3$ μm:

$$\Delta n = \Delta n_e + \Delta n_h = -[6.2 \times 10^{-22}\, \Delta N_e + 6.0 \times 10^{-18} (\Delta N_h)^{0.8}] \quad (2)$$

where:

Δn_e change in refractive index resulting from change in free electron carrier concentrations.

Δn_h change in refractive index resulting from change in free hole concentrations.

The active cross section of the phase modulator device has been used in this work is shown in Figure 1.

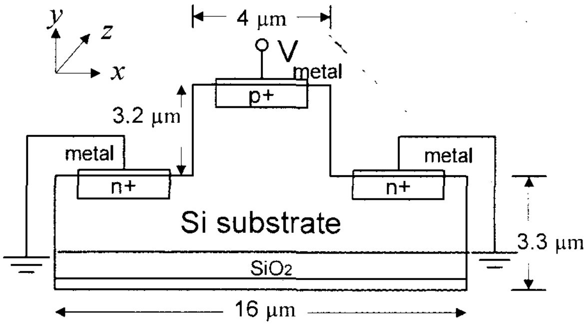

Figure 1: Cross section of the p-i-n phase modulator.

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By observing the doping concentrations variations at the waveguide centre (x=4μm, y=8μm), it enable us to work out for the refractive index change for a specific forward bias voltage and therefore the resulting phase shift of the device, in which the relationship can be summarized as:

$$\Delta\theta = 2\pi\Delta nL/\lambda \tag{3}$$

where L is the length of the modulator. In this work, the length of the modulator is assumed as 500μm.

II. PHASE MODULATOR DESIGN

The simulation process is divided into two parts. The first part is the simulation of the device fabrication and the second part is the simulation of the device analysis. In the first part, the simulation development has been developed using the component of the 2D package SILVACO software, the ATHENA.

The design of the simulation begins by the construction of the p-i-n diode structure. The P^+ type region is doped with 5×10^{18} cm^3 boron concentrations while the N^+ type region is doped with 5×10^{18}cm^3 phosphorus concentrations. The structure has a background doping concentrations of 1×10^{14} cm^3. The depth of the doped region is about 1.8μm for N^+ region and 1.6μm for P^+ region. The rib height and width for the structure is chosen to have a single mode behaviour. The rib structure is designed to have 3.2 μm in height and 4 μm in width.

ATLAS, another component of the SILVACO device simulation package has been utilized to simulate the device operation. The software simulates the internal physics and device characteristics using the Poisson's equation and the charge continuity equations for the electrons and holes calculation. The software also uses a complete statistical approach (Fermi–Dirac statistics). The Carrier recombination models are also included with the Shockley–Read–Hall (SRH) recombination, Auger recombination, and the surface recombination.

The simulator has been used to determine the change of refractive index at the optical wavelength 1.55μm. The mportant parameters used in the simulations are shown in Table 1.

TABLE 1
SIMULATION PARAMETERS

Si refractive index	3.475
Si background carrier conc. (cm^3)	1×10^{14}
τ_p (sec)	2×10^{-6}
τ_n (sec)	2×10^{-6}
Temperature (K)	300

III. RESULTS AND DISCUSSION

The DC characteristic is done by employing a forward-biased effect with 0.75, 0.8, 0.85, 0.9, 0.95 and 1V. The results are depicted in Figure 2 and Table 2.

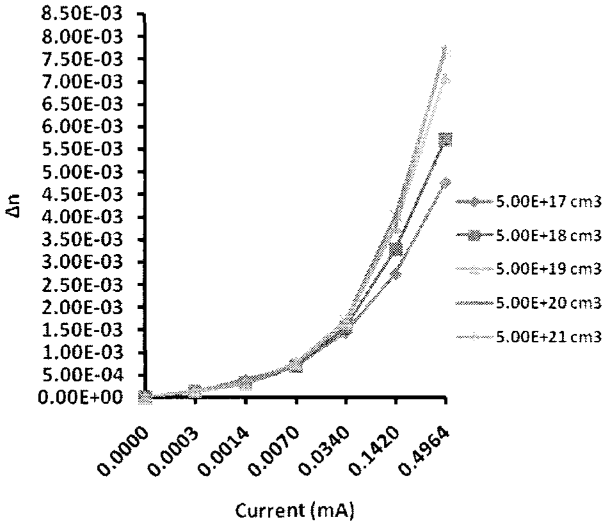

Figure 2: Refractive index change against various doping concentration of p+ and n+ regions.

Figure 2 displays the change of refractive index with different doping concentrations of p+ and n+ regions. The least doping concentration of p+ and n+ region produces the least change of refractive index of the modulator. For instance, with 0.4964 mA drive current, the refractive index change for concentration of 5E17cm^3 is 4.76021E-03. Meanwhile, at doping concentration of 5E21cm^3 with the same drive current, the change of refractive index is larger with 7.781809E-03. Therefore, higher doping concentration is in favour for a larger refractive index change.

TABLE 2

Doping Concentration (cm^3)	*Iπ (mA)*
5e17	*0.0448*
5e18	*0.0313*
5e19	*0.0286*
5e20	*0.0259*
5e21	*0.0245*

One of the method to evaluate the performance of a modulator is by determining the current (Iπ) needed for a 180° of phase shift. Lower value of Iπ is favorable since lower drive current is needed for a modulator to modulate the phase. By using (3), the value of refractive index change for 180° phase shift of the design is 1.5E-3. Therefore, the value of Iπ is obtained from graph in Figure 2. The values of Iπ against various doping concentrations are depicted in Table 2.

Table 2 concludes that by increasing the doping concentrations, the value of Iπ decreases. This means that the phase modulator performance is better with increasing doping concentrations.

IV. CONCLUSION

ther optimization of experimental devices based on the dicted results and scope are promising. While this paper ;usses the results of a specific phase modulator design, the ılts suggest that increasing the doping concentrations of p+ . n+ regions would also enhance the performance of other ·n phase modulator geometries, although there would ırly need to be a specific evaluation of any design.

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