EFFECTS OF WAVEGUIDE WIDTHS FOR CARRIER INJECTION SOI OPTICAL MODULATOR

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ABSTRACT

Optical modulation in photonic circuits is implemented by devices that cause direct changes in optical intensity by absorption or cause changes in the refractive index of the material, which can be converted to an intensity change via an interferometer or a resonant device. The development of high performance optical modulators formed in silicon is important for the technology to be viable. Silicon optical modulator performs the functions of writing electrical data to an optical data carrier is for the development rate of silicon photonics. This project uses SOI optical modulator for PIPIN carrier depletion where the waveguide width varies. The project is to propose what is the best waveguide width for the best performance of PIPIN carrier depletion SOI optical modulator. The project was designed and simulated using ATHENA and ATLAS from Silvaco at 1.55µm. The waveguide widths were varied and the changes in the parameters such as refractive index, modulation efficiency and absorption coefficient were observed. The structure consists of intrinsic region; p-type or n-type semiconductor regions with forward biased applied to the voltage. The effects of the structures with different waveguide widths were observed. The parameters observed consist of the change in refractive index (Δn), modulation efficiency ($V_\pi L_\pi$) and absorption coefficient ($\Delta\alpha$). Based on the results, the waveguide width of 5 micron exhibits the highest refractive index (Δn) with; $17.8583 \times 10^{-3}\ cm^3$. This is followed by modulation efficiency($V_\pi L_\pi$); $0.0048\ V.cm$. However, the structure also has the highest absorption coefficient ($\Delta\alpha$) of $-112.7477\ cm^{-1}$.

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ABSTRAK

Modulasi optik dalam litar fotonik dilaksanakan oleh peranti yang menyebabkan perubahan langsung dalam keamatan optik oleh penyerapan atau sebab perubahan dalam indeks biasan bahan, yang boleh ditukar kepada perubahan keamatan melalui interferometer atau peranti salunan. Pembangunan Prestasi tinggi modulator optik ditubuhkan pada silikon adalah penting bagi teknologi yang berdaya maju. Silicon modulator optik melaksanakan fungsi menulis data elektrik kepada pembawa data optik ialah untuk kadar pembangunan fotonik silikon. Projek ini menggunakan SOI modulator optik untuk PIPIN pembawa kekurangan di mana lebar pandu gelombang yang berbeza-beza. Projek ini adalah untuk mencadangkan apakah lebar pandu gelombang terbaik untuk prestasi yang terbaik pengangkut PIPIN kekurangan SOI modulator optik. Projek ini telah direka dan simulasi menggunakan ATHENA dan ATLAS dari Silvaco di 1.55μm. Lebar pandu gelombang telah diubah dan perubahan dalam parameter seperti indeks biasan, kecekapan modulasi dan pekali penyerapan diperhatikan. Struktur ini terdiri daripada kawasan intrinsik; p-jenis atau jenis-n kawasan semikonduktor dengan terpincang ke depan digunakan untuk voltan. Kesan daripada struktur dengan lebar pandu gelombang yang berbeza telah dipatuhi. Parameter diperhatikan terdiri daripada perubahan dalam indeks biasan (Δn), kecekapan modulasi ($V_\pi L_\pi$) dan pekali penyerapan (Δα). Berdasarkan kepada keputusan, lebar pandu gelombang 5 mikron pameran indeks tertinggi biasan (Δn) dengan; $17.8583 \times 10^{-3}\ cm^3$. Ini diikuti dengan kecekapan modulasi ($V_\pi L_\pi$); 0,0048 V.cm. Walau bagaimanapun, struktur itu juga mempunyai pekali penyerapan tertinggi (Δα) daripada $-112.7477\ cm^{-1}$.

CHAPTER 1

INTRODUCTION

Photonic is where the generation, emission, transmission, modulation, signal processing, switching, amplification and detection/sensing of light. It is one of the fastest growing high-technology industries in the world. Silicon photonic is a technology platform for a wide range of applications in telecommunication, data communication, interconnect and sensing that uses silicon as the substrate.

Optical communication is communication at a distance using light to carry information. It can be performed visually or by using electronic devices. The main benefits of optical communication include high bandwidth, low loss, great transmission range and no electromagnetic interference.

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1.1 Report Overview

This report is divided to four chapters which conclude what had been done throughout the project. Chapter 1 would be the introduction of the project. This chapter elaborates on the introduction of the project, background of the project, objectives, and scope.

In Chapter 2, the presentation of the theories and literature review for the project. The important details of the project are explained in this chapter.

For Chapter 3, the methodology on what program used and the flow chart for this project.

Next, in Chapter 4 will represent the results obtained throughout the project from the simulation of Silvaco. In this chapter, the characteristics of the device can be analyzed based on the simulation results. This chapter shows the coding and figures of the substrate and differentiates the structure when the waveguide width is varied.

Finally, the conclusion of this thesis will be in Chapter 5 where it would also include the conclusion of ht results obtained, achievement of the project objectives and any recommendations for future project.

1.2 Background of Project

For this project, the PIPIN structure is used in the optical modulator. The PIPIN structure consists of regions such as intrinsic region, p-type or n-type semiconductor regions. The configuration of the PIPIN structure uses Silicon-on-Insulator (SOI) as the substrate. The main purpose for this project is to study the effects of different waveguide widths for PIPIN carrier injection for SOI optical modulator.

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Wavelengths that are normally used for SOI applications are 1.31µm and 1.55µm. This is due as longer wavelengths are suitable due to absorption spectra of silica oxide. The waveguides behave as a single-mode assuming that higher order vertical modes confined under the rib were coupled to the outer slab region during propagation yielding high propagation losses for the higher order modes. The effect of waveguide width at the operating wavelength depends on the waveguide height, etch depth, top oxide cover the thickness and the side wall angle. The effect of varying waveguide widths are designed and simulated in Silvaco using ATHENA and ATLAS.

1.3 Problem Statement

The waveguide widths for PIPIN carrier for SOI optical modulator affects on the refractive index change, modulation efficiency and absorption coefficient. Hence, this project is to determine the best waveguide width performance depending on the factors stated.

1.4 Objectives

The objectives for this project are stated as below:

- To design and simulate PIPIN carrier injection for SOI optical modulator
- To observe the effects of different width waveguide for PIPIN carrier injection for SOI optical modulator
- To recommend the best waveguide width waveguide for PIPIN carrier injection for SOI optical modulator performance

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1.5 Scope

The scope of this project is to design and simulate PIPIN carrier injection for SOI optical modulator. The wavelength used is 1.55µm for this project. The structure design is in single-mode condition. The waveguide width is varied to observe the effects on the PIPIN carrier injection for SOI optical modulator where the refractive index change, modulation efficiency and absorption coefficient due to the effects of the waveguide widths.

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CHAPTER 2

LITERATURE REVIEW

Silicon photonics is on the verge to revolutionize several data communication applications. The development of high performance optical modulators formed in silicon is essential for the technology to be viable. It has a technology based in which has high performance in photonics components and circuits. The technology is motivated by a low cost production and integration with CMOS that can also offer enhanced functionality of the silicon photonics. For example, the silicon optical modulator performs the functions of writing electrical data to an optical carrier is for the development rate of silicon photonics. The performance from the first proposed design for 1GHz modulation to modulation at data rates in excess of 40Gbits/s. Most silicon photonics are focused applied on short reach links with products that already emerge in area of active optical cables. Majority of optical modulators formed in silicon are based on the plasma-dispersion effect where a change in the concentration of free electrons and holes causes a change in the refractive index. [14]

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2.1 Optical Modulator

2.1.1 Optical Phase Modulator

Modulation of optical signal is where the ability to modulate an optical signal is important function of photonic circuit. The modulation implies an induced change in the optical field. This happens as there is a change in the complex refractive index, n. the refractive index of silicon, n=3.45, [8] does exhibit a change in response to applied electric field. [9]

2.1.2 Mach-Zahnder Optical Modulator

Integrated silicon-on-insulator (SOI) Mach-Zehnder Interferometer (MZI) is used as modulators, wavelength multiplexers, and sensors. The design of MZI is important to obtain the best performance. The aspect such as high extinction ratios, low parasitic reflections, low wavelength dependence, and low optical losses needs to be considered. A compact design with a simple fabrication is important for commercialization. [6] It is very useful for analog transmission when a large bandwidth is required. Optical transmissions require low power and optical fibers present a good immunity to electromagnetic noise. [7]

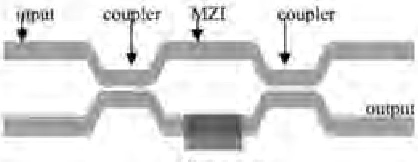

Figure 2.1: Mach-Zehnder Interferometer

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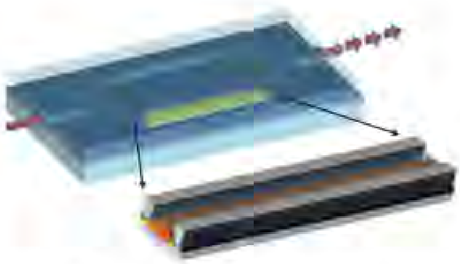

Figure 2.2: SOI Mach-Zehnder Interferometer with optical phase modulator inserted

2.2 Material Used for Photonic

2.2.1 Silicon on Insulator

Silicon is used for high-speed devices exhibiting unprecedented bandwidth performance that can overcome the limitations of conventional microelectronics. This is due to its intrinsic structural properties as silicon does not exhibit a useful electro optic effect that could enable light modulation. Silicon is a popular choice as for its transparency to infrared communication wavelengths and its high refractive index which facilitates the miniaturization of photonic devices. Hence, enables a high level of light confinement in nanometersized waveguides and provides an excellent basis to fabricate micro-optical devices. The rule of design for optical modulators in silicon is that it should consider a single-mode waveguide design, high modulation speed, device small in size and low power consumption. [5]

2.2.2 Germanium

Germanium is used as a common approach to the material system to reduce the bandgap. It is another form of semiconductor material that has the lowest energy absorption. The effect on the absorption coefficient and penetration depth is defined as the distance that the light travels before the intensity falls. Germanium absorbs strongly when the wavelength is shorter. [22]

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2.3 Structure

2.3.1 PN Structure

The free carrier dispersion effect operates in three conditions; forward biased (injection), reverse biased (depletion) and MOS capacitor (accumulation). The advantage of PN structure is; it's simple to fabricate as there is no critical alignment of the implant windows required. The concentration of the n-type region and p-type region are determine in order to ensure that large concentration variation in the waveguide with the applied voltage, while maintaining reduced optical loss. [13]

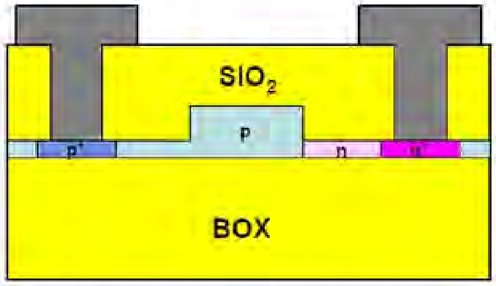

Figure 2.3: Optical modulator based PN diode

2.3.2 PIN Structure

The PIN structure normally consists of optical waveguide embedded into p-type and n-type regions. When the structure is forward biased minority carrier moves through the intrinsic region where the mode propagates produced. Forward biased of the device produce a free electrons and holes to be injected to the intrinsic region. The optical mode is confined in the intrinsic region in order to avoid losses due to doped p-type region and n-type region. The advantage of PIN: high amount of charge carriers in the electrical process produces a high change in the value of silicon refractive index. Hence, the smaller modulation length causes non-negligible power consumption. [21]

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Figure 2.4: Optical modulator of PIN structure

2.3.3 PIPIN Structure

The PIPIN structure for this project is designed in a single-mode condition. [12] Carrier depletion can also be obtained in a lateral PIPIN diode, as represented in figure 4. The P and N doped regions of the diode are on each side of the waveguide, and a p-doped slit is inserted in the middle of the waveguide, to bring holes at equilibrium in the center of the waveguide. The n-doped region slightly overlaps the guided mode, to ensure an efficient depletion of the thin p-doped slit. This structure appears very flexible to achieve given specifications. Indeed, as a large part of the waveguide does not include any doped regions it is possible to increase doping levels of the doped regions without increasing optical loss. [13]

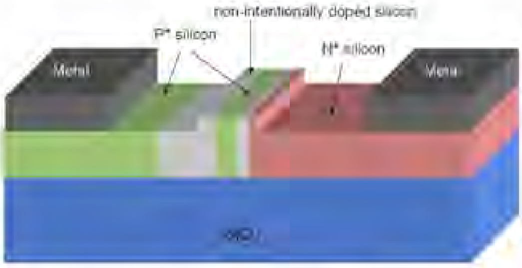

Figure 2.5: Lateral view of PIPIN structure

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2.4 Free Carrier Dispersion Effect

2.4.1 Absorption

Free carrier absorption occurs when a material absorbs a photon, electron or holes are excited from an already-excited state to another at an unoccupied state in the same band. It is different from interband absorption because the excited carrier is already in an exited band, such as electrons in the conduction band or holes in the valence band, where it is free to move. In interband absorption, the carrier would start in a fixed, non-conducting band and be excited to a conducting one. Silicon optical modulator is a device where the conversion of data from electrical data to optical data. Studies are mostly for high speed modulation in silicon (Si) or silicon based devices according on the free carrier absorption; injection or depletion of free carriers that are related to the refractive index change and phase modulation of wave travelling through the active region. [15]

2.4.2 Carrier Injection and Depletion

The diffusion from one side of the junction to the other increases, it causes a minority carrier injection at the edge of the depletion region. The carrier moves away from the junction when the diffusion occurs and will recombine with the majority carrier. The majority carrier comes from the external circuit causing the net current flows in the direction of forward bias. If the recombination does not occur, the minority carrier concentration would reach higher concentration equilibrium and the diffusion of the carriers from one side to the other would stop. However, in semiconductor, the injected minority carriers recombine causing more carriers to diffuse across the junction. This causes it to be in forward bias direction. In reverse bias, when a voltage is applied across the device it will cause the junction to increase in size. The higher the electric field in the depletion region causes the decrease in the probability of the carrier to diffuse from either side other the junction. Hence, the diffusion current decreases.

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Like forward bias, the drift current is limited by the number of the minority carriers on either side of the junction and unchanged by the increased electric field. A small increase in the drift current is experienced due to the small increase in the width of the depletion region.

2.5 Waveguide

Silicon waveguide was first recorded in 1980s. [11] The SOI optical modulator in this project is based on the PIPIN structure. The type of waveguide used is the rib waveguide. Typical wavelengths for SOI applications are 1.31 and 1.55 m, but longer wavelengths are not suitable (except in the 3–3.5- m range) due to absorption spectra of silicon dioxide. [1] For this project the waveguide width is varied to observe the effects for PIPIN carrier depletion SOI optical modulator.

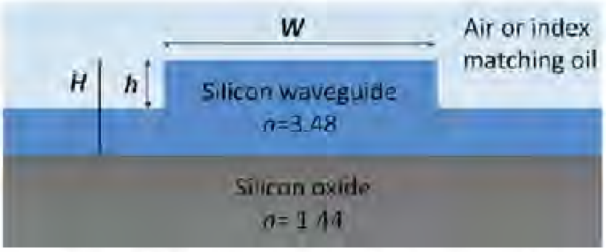

Figure 2.6: Cross-section of rib waveguide

2.6 Single-Mode Condition

For SOI to be single-mode condition, the rib waveguide structure of width W and height H with symmetric slab height h will support only the fundamental mode when the equation below must be satisfied; [10]

$$\frac{W}{H} \leq 0.3 + \frac{r}{\sqrt{1-r^2}} \qquad for\ 0.5 \leq r \leq 1.0 \tag{1}$$

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The analysis was based on the assumption that higher order vertical modes confined under the rib, were coupled to the outer slab region during propagation. This will yield the high propagation losses for the higher order modes. Thus, the waveguides behave as single-mode waveguides, as all other modes are lost. [1] The single-mode condition is used to make it easier the coupling with single mode fiber optic cable.

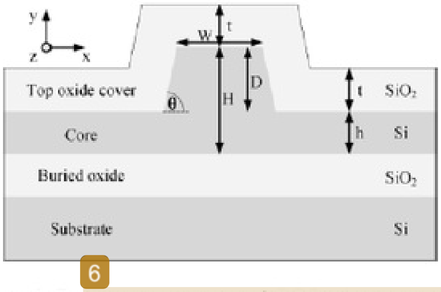

Figure 2.7: Cross section of SOI rib waveguide

2.7 Formula Analyzing the Performance of the Modulator

The formulae below are used to evaluate the performance of the modulator based on the results obtained from the simulation in Silvaco;

i. For standard telecommunication purposes, wavelength of $\lambda_o = 1.55\mu m$

The modulated wavelength used is fixed at $1.55\mu m$ for standard telecommunication purposes.

ii. Change of electron and hole concentration

Change of electron concentration, Δn_e

$$\Delta n_e = n_{electron}\ at\ variable\ volt - n_{electron}\ at\ 0\ volt \tag{2}$$

Where Δn_e is the change of the refractive index based on the change in electron concentration.

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Change of holes concentration, Δn_h

$$\Delta n_h = n_{hole}\ at\ variable\ volt - n_{hole}\ at\ 0\ volt \tag{3}$$

Where Δn_h is the change of the refractive index based on the change in holes concentration.

iii. Change of refractive index, Δn

$$\Delta n = \Delta n_e + \Delta n_h = -[8.8 \times 10^{-22} \Delta n_e + 8.5 \times 10^{-18} (\Delta n_h)^{0.8}] \tag{4}$$

Where Δn is the change of refractive index; addition of Δn_e (change in electron concentration) and Δn_h (change in holes concentration).

iv. Change of absorption coefficient, $\Delta\alpha$

$$\Delta\alpha = \Delta\alpha_e + \Delta\alpha_h = -[8.5 \times 10^{-18} \Delta n_e + 6.0 \times 10^{-18} \Delta n_h] \tag{5}$$

Where $\Delta\alpha_e$ is the of absorption change based on the change in electron concentration while $\Delta\alpha_h$ is the of absorption change based on the change in hole concentration.

v. Absorption loss, α_π

$$\alpha_\pi = 10 \log e^{-(\Delta\alpha) L_\pi} \tag{6}$$

Where α_π is the absorption loss based on the change of absorption coefficient and modulation length in radian.

vi. Phase shift, $\Delta\theta$

$$\Delta\theta = 2\pi \Delta n L / \lambda \tag{7}$$

Where L is the length of the device phase shift is $500\mu m$.

vii. Length in radian, L_π

$$L_\pi = \lambda/2\Delta n \tag{8}$$

4

Where L_π is the length in the z-direction to obtain π phase shift modulation.

viii. Modulation efficiency, $V_\pi L_\pi$

$$V_\pi L_\pi = V_\pi \times L_\pi \tag{9}$$

The value of the modulation is the multiplication of V_π and L_π where V_π is the voltage supplied to the device to achieve a π phase shift.

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CHAPTER 3

METHODOLOGY

The flow on how the project is conducted is elaborated in this chapter. In this chapter, the method, technique, procedure and step taken in obtaining the preliminary results for this project is discussed.

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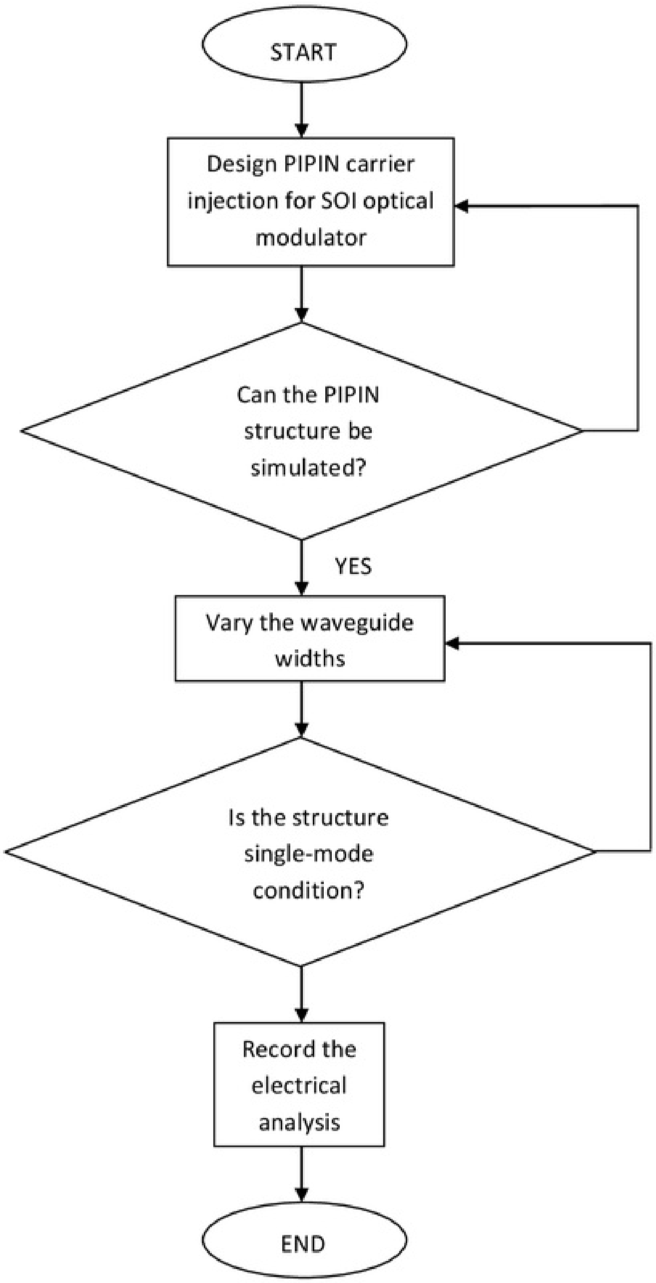
3.1 Flow Chart



The flowchart shows steps to design different waveguide widths for PIPIN carrier injection SOI optical modulator.

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3.2 Software

In order for this project to simulate, the Technology Computer Aided Design (TCAD) software using the program Silvaco is used. The command of ATHENA and ATLAS command are used for the coding of the design structure. The structure is designed in Deckbuild interactive tool where the PIPIN structure is designed using coding in order to obtain the graph for electron concentration and holes concentration of the structure.

3.3 Design Steps in Silvaco Software

The process in which the PIPIN structure created is called patterning. The techniques used and applied to design process of the PIPIN structure are as follow:

i. Deposition – to deposit the material in order to make the PIPIN structure in Silvaco software using Deckbuild.
ii. Etching – to remove the selected area of unprotected area of the PIPIN structure.
iii. Masking – a second material is used to cover and protect the selected PIPIN structure area.
iv. Doping – layer of doping concentration implant of phosphorus p-type and boron at n-type.

3.4 Fabrication Steps Using Silvaco Software

The fabrication of the PIPIN structure is by using coding of ATHENA and ATLAS command to simulate the structure in order to obtain the effect of different waveguide widths of the structure.

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i. Deposition

This step is where the process of designing the silicon substrate and oxide layer according to the wanted length of 0 to 16 microns on the x-axis and 0 to 7 microns on the y-axis. Then, the oxide layer is deposited from 0 to 16 microns at x-axis and 7.5 to 7.9 microns at y-axis. The thickness of the oxide layer is 0.4 microns. Based on the size deposition, the structure produced is as shown in Figure 3.1.

Figure 3.1: Material silicon substrate and oxide layer deposition

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ii. Etching

The etching process is where the unwanted area from the deposition of the original structure is removed. The etching process is done at coordinates of (0, 3.5), (0, 0), (6.5, 0) and (6.5, 3.5) on the left side. For the right side, the etching process is done at coordinates of (9.5, 3.5), (9.5, 0), (16, 9.5) and (16, 0). The structure produce once the etching process is done is as shown in Figure 3.2.

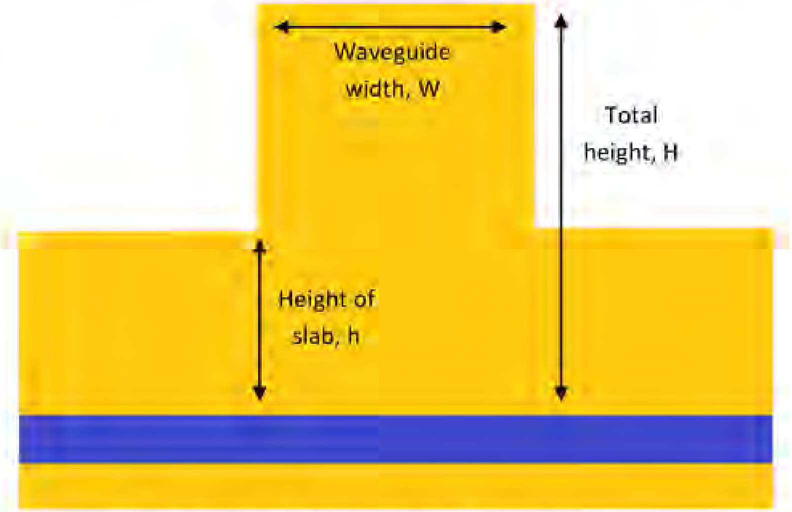

Figure 3.2: Etching of silicon substrate

iii. Masking

In this step is where the masking of the structure occurs. The masking process is where a second material is placed layer on the silicon substrate so that the doping of the substrate can be applied at the wanted area only. The result of masking can be seen in Figure 3.3.

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Figure 3.3: Masking selected area of silicon substrate

iv. Doping

The initial doping of the silicon concentration of boron is 5e24. After, the doping concentration implant for phosphorus at P^+ region (anode) and doping concentration implant for boron at N^+ region (cathode). The result of doping the selected area is shown as Figure 3.4.

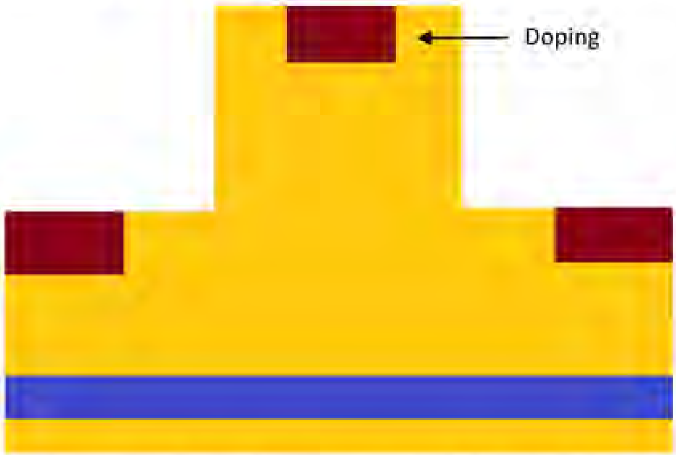

Figure 3.4: Doping concentration of silicon substrate

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v. Metal Contacts

Lastly, the deposition of metal contact of aluminium at thickness of 0.1 for P^+ region (anode) and N^+ region (cathode). The function of the metal contact is to supply voltage to the PIPIN structure in order to produce electron concentration and holes concentration of the PIPIN structure. The placing of metal contacts can be seen as shown in Figure 3.5.

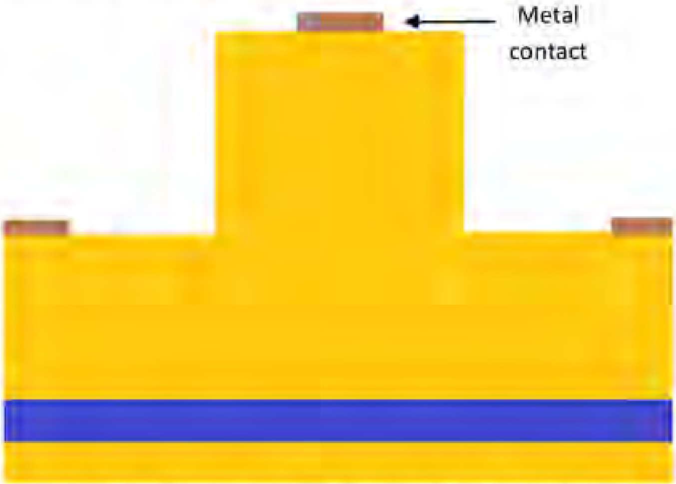

Figure 3.5: Metal contacts are placed on the silicon substrate

3.5 Varying Parameter

The steps of deposition, etching, masking and metal contact are repeated in order to observe and analyze the effects of different waveguide width of the PIPIN carrier depletion SOI optical modulator. The PIPIN structure waveguide is modified to satisfy the single mode condition accordingly. The design structure for parameter 1 with waveguide width of 5 micron, parameter 2 with waveguide width of 4 micron and parameter 3 with waveguide width of 3 micron are shown and analyzed in the next chapter, Chapter 4.

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