EFFECT OF DIFFERENT DOPING CONCENTRATION FOR PN CARRIER DEPLETION SILICON-ON-INSULATOR (SOI) OPTICAL MODULATOR

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To my beloved parents,

To my sister, brothers and friends,

You are the secret of my strength and happiness.

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All praise to Allah for my good health and well being. Without His permission, I won’t be able to finish my journey until now.

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ABSTRACT

Recently, SOI optical modulator is one of the trending technology that is widely used due to its good performance and it is also cost effective. This project highlights the design of PN carrier depletion SOI optical modulator structure and the investigation on the effect of various doping concentration to the device. The device was designed using Atlas and Athena tool provided in Silvaco software. The parameters used to investigate the effect are the change of refractive index and the change of absorption loss. This device is operated at 1.55 µm telecommunication wavelength. The applied reverse biased voltage was -0.75 V. Five different doping concentrations were used and the higher density of doping concentration produces a higher change of refractive index. As the change of refractive index is increases, the change of absorption loss is also increasing. In this project, the device doped with 5×10^{20} cm^{-3} has the highest change of refractive index which will give a good performance to the device.

ABSTRAK

Akhir-akhir ini, pemodulat optik SOI telah menjadi satu trend didalam teknologi terkini dimana ianya telah digunakan secara meluas kerana harganya yg berpatutan dan memberi prestasi yang baik. Project ini mengetengahkan tentang reka bentuk pemodulat optic SOI dengan struktur pembawa susutan PN dan kajian tentang kesan beberapa kepekatan dopan terhadap prestasi peranti tersebut. Peranti in direka menggunakan Atlas dan Athena yang terdapat didalam pakej simulasi perisian Silvaco. Parameter yang digunakan untuk mengkaji kesan tersebut adalah perubahan indeks refraktif dan perubahan kehilangan serapan. Peranti ini beroperasi pada panjang gelombang telekomunikasi sebanyak 1.55 µm. Voltan yang dialirkan pada peranti in adalah -0.75 V pada pincangan songsang. Lima kepekatan dopan yang berbeza digunakan dan kepekatan dopan yang tinggi akan menghasilkan perubahan indeks refraktif yang tinggi. Pada masa yang sama, perubahan kehilang serapan juga akan meningkat. Dalam projek ini, peranti yang telah didopan dengan kepekatan dopan sebanyak 5×10^{20} cm^{-3} telah menghasilkan kadar perubahan indeks refraktif yang tinggi dimana ianya akan menjadikan peranti berprestasi dengan lebih baik.

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CHAPTER 1

INTRODUCTION

Silicon-on-insulator (SOI) optical modulator is the device that is using SOI as the material for optical modulator. The optical modulator is the device to modulate data into light. There are few outputs that will be exist in the process such as the change of refractive index, change of absorption loss and change of phase shift of the light. These outputs can be changed by changing the device's properties such as the doping concentration, doping position and waveguide width. In this project, the study is on how the doping concentration can affect the PN carrier depletion SOI optical modulator.

1.1 Project Introduction

Silicon-on-insulator (SOI) is a semiconductor that consists of the layers of a silicon, insulator and silicon substrate. Figure 1 shows the SOI structure that is layered with a thin silicon, insulator and silicon substrate. Recently, SOI is one of the trending technology that is widely used to fabricate optoelectronic devices due to high index contrast between the silicon core and the silica cladding. It is also becoming popular as it is cheap and demonstrates very good performance.

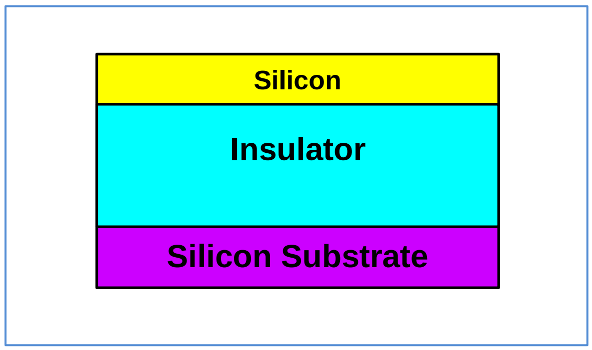

Figure 1 Silicon On Insulator layers

The application of silicon in modulator has been discovered ever since the research of using Silicon in the photonic circuit. In the mid-1980s, they have been studied the Si photonic circuit as the initial work on the fundamental waveguide technology and it is showed that the silicon is a feasible device to use in semiconductor field [1].

Optical modulator will modulate data into light. The outputs that will be exist in this process are the change of refractive index, change of absorption loss and change of phase shift of the light. These outputs can be measured so that the performance can be analyzed.

The doping process is important for semiconductor in order to control their conductivity by adding impurities using ion implantation method. The quantity of determining its concentration and indirectly affects many of its electrical properties. Thus, the performance of carrier depletion SOI optical modulator with various doping concentrations can be investigated.

To investigate the performance, parameters such as the refractive index changes, the absorption loss and the phase shift of the phase modulator can also be compared. The parameters that have been compared are assumed to give result of different performance of the SOI. This project will also produce the structure of PN carrier depletion SOI optical modulator and it is also supplied with reverse supply (reverse bias).

1.2 Problem Statement

The various doping concentrations affect the performance of the SOI optical modulator. Therefore, the analysis of varying different doping concentration on the modulator's performance should be conducted for guidance in fabrication process.

1.3 Objectives

After completing the project, student will be able to:

- Design the PN carrier depletion SOI optical modulator structure using Silvaco Software.
- Investigate the effect of variation doping concentration to the PN carrier depletion SOI optical modulator.

1.4 Scope of Project

The Silvaco software is utilized in the project in order to design the optical modulator and it is also involved the Atlas and Athena tools. The Atlas tool is used as the medium to find the refractive index, the absorption loss and the phase shift modulator. While Athena tool is used to design the structure. This device is designed to operate at 1.55 µm optical wavelength.

1.5 Report Structure

This report consists of 5 chapters. There are Chapter 1: Introduction, Chapter 2: Literature Review, Chapter 3: Methodology, Chapter 4: Results and Discussions and also Chapter 5: Conclusion. The project background, objectives, the problem statement and the scope of the project are discussed in the chapter of Introduction. While the background studies of this project are written in the Literature Review's chapter. Chapter of Methodology briefs the method used to design the structure and how the project is being studied. All the results are written and discussed in Chapter 4. The last but not the least is Chapter 5 which contains the conclusion of the project and its future development.

CHAPTER 2

LITERATURE REVIEW

Since the first era of research on optical circuits in the 1970s, there have been visions of designing an optical chip that has the capabilities to conduct optical circuit's behavior. The optical superchip was said to have variety optical components and may carry out modulation, manipulation, light generation, detection and also amplification [1].

In the early phase of optical circuit research, the optical circuit was associated with materials such as lithium niobate ($LiNb0_3$) and III-IV semiconductor which are in a group of ferroelectric material. The characteristics of the material are exhibit, can go over in the range of temperature and have a natural electric polarization. However, the choice to use silicon (Si) as the semiconductor and been widely used in microelectronics, have bring to investigation of silicon photonic circuit [1].

In silicon optical circuit, the light modulation is usually achieved via free carrier plasma dispersion effect. The dispersion effects which are the change in holes and electron concentration led to the change of refractive index of the device. The effect will also modify the propagation velocity of light and the absorption coefficient [2].

2.1 Silicon-on-Insulator (SOI)

The fundamental silicon material consists of a crystalline solid that have the arrangement of an atom in repetitive structure. Figure 2 shows the unit cell of the silicon crystal and each sphere represents a silicon atom. The unit cell is duplicated in all three directions that strap together in order to form a silicon crystal structure. Each of the Si atom is also has four closest neighbors [3].

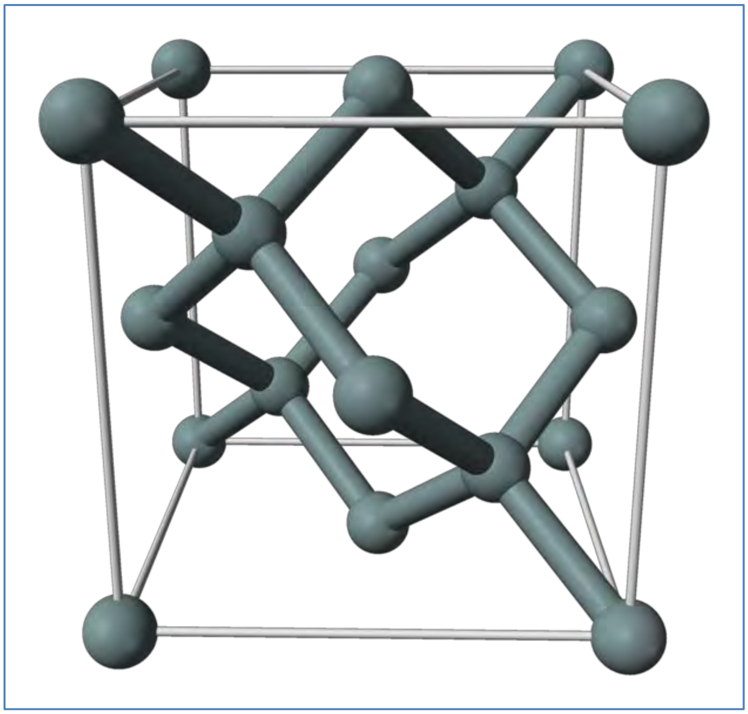

Figure 2 Ball-and-stick model of the unit cell of silicon [15]

In an intrinsic Si crystal, there are few mobile electrons and holes. The concentration for Si is ~10^{10} cm^{-3} which are the intrinsic carrier concentration. Electrons and holes are also the most significant character in semiconductor as it convey a negative charge, positive charge and free electron mass [2].

In the manufacturing, there are a few major steps to be done to produce SOI wafer such in the Figure 3. While Figure 4 shows the illustration of step to make the SOI wafer. The silicon wafer is implanted with hydrogen and the hydrogen concentration peaks at some distance below the surface. Then, two wafers are holding each other by the atomic bonding force, upside down. A low temperature annealing causes the two wafers to fuse together. The silicon wafer is then applied with another annealing step that causes the implanted hydrogen to coalesce and form a large number of tiny hydrogen bubbles at the same distance of the peak below the surface. This step will create sufficient mechanical stress to break the wafer at that plane.

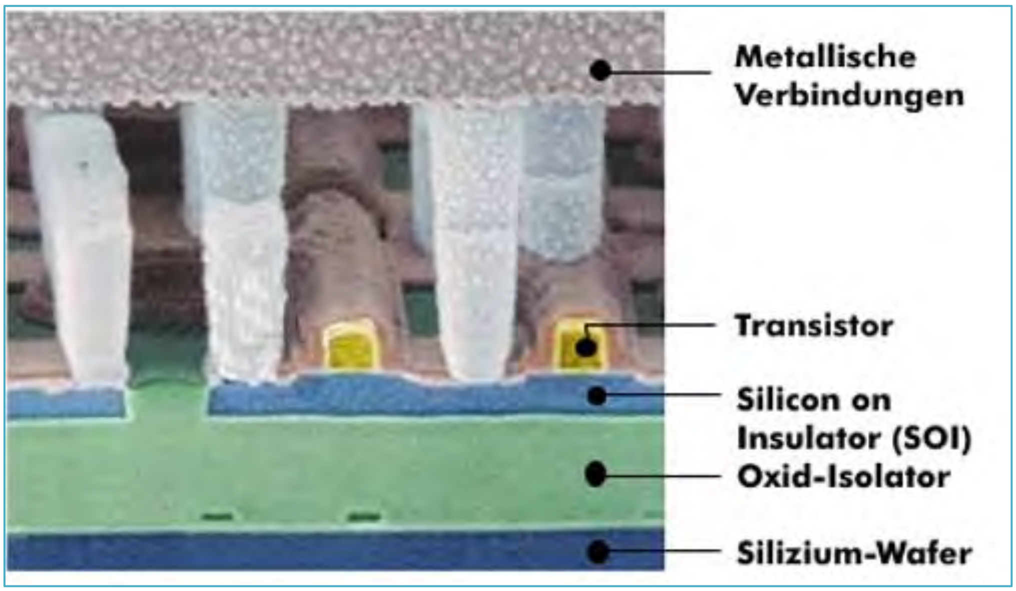

Figure 3 SOI on chip [4]

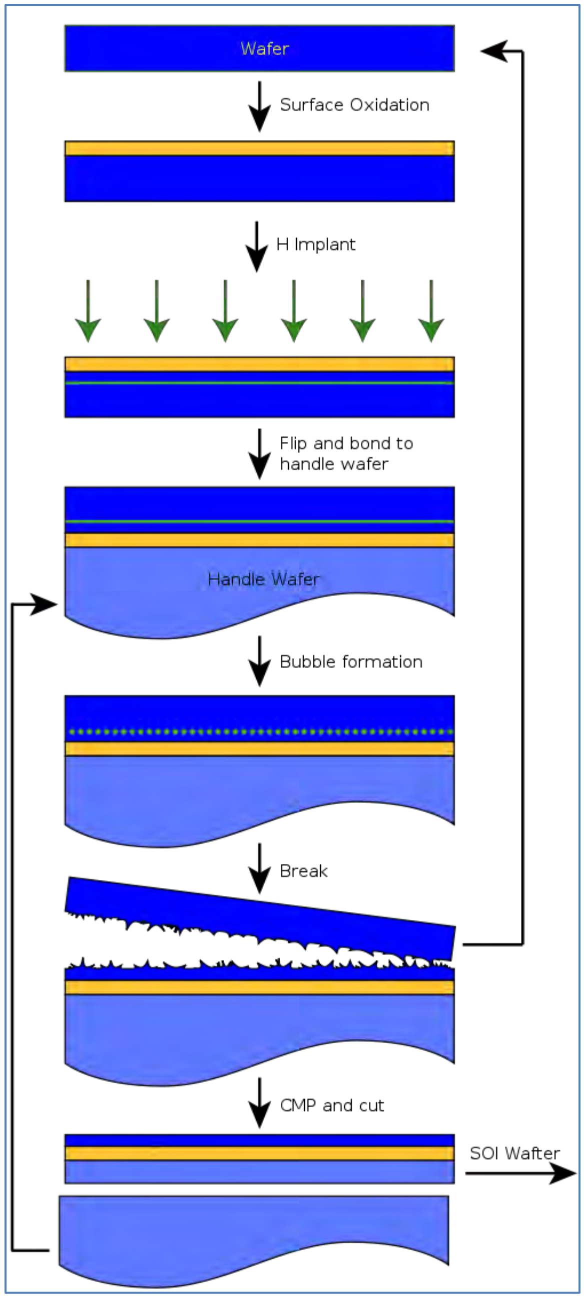

Figure 4 Steps of making SOI wafer [5]

2.2 SOI Optical Modulator

Silicon developments have also continued to grow silicon based technology to improve the frontiers of device integration, complexity and speed. For example, computer and high speed electronics device are the application that is demand in switching field [6].

The other type of semiconductor material such as III-V alloys, it has the characteristics that maintains to be part of the construction of the optoelectronic and a plain photonic device. The relationship of photonics is the technology and the signal generation, processing, transmission and detection is where the signal is carried by light. The examples of photonic devices are such as lasers, waveguides, modulators, detectors and optical fiber [7].

The optical modulator is an optoelectronic device that provides modulated optical signal at the output and driven by an electrical command when a continuous input beam is provided at the input. This can be shown in Figure 5 which it is an example of one type of modulator. [8]

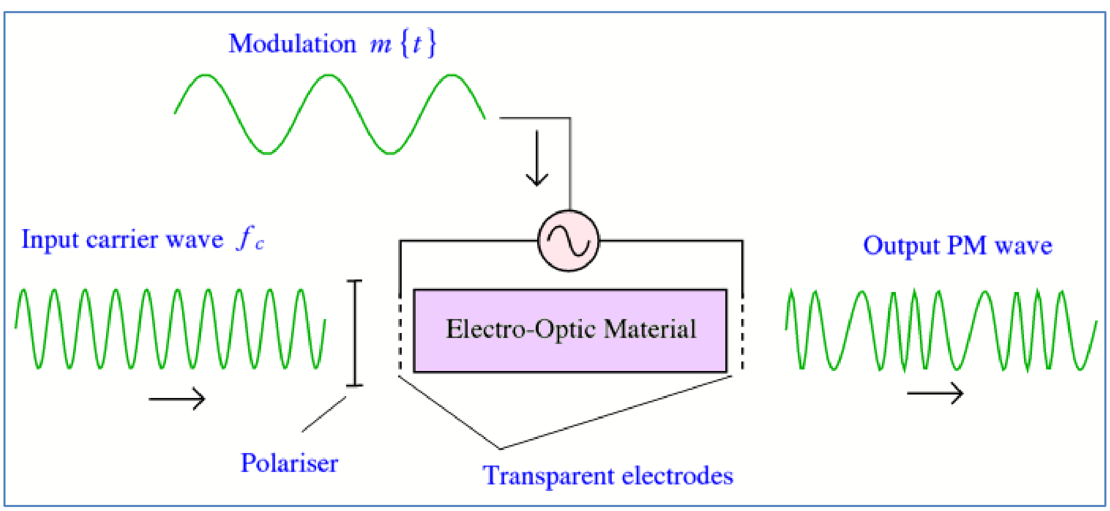

Figure 5 Electro-optic modulator [9]