ELECTRICAL ANALYSIS OF SILICON PHASE MODULATOR BASED ON CARRIER DISPERSION EFFECT AT λ, 1.3 μM AND 1.55 μM

Hazura H, Hanim A.R, Mardiana B, Sahbudin Shaari, Member IEEE

Institute of Microengineering and Nanoelectronics
Universiti Kebangsaan Malaysia
43600 Bangi, Selangor, MALAYSIA

hazura@utem.edu.my, hanim@utem.edu.my,
mardiana@utem.edu.my, sahbudin@eng.ukm.my

Abstract

This paper highlights study of carrier dispersion effect on silicon waveguide with p-i-n diode and n-p-n structure. The device performance is predicted by using 2D Silvaco CAD software under different applied voltages. This report investigates on three aspects which are effective refractive index variations of the device in forward and reverse biased, performance modulation efficiency and free carrier absorption loss. The phase modulator device has less sensitivity to the effective refractive index changes when operating in reverse biased or depletion mode compared to the forward biased or injection mode. Both designs prove that working at wavelength 1.55 μm is suggested to have a device with better phase modulation efficiency. Structure-wise, n-p-n structure is more efficient with VπLπ 0.8 Vcm but suffers more absorption loss with 0.03452082 dB/cm. The modulation efficiency for p-i-n structure is less with 1.2Vcm but experiences less absorption loss with 0.03373607 dB/cm.

Keywords: *phase modulator, effective refractive index variations, modulation efficiency, free carrier absorption loss.*

I. INTRODUCTION

Since the 1980's, silicon photonic devices have been extensively studied, however a submicrometre-size photonic devices have been realized only in the last few years. Silicon properties namely the transparency in the range of optical telecommunications wavelengths and high index of refraction, have enabled the fabrication of low loss submicron waveguide. Photonic devices such as splitter, coupler, and filter have been demonstrated in silicon but once the device has been fabricated, the properties of the device are predetermined. A silicon based modulator can be used to control the flow of light, where the refractive index of the silicon waveguide can be varies thus, induce a change in the transmission properties.

A refractive index of a silicon modulator can be physically altered based on free carrier concentration variation. There are several means that can be used to vary the carrier concentration in silicon: injection, accumulation, depletion, or inversion of carrier. In this paper, we investigated the performance of the silicon modulator for carrier depletion based device. Recent works have focused on designing a smaller and high speed device, while less on the effect of the optical and electrical properties to the design. The fundamentals study based on the device performance is crucial as the motivation for designing high speed and high efficiency photonic device to be integrated in any optoelectronic applications.

According to Reed [1], there are three sources of losses in an optical waveguide namely absorption, scattering, and radiation. However, for the purpose of this study, absorption loss is of the primary focus.

Band edge absorption (or interband absorption) and free carrier absorption are the two main potential sources of absorption loss. Interband absorption is due to the absorption of photons with energy greater than the band gap to excite electrons from the valence band to the conduction band. Thus, in order to avoid interband absorption, a wavelength selection must be longer than the absorption edge wavelength of the material. Since the band edge wavelength of silicon is 1.1μm, for wavelength less than 1.1μm, silicon absorbs very strongly. The absorption of pure silicon at 1.15μm exhibits loss of 2.83dB/cm while at 1.52μm, the loss is reduced to 0.004dB/cm. Thus, a suitable selection of wavelength will ensure negligible band edge absorption of semiconductor waveguide. Therefore, the band edge absorption is negligible at 1.3 and 1.55μm.

The significant absorption in semiconductor waveguides is therefore the free carrier absorption. The real and imaginary refractive indices will be affected by the concentration of free carriers.

The Drude-Lorenz equations generally described the change in the concentration of electrons (ΔNe) and holes (ΔNh) to the absorption coefficient ($\Delta\alpha$) and refractive index change (Δn) [1,2,3]:

$$\Delta\alpha = (e^3 \lambda^2/4\pi^2 c^3 \varepsilon_0 n)[\Delta N_e/m^*{}_e{}^2\mu_e + \Delta N_h/ m^*{}_h{}^2\mu_h] \quad (1)$$

where

e	electron charge
c	light vacuum
ε_0	vacuum permittivity
λ	wavelength in the vacuum
n	refractive index of intrinsic silicon
m^*_e	effective mass of electron
m^*_h	effective mass of electron
μ_e	electron mobilities
μ_h	hole mobilities

Soref and Bennet [4] quantified the changes that they had identified from the literature for both changes in refractive index and in absorption. 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 λ_0 = 1.55 μm:

$$\Delta n = \Delta n_e + \Delta n_h = -[8.8 \text{ x } 10^{-22}\, \Delta N_e + 8.5 \text{ x } 10^{-18}\, (\Delta N_h)^{0.8}] \quad (2)$$

$$\Delta\alpha = \Delta\alpha_e + \Delta\alpha_h = 8.5 \text{ x } 10^{-18}\, \Delta N_e + 6.0 \text{ x } 10^{-18}\, \Delta N_h \quad (3)$$

At λ_0 = 1.3 μm:

$$\Delta n = \Delta n_e + \Delta n_h = -[6.2 \text{ x } 10^{-22}\, \Delta N_e + 6.0 \text{ x } 10^{-18}\, (\Delta N_h)^{0.8}] \quad (4)$$

$$\Delta\alpha = \Delta\alpha_e + \Delta\alpha_h = 6.0 \text{ x } 10^{-18}\, \Delta N_e + 4.0 \text{ x } 10^{-18}\, \Delta N_h \quad (5)$$

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
$\Delta\alpha_e$	change in absorption resulting from change in free electron carrier concentrations
$\Delta\alpha_h$	change in absorption resulting from change in free hole carrier concentrations

From (2) and (3), it is shown that as the number of injected carriers decreases, the change in refractive index increases. At wavelength of λ = 1.3 μm, the change in refractive index is less. It is also shown from (3) and (5) that the change of absorption is influenced by the change in the silicon refractive index.

The free carrier absorption loss at π phase shift, $\alpha\pi$ (in dB) in the length of $L\pi$ is given by the following relationship[3,4].

$$\alpha_\pi = 10 \log \{\exp[-(\Delta\alpha)\, L_\pi]\} \quad (6)$$

where

L_π	length required to obtain a π phase shift of the guided wave
Δ_α	change in free carrier absorption

II. SILICON MODULATOR DESIGN

To date, several device configurations such as p-i-n diode structure [5,6,7] and, MOS capacitor [8] have been proposed. We studied a micrometer scale silicon modulator based on p-i-n diode and NPN structures to be operated at 1.55μm and 1.3μm optical wavelength.

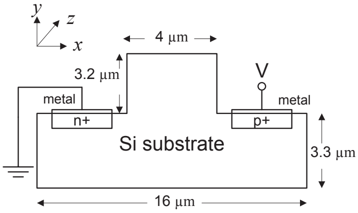

Fig.1 Silicon modulator p-i-n structure cross section.

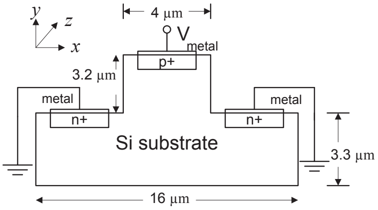

Fig.2 Silicon modulator n-p-n structure cross section.

Fig.1 and Fig.2 show the waveguide cross section of the silicon optical modulator where the modulation acts. The p-i-n and n-p-n diode configurations have been employed in our design to study the performance of each modulator design.

The P^+ type region is implanted with 5x1018 cm^{-3} Boron concentrations while the N+ type region is phosphorus implanted region with a concentration of 5x1018 cm-3. Both structures have a background doping concentrations of 1x 1014. For both structure, the depth of the implanted region is about 1.8 μm for N+ region and 1.6 μm for P+ region. The rib height and width for both structure is chosen in order to have a single mode behavior. The rib structure is designed to have 3.2 μm in height and 4 μm in width. With the chosen doping concentrations for both structures, the distance of the doped regions to the rib sidewalls turns to be 1.4 μm for the first proposed structure and 1μm for the second structure.

As mentioned before, in order to alter the refractive index of the silicon waveguide, the free carrier concentrations of the waveguide can be varied by depletion [9,10] or injection [11,12] carrier method. In carrier depletion method, a negative bias is applied to the P electrode which in turns changes the width of the depletion region thus eventually changing the effective refractive index. In contrast, the carrier injection can be obtained with the structure is forward. The injected current will proportionally vary the refractive index and optical absorption of the silicon waveguide.

The optical power of 1mW is applied to our design for both structures and the effect of refractive index variations for 1.55μm and 1.3μm optical wavelength is investigated. The important parameters employed in the simulations are shown in Table 1.

Table 1 Simulations parameters

Si refractive index	3.475
Si background carrier conc. (cm^{-3})	$1x10^{14}$
τ_p	$2x10^{-6}$
T_n	$2x10^{-6}$
Temperature (K)	300

III. RESULTS AND DISCUSSION

The carrier dispersion effect on refractive index of a silicon waveguide has been theoretically investigated by using a two dimensional simulation package, Silvaco. We used ATHENA to simulate the device structure and ATLAS to obtain the device characteristics. This report investigates on three aspects which are effective refractive index variations of the device in forward and reverse biased, performance modulation efficiency and free carrier absorption loss.

A. Effective Refractive Index Variations

In this study, the active region of the modulator has been tested under DC operation. The active device will be operated by applying an external electrical signal to the electrodes. The disturbed free carriers will cause a distinct change in the effective refractive index [5].

Two type of dc testing have been done in this work. They are forward biased and the reverse biased. In the forward biased, a positive bias is applied to the P electrode. It is expected, the extra carriers will be injected into the waveguide.

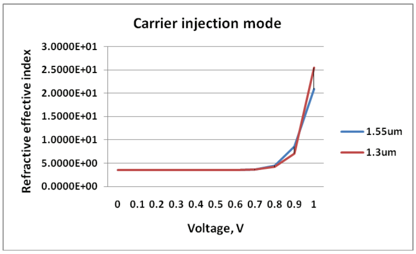

Fig. 3: Effective refractive index change for increasingforward bias voltage.

Fig. 3 shows the result of the effective refractive index changes by varies the forward bias voltage from 0 to 1V. The result show the effective refractive index have changed drastically at 0.9V onwards. The index variation of 1.74x10 is obtained in between 0 and 1V. It's means, the effective refractive index have a high sensitivity changes with a little increasing of forward bias value after 0.9V and it will give a significant effect to the phase modulation. By injecting both holes and electrons in the active region of the modulator, a much higher changes in the index of the refraction can be realized. It is due to both electrons and holes contribution.

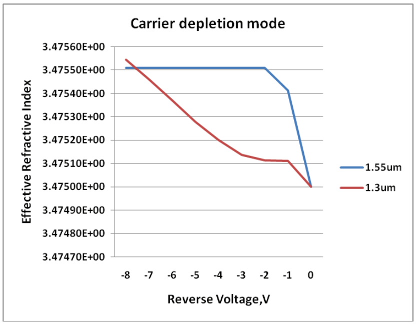

Fig.4: Effective refractive index change for increasing reverse bias voltage.

In the reverse biased testing, a negative bias is applied to the P electrode in which it will change the width of the depletion region thus eventually changing the effective refractive index.

Fig. 4 shows the changes of effective refractive index in reverse bias. The effective index variation increases as the reverse bias voltage increases. The index variation of 5.09x10-4 is obtained between 0V and -8V. Its indicate the index variation value of the effective refractive index in reverse bias is much more smaller than the value of the index variation in the forward bias testing.

When a reverse bias is applied to the diode, the holes were rid out. The holes concentration variation is responsible for the effective index variation in which created a phase shift of the guided mode. To get a high effective refractive index changes, a huge overlapping between the carrier density zone and the guided mode must be obtained.

In conclusion, the active region of the device possess less sensitivity to the effective refractive index changes when operating in reverse biased or depletion mode compared to the forward biased or injection mode. Therefore, the following analyses will focus on carrier depletion mode.

B. Phase Modulation Efficiency

The performance of the silicon modulator is evaluated based on the device modulation efficiency. By observing the doping concentrations variations at the waveguide center (x=4µm, y=8µm), it enables us to work out for refractive index change for a specific bias voltage and therefore the resulting phase shift and length of the device, where the relationship can be summarized as:

$$\theta = (2\pi\Delta n)/\lambda_o \qquad (7)$$

where *L* is the length of the modulator. For π-radian phase shift, the estimated length will be:

$$L_\pi = \lambda_o/2\Delta n \qquad (8)$$

Based on (8), graphs as shown in Fig.5 and Fig.6 are plotted.

For p-i-n diode structure, between -2 to -8 bias voltage, the estimated modulator length is nearly the same for both 1.55µm and 1.3 µm wavelength.

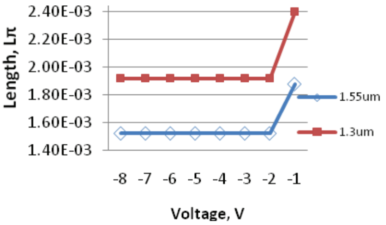

Fig.5 Estimated modulator length for p-i-n diode configuration.

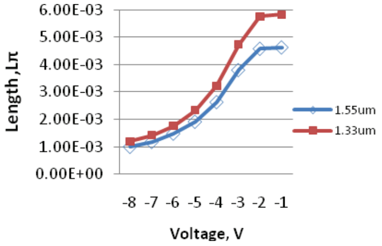

Fig.6 Estimated modulator length for n-p-n diode configuration.

For 1.55µm, the predicted length is about 1.52 mm while for 1.3 µm, 1.92mm. The estimated length of the device is dramatically increased when -1 bias is applied where the length is about 2.4 mm for 1.3 µm and 1.88mm for 1.55 µm.

In contrast, the length of the modulator employing NPN structure decreased linearly with the increase of reverse voltage. With -8 applied voltage, the possible length is about 0.99 mm for 1.55 µm and 1.2 mm for 1.3 µm.

Both results show that a smaller device can be realized if the device is designed to be operated at 1.55 µm compared to 1.3 µm wavelength. But since the free carrier dispersion effect is relatively weak in silicon, a long device is well expected to be functioned as a modulator for both wavelengths.

From (8), it can be seen that the length of the modulator will shrink as the refractive index variation increased. The phase modulation efficiency of the device can be calculated by VπLπ, where Vπ is the voltage to achieve a π phase shift. The simulation shows that with -8 V, the VπLπ of the p-i-n diode modulator is 1.53 Vcm for 1.3 µm wavelength and 1.2 Vcm for 1.55 µm. While for NPN configuration, the VπLπ for 1.3 µm is 0.96 Vcm and 0.8 Vcm for 1.55 µm. Both designs prove that working at wavelength 1.55 µm is suggested to have a device with better phase modulation efficiency.

An improved phase modulation efficiency can be obtained by shortening the device length. This can be made by shrinking the size of the waveguide to a smaller dimensions [13,14,15,16].

We have estimated the theoretical performance of silicon modulator. In our design, carrier depletion is used as one of the most efficient means of implementing optical modulation. For NPN waveguide configurations, the overlapping between the optical mode and the nonequilibrium charge distributions is larger; therefore a smaller device is expected due to higher refractive index change. Even though simulation shows that the demonstration of a high efficiency silicon modulator looks promising, a real challenge still depends on the fabrication technology.

C. Free Carrier Absorption Loss

The simulated results are plotted in Fig. 7 and Fig. 8 at wavelength $\lambda = 1.55$ µm and $\lambda = 1.3$ µm respectively.

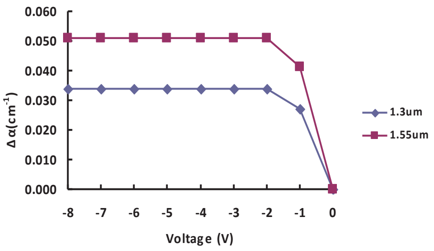

Fig. 7 Change of absorption against applied voltage for p-i-n structure

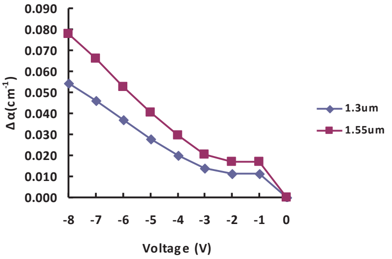

Fig. 8 Change of absorption against applied voltage for n-p-n structure

For both structures, $\Delta\alpha$ for 1.3µm is less than that of 1.55µm. It also can be noted that the more negative the applied voltage is, the higher $\Delta\alpha$ is.

At π phase shift at applied voltage of -8V, $L\pi$ for both wavelength were calculated and the free carrier absorption loss has been determined as in Table 2 and Table 3 for both structure using (6).

Table 2 Free carrier absorption loss for p-i-n structure

λ (µm)	Δα	α_π (dB/cm)
1.3	0.0340000	0.02829864
1.55	0.0510000	0.03373607

Table 3 Free carrier absorption loss for n-p-n structure

λ (µm)	Δα	α_π (dB/cm)
1.3	0.0543999	0.02822914
1.55	0.0799999	0.03452082

For both structures, the free carrier absorption loss at 1.55µm is higher than the loss at 1.3µm. Meanwhile, the free carrier absorption loss for n-p-n structure is greater than p-i-n structure at 1.55 µm. N-p-n structure experiences a trade-off between modulation efficiency and free carrier absorption loss. Even though a three- terminal devices offer more efficient carrier injection/depletion but the main drawback is extra optical attenuation occurs due to the doping contact at the rib top.

ACKNOWLEDGMENT

The authors would like to thank Universiti Teknikal Malaysia Melaka (UTeM) for the support and to the staff of Photonic Technology Lab and Clean room of Institute of Microelectronic and Nanotechnology, Universiti Kebangsaan Malaysia for the guidance and co-operation.

REFERENCES

[1] G. T. Reed and A. P. Knights, Silicon Photonics –An Introduction, John Wiley & Sons (2004).

[2] R.A. Soref and J.P. Lorenzo, "All-silicon active and passive guided-wave components for λ = 1.3 and 1.6 µm," IEEE Journal of Quantum Electronics, vol. QE-22, no.6, pp.873-879 (1986).

[3] R. A. Soref and B. R. Bennet, "Electrooptical effects in silicon", Journal of Quantum Electronics, vol. QE-23, no. 1, pp. 123-129 (1987).

[4] Z. Li, D. Xu, W.R. McKinnon, S. Janz, J.H. Schmid, P. Cheben and J. Yu, "Silicon waveguide modulator based on carrier depletion in periodically interleaved PN junctions", Optics

Express, vol. 17, no. 18, pp. 15947-15958 (2009).

[5] A. Brimont, F.Y Gardes, P. Sanchis, D. Marris-Morrini, P. Dumon, J.M Fedeli, L. O'Faolin, W. Boagert, L. Vivien, J. Marti, G.T Reed, and T.F. Krauss, "Design of a micro-ring resonator electro-optical modulator embedded in a reverse biased PN junction", Proc. ECIO, ThD4, pp. 15947- 15958, 2008.

[6] Zhi-Yong Li, Dan-Xia Xu, W. Ross Mc Kinnon, Siegfried Janz, Jens H. Schmid, Pavel Cheben, and Jin-Zhong Yu, "Silicon waveguide modulator based on carrier depletion in periodically interleaved PN junctions", Optics Express, Vol.17, No.18, pp. 15947-15958, 2009.

[7] Giuseppe Coppola, Iodice Mario, Ivo Rendina, "Analysis of a planar silicon optoelectronic modulator based on the waveguide- vanishing effect", Proc. Of SPIE, Vol. 6593, 2007.

[8] L.Liao, D. Samara-Rubio, M.Morse, A. Liu, H. Hodge, D. Rubin, U.D Keil, T. Franck, "High Speed silic.on Mach-Zehnder modulator", Opt. Express 13, pp.3129-3135, 2005.

[9] A. Brimont, F.Y Gardes, P. Sanchis, D. Marris-Morrini, P. Dumon, J.M Fedeli, L. O'Faolin, W. Boagert, L. Vivien, J. Marti, G.T Reed, and T.F. Krauss, "Design of a micro-ring resonator electro-optical modulator embedded in a reverse biased PN junction", Proc. ECIO, ThD4, pp. 15947- 15958, 2008.

[10] Zhi-Yong Li, Dan-Xia Xu, W. Ross Mc Kinnon, Siegfried Janz, Jens H. Schmid, Pavel Cheben, and Jin-Zhong Yu, "Silicon waveguide modulator based on carrier depletion in periodically interleaved PN junctions", Optics Express, Vol.17, No.18, pp. 15947-15958, 2009.

[11] Giuseppe Coppola, Iodice Mario, Ivo Rendina, "Analysis of a planar silicon optoelectronic modulator based on the waveguide- vanishing effect", Proc. Of SPIE, Vol. 6593, 2007.

[12] V. R. Almeida, C. A. Barrios, R.R Panepucci, and M. Lipson, "All-optical control of light on a silicon chip", Nature, vol.431, no.7012, pp. 1081-1084, 2004.

[13] Delphine Marris-Morrini, Xavier Le Roux, Daniel Pascal, Laurent Vivien, Eric Cassan, Jean Marc Fedeli, Jean Francois Damlencourt, David Bouville, Jose Palomo, and Suzanne Laval, "High speed all- silicon optical modulator", Journal of Luminescence, vol. 121, pp.387-390, 2006.

[14] A.Cutolo, M.Iodice, A.Irace, P.Spirito, and Zeni, "An electrically controlled Bragg reflector integrated in a rib silicon on insulator waveguide," Appl. Phys.Lett., vol.71, no.2, pp.199, 1997.

[15] C. Angulos Barrios, V.R Almeida, and M. Lipson, "Low-power-consumption short-length and high- modulation-depth silicon electro-optic modulator," J. Lightwave Technol., vol.21, no.4, pp. 1089-1098, 2003.

[16] C. Angulos Barrios, V.R Almeida, R.Panepucci,and M. Lipson, "Electrooptic modulation of silicon-on-Insulator submicronmeter-size waveguide devices", J. Lightwave Technol., vol.21, no.10, pp. 2332-2339, 2003..

[17] S. Libertino and A. Sciuto, Electro-Optical Modulators in Silicon, Springer Series in Optical Sciences (2006).