# EC 4094 : SEMINAR

# ‘SILICON PHOTONICS’

Submitted by

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## CERTIFICATE

This is to certify that this report titled “Silicon Photonics” is a bonfide record of the seminar work presented by Kasyap V Karun (B130241EC) in partial fulfilment of the requirements for the award of the Degree of Bachelor of Technology in Electronics and Communication Engineering from the National Institute of Technology Calicut.

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# Contents

# Acknowledgement

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# Abstract

Silicon photonics is widely accepted as the next generation technology in data communication and data interconnects. The potential of integrated silicon-photonics is recognized initially in the studies of waveguides in silicon on insulator (SOI) wafer structure [1]. The computer industry has been governed by Moore's Law for more than half a century. But the problem with Moore's Law is that it is reaching the limit. The other concern is huge power dissipation in the devices. One of the fastest computers nowadays named Tianhe-2, consumes 17MW to power it and additional 7MW for cooling [2]. Silicon photonics (or Silicon Nano Photonics) uses light instead of electrical signal to transfer data, allowing larger amount of data to be transferred in little time between computer chips with lesser power dissipation. In practical scenario, Optics will replace copper if and only if it has compelling advantages. If research and development succeed in making on-chip optical linkages sufficiently fast, small, efficient, cheap, and reliable, then "long" copper paths would be replaced and many millions of such OE chips would appear in next-generation personal computers, notebooks, and gaming boxes [3]. Since most of the energy loss in devices nowadays is due to long copper/metal buses, photonics will be definitely a better alternative for present energy efficient device technologies. On current technology, we can go up to single atomic transistors, but can't go beyond that; it will be literally nuclear fission. So in order to accomplish our rapidly increasing communication needs and simultaneously efficiently use the energy we have to switch to silicon photonics.

# Chapter 1

# Introduction

Recently silicon photonics has attracted attention as an emerging technology in the field of optical communication and for optical interconnections in electronics. Silicon photonics provides us with highly integrated platform with electronics-photonics convergence. Since the saturation of Moore's law had been an issue in developing high speed and low loss electronic gadgets, engineering society is indeed in situation of developing a new technology for low loss-high speed transmission[1]. As the copper wires used nowadays are prone to comparatively high loss and are more temperature sensitive, it would be silicon photonics that will perform the role of transmission lines in ICs in the future [2]. For the practical achievement of this platform, we must search for ways to reduce the propagation loss and coupling loss to external fibres and overcome the polarization dependence. Silicon photonics offers the transmission of light through Si wafer which is of course a non-transparent material. The transmission can be controlled by applying transverse electric potential across the Si wafer which leads to direct coupling of optics with electronics [4]. Silicon photonics has the potential to radically change the landscape of photonics. Its compatibility with well-known and mature CMOS fabrication technology offers advantages, such as low-cost, high-volume and reliable manufacturing with Nano scale precision. Applications can typically be found in telecommunication and data-communication, sensing and advanced instrumentation. Integration with CMOS-based electronics allows for adding the driver and control electronics on the same chip, greatly reducing packaging complexity and cost. Vice-versa the addition of a photonic layer and interconnects hold the promise of solving speed bottlenecks in future computing and chip platforms. Silicon photonics consists of optical sources, optical waveguides, optical modulators and photo detectors [5].

One of the main goals of silicon photonics is to enable the fabrication and integration of electronic and photonic components on the same chip using the existing complementary metal oxide semiconductor (CMOS) processing platform. Due to its intrinsic structural properties, silicon does not exhibit a useful electro-optic effect that could enable light modulation. However, what makes silicon an attractive optical material is its transparency to infrared communication wavelengths and its high refractive index which facilitates the miniaturization of photonic devices. This also enables a high level of light confinement in nanometer sized waveguides and provides an excellent basis to fabricate micro-optical devices [5].

# Chapter 2

# SILICON PHOTONICS SYSTEM

## 2.1) On Chip Optical Sources

Serving as the electrical to optical converter, the on-chip silicon light source is an unavoidable component of silicon photonic technologies and has long been pursued. Recently, the merits and de-merits of on-chip and off-chip light sources respectively for optical interconnections have been comprehensively analysed and discussed. An off-chip light source displays high light-emitting efficiency and good temperature stability but suffers from relatively large coupling losses between the off-chip light source and the Si chip and a high packaging expense. An ideal light source should satisfy the following requirements to fully utilize the current microelectronics and optical communication technologies [6];

- Could emit at approximately 1310 or 1550 nm to connect directly with the fiber optical network.
- Should display high power efficiency for sufficient output power and low energy cost-per-bit in data transmission.
- May be integrated on Si with complementary metal oxide semiconductor (CMOS)-compatible fabrication techniques for large-scale manufacturing.

Fig 2.1.a.Light emitting from an on-chip light source

Present researches primarily focus on the following three types of light sources [7];

1) Er-related light source

2) Ge-on-Si laser

3) III-V-based Si laser

Erbium has an incompletely filled 4f shell, which is well screened by the outer, closed 6s, 5s and 5p shells. The host crystal acts only as a weak perturbation of the free ion energy levels and the electronic states couple very weakly to lattice vibrations when incorporated as a dopant in a semiconductor. So the internal excitations and de excitations of the 4f shell result predominantly in radiative transitions, with extremely narrow line widths and temperature independent wavelengths. Therefore, rare earth ions are widely used as luminescence activation in wide band gap crystals and glasses, with the desired wavelength controlled by a suitable choice of the particular Erbium(Er) ion [8].

Monolithic lasers on Si are ideal for high-volume and large-scale electronic-photonic integration. Ge is an interesting candidate owing to its pseudo direct gap properties and compatibility with Si complementary metal oxide semiconductor technology. They could experimentally produce a gain bandwidth of 1590-1610 nm [9].

III-V semiconductors are obtained by combining group III elements such as Gallium (Ga) and Indium (In) with group V elements such as Phosphorous (P), Arsenic (As) and Nitrogen (N). The band gap and other properties of III-V semiconductors can be varied according to the composition of constituent elements. The lasers made of these materials are also an emerging possibility for high coupling optical sources [7].

The optical information produced by these on-chip light sources according to the available digital information is transferred to optical fibres and then to silicon waveguides.

## 2.2) Silicon Waveguides

A schematic of silicon photonic wire waveguide is shown in Fig. 2.2a. The waveguide consist of a silicon core and silica based cladding.

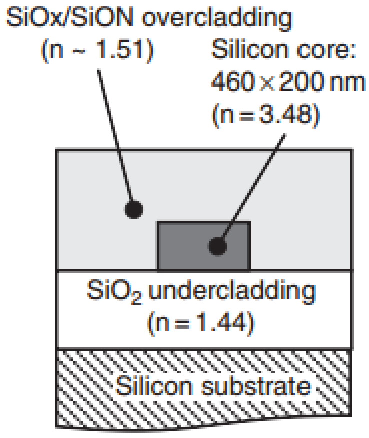


Fig 2.2a.Cross sectional view of Silicon Waveguide

The core dimension of single-mode silicon photonic wire waveguides is significantly smaller than that of conventional single-mode silica waveguides. Unlike silica waveguides which can be relatively easily designed to be single mode, Silicon on Insulator (SOI) waveguides with dimensions larger than a few hundred nanometres in cross-section will support multiple modes. Such multimode waveguides are usually undesirable in photonic circuits as their operation can be seriously compromised by the presence of multiple modes. This situation is similar to that in metallic rectangular waveguides, whose waveguide dimensions are smaller than or comparable to a half-wavelength of the guided electromagnetic waves [10]. In silicon photonic wire waveguides, therefore, the core dimension that fulfils a single-mode condition should also be smaller than or comparable to a half-wavelength of a guided wave in silicon. Since the refractive index of silicon is about 3.5 for photon energies below the band-gap energy, the core dimension of a silicon photonic wire waveguide should be less than or comparable to 400 nm for 1,310~1,550-nm telecommunications-band infrared light [11]. Moreover the rib structure present at the edge of silicon waveguide should be very narrow (of the order of few Nano meters) as shown in the Fig 2.2b [10].

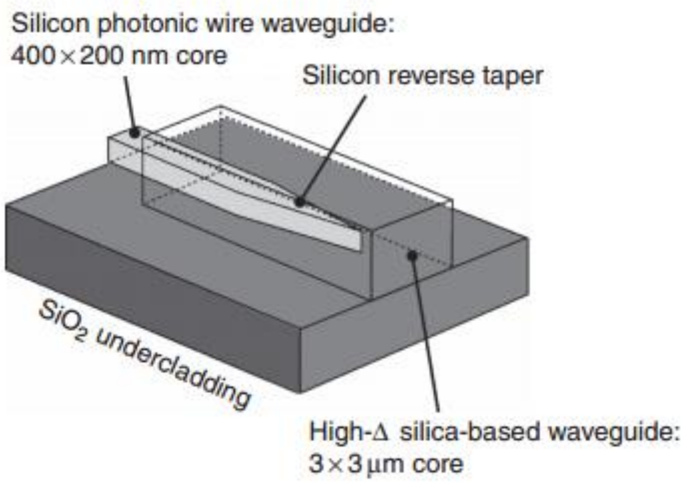


Fig 2.2b.Isotropic view of Silicon waveguide with additional rib like structure

The absence of rib like structure in Si waveguide causes the light energy to be dispersed. The comparison of normal Si waveguide and tapered Si waveguide is shown in below figure;

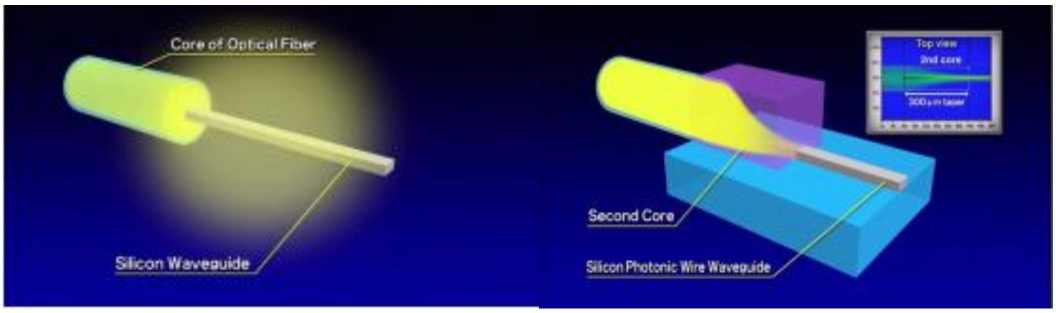


Fig 2.2c.Light dispersion comparison at the end of normal waveguide and waveguide with rib like structure

In the waveguide system consisting of silicon core and silica ($SiO_2$) cladding, the relative refractive index difference is about 40%. As in normal waveguides, the silicon optical waveguide acceptance angle is also having square root dependence on relative refractive index difference and hence allows an acceptance angle up to 60 degrees [11].

Usually silicon photonic transmission system experiences propagation loss and radiation losses due to bending along with coupling losses. The intrinsic loss in undoped silicon is very low for the photon energies below the band gap (~1.1eV); therefore, the propagation loss of photonic wire waveguides is mainly determined by scattering due to surface roughness of the core. The upper bound of the scattering loss $\alpha_{max}$ depends on many factors including the root mean square roughness factor ($\sigma$). The exact relationship is given below in equation 2.2.1.

$$\alpha_{\max} = \frac{\sigma^2 \kappa}{k_0 d^4 n_1}, \tag{2.2.1}$$

where k0, *d*, and *n*1 are wave vector of the light in vacuum, the half-width of the core, and effective index of a silicon slab with the same thickness as the core. The factor $\kappa$ depends on the waveguide geometry and the statistical distribution (Gaussian, exponential, etc.) of the roughness respectively. $\kappa$ is on the order of unity for most practical waveguide geometries. Thus, the scattering loss is inversely proportional to the fourth power of *d*. To achieve a practical scattering loss of a few decibels per centimeter, the surface roughness should be about 1 nm or less.

Since a silicon photonic wire waveguide has a very small mode profile, spot-size conversion is essential for connecting it to external circuits such as single-mode optical fibers. A highly efficient spot size converter (SSC) with a silicon reverse adiabatic taper has already been proposed. The isotropic view of the structure is shown in Fig 2.2d,

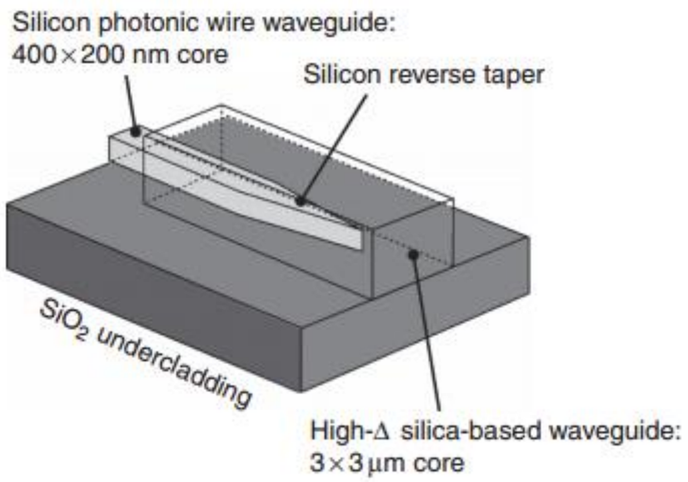


Fig 2.2d.Isotropic view of Silicon waveguide

The tip of the taper should be ultimately reduced to less than 100 nm in a typical design for 1,550-nm-wavelength infrared light and the silica-based waveguide has a 3 $\mu m^2$ core with a 2.5% index contrast to the cladding. Light leaking from the silicon taper is captured by a silica-based waveguide in the above mentioned a double-core structure, which guarantees efficient optical coupling to external optical fibers.

## 2.3) Silicon Modulators

Silicon modulators are devices which do the purpose of modulators in digital communication. The amplitude, phase or polarization of the light or any of the two parameters or all the three parameters is altered according to the arrived data bits at the modulator. Silicon is the preferred material as in waveguide fabrication since it will enhance the ease of fabrication once the technology is invented. Light modulation in silicon modulators is usually achieved via the 'free-carrier plasma dispersion effect'. It is the effect in which a change in carrier concentration (holes and electrons) is used to change the refractive index of the semiconductor, which, in turn modifies the propagation velocity of light and the absorption coefficient.

The method of varying real refractive index is called 'electro absorption' and Electro-absorption modulator (EAM) is a semiconductor device which can be used for modulating the intensity of a laser beam via an electric voltage. Its principle of operation is based on the Franz-Keldysh effect, i.e., a change in the absorption spectrum caused by an applied electric field, which changes the band gap energy (thus the photon energy of an absorption edge) but usually does not involve the excitation of carriers by the electric field [11]. The relation between refractive index of the medium ($n_0$) and its absorption coefficients ($\alpha$) are related as given in equation 2.3.1. [12];

$$\alpha = \frac{2\omega k_0}{c} = \frac{\omega \kappa_2}{n_0 c}. \tag{2.3.1}$$

where $\omega$ is angular frequency of the wave and c is the speed of light in the medium which is in turn a function of refractive index.

The method of varying imaginary refractive index of the medium is called Electro refraction modulation.

In resonators or interferometers, this effect enables the fabrication of modulators based on silicon-on-insulator (SOI) technology, which uses a layered silicon-insulator-silicon substrate in place of conventional silicon substrates. The scaling of waveguides using the plasma dispersion effect has enabled optical modulation frequencies to evolve in silicon from the MHz range to approximately 30GHz. This substantial leap in operating frequency now allows silicon-based optical devices to match the high-speed data transfer requirements of networking, board-to-board or chip-to-chip interconnects applications. Some of the most promising devices based on the plasma dispersion effect use injection of carriers (see Figure 2.3a), accumulation of carriers on both sides of an insulating region (see Figure 2.3b) and positive-negative (PN) junction depletion (see Figure 2.3c) configurations [7].

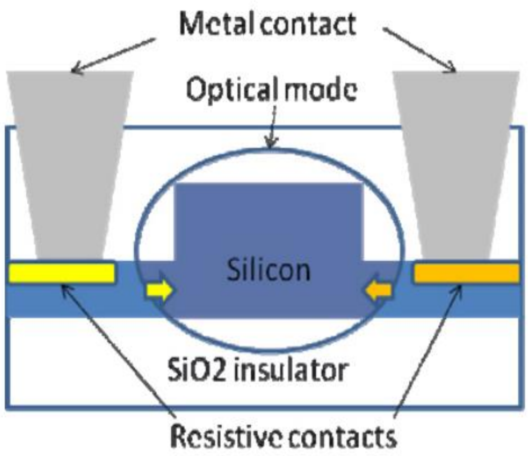


Fig 2.3a

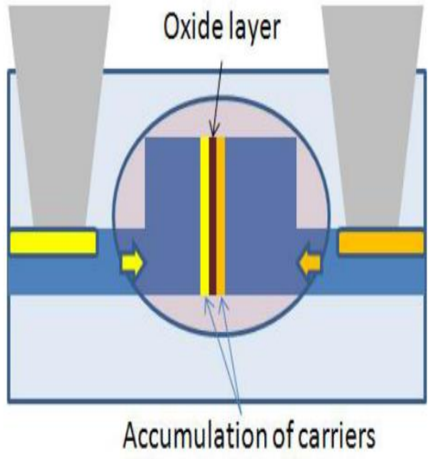


Fig 2.3b

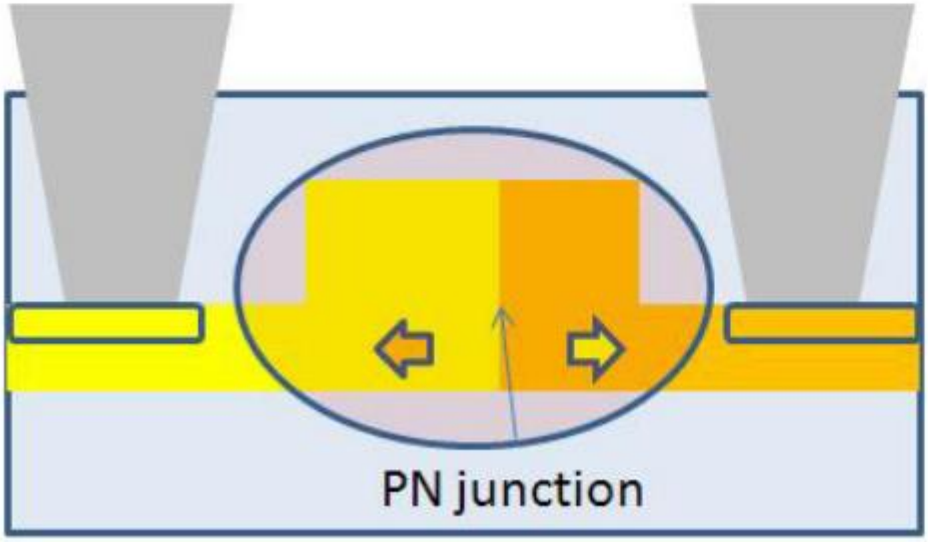


Fig 2.3c

Injection modulators are based on the injection of carriers (holes and electrons) in the waveguide core. The modulation speed, however, is limited by the recombination lifetime and by the physical dimensions of the waveguide which requires the resistive contacts (highly doped regions) to be only a few hundred nanometers away from each other to avoid limiting the bandwidth. High-speed interferometers (see Figure 4) based on this concept with a bandwidth of 1GHz were first proposed in 2004, followed in 2005 by a design featuring a much reduced waveguide size and significant bandwidth increase (24GHz), achieved by insertion of ”lifetime killers” (impurities) in the waveguide area [6].

Metal-oxide-semiconductor (MOS) capacitor-type modulators are accumulation devices in which only majority carriers are accumulated on both sides of an insulating layer of silicon dioxide. This layer, placed in the wave guiding region, limits the bandwidth of the device to the resistance-capacitance cut-off frequency. An important milestone in silicon photonics was reached by Intel in 2004 with the first demonstration of a micrometer-size MOS modulator on SOI with a modulation bandwidth exceeding 1GHz. This breakthrough was quickly followed by experimental devices with a bandwidth improved to 6 GHz. Smaller MOS-type devices have also been proposed in 2006, with a six-fold increase in efficiency for an equivalent data rate [9].

Depletion-type modulators are based on a PN junction located in the waveguide core. In these devices, the P-type region is designed to have a higher overlap with the optical mode than the N-type region (as the change in refractive index is higher for holes for a given density). The expected theoretical intrinsic bandwidth for this type of modulator is expected to exceed 50GHz [12].

Stark and Pockel's effects are two other very promising effects that were recently reported in silicon which could very well replace plasma dispersion. They were first demonstrated in 2006. If the refractive index changes in proportion to the applied electric field, the effect is known as the linear electro-optic effect and if the change is proportional to the square of applied electric field, then it is known as Quadratic electro optic effect or Kerr effect. The dependence of refractive index of Kerr and Stark medium are given in Figure 2.3d,

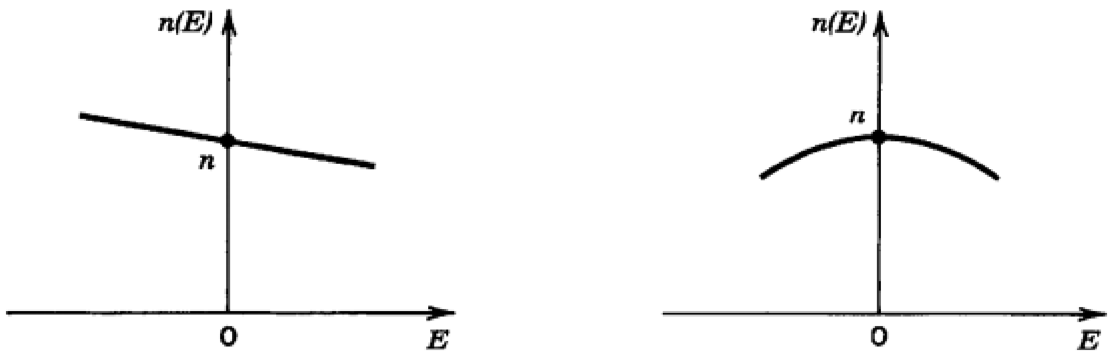


Fig 2.3d.Variation of refractive index with variation of electric field in Stark medium (left) and in Kerr medium (left)

The change in the refractive index is typically very small. Nevertheless, its effect on an optical wave propagating a distance much greater than a wavelength of light in the medium can be significant. If the refractive index increases by $2x10^{-2}$, for example, an optical wave propagating a distance of $10^2$ wavelengths will experience an additional phase shift of $\pi$ [12].

The modulation can be done to the phase, intensity and polarization of the light. Phase modulation and intensity modulation are usually used techniques in experimental basis.

### 2.3.1) Phase Modulation

Let the electric field is obtained by applying a voltage V across two faces of the cell separated by distance d, then E = V/d, the effect of phase of the light is given by equation 2.3.1.1

$$\varphi = \varphi_0 - \pi \frac{V}{V_\pi}$$

(2.3.1.1)

The parameter $V_\pi$ is the voltage at which the phase of the light changes by $\pi$ radians or $180^0$ and is known as 'half wave voltage'. One can therefore modulate the phase of an optical wave by varying the voltage V that is applied across a material through which the light passes. The parameter $V_\pi$ is an important characteristic of the modulator. It depends on the material properties such as refractive index (n) and electro optic coefficient (r), on the optic wavelength $\lambda$ and on the device aspect ratio d/L [10]. The experimentally obtained expression for half wave voltage is given as equation 2.3.1.2 [10],

$$V_\pi = \frac{d}{L} \frac{\lambda_o}{r n^3}$$

(2.3.1.2)

So we can deduce that the extents of phase modulation using silicon phase modulators by measuring the transverse voltage applied.

### 2.3.2) Intensity Modulation

Phase delay (or retardation) alone does not affect the intensity of a light beam. However, a phase modulator placed in one branch of an interferometer can function as an intensity modulator. Consider, for example, the Mach-Zehnder interferometer (as shown in Fig 2.3.2a),

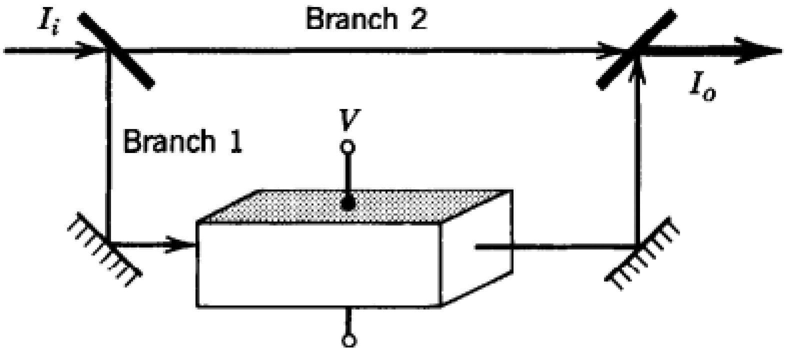


Fig 2.3.2a.Pictorial representation of Intensity modulation with two branches

If the beam splitters divide the optical power equally, the transmitted intensity $I_o$ is related to the incident intensity $I_i$ by equation 2.3.2.1,

$$I_o = \tfrac{1}{2}I_i + \tfrac{1}{2}I_i \cos\varphi = I_i \cos^2\frac{\varphi}{2} \tag{2.3.2.1}$$

where $\phi$ is the difference between the phase shifts ($\phi_2$-$\phi_1$) encountered by light as it travels through the two branches.

The transmittance ($\Gamma$) of the device is therefore a function of the applied voltage (V),

$$\mathscr{T}(V) = \cos^2\left(\frac{\varphi_0}{2} - \frac{\pi}{2}\frac{V}{V_\pi}\right) \tag{2.3.2.2}$$

The device may be operated as a linear intensity modulator by adjusting the optical path difference so that $\phi_0 = \pi/2$ and operating in the nearly linear region around $\Gamma = 0.5$. Alternatively, the optical path difference may be adjusted so that $\phi_0$ is a multiple of $2\pi$. In this case $\Gamma(0) = 1$ and $\Gamma(V_\pi) = 0$, so that the modulator switches the light on and off as V is switched between 0 and $V_\pi$ [6].

A Mach-Zehnder intensity modulator may also be constructed in the form of an integrated-optical device. Waveguides are placed on a substrate in the geometry shown in Fig 2.3.2b. The beam splitters are implemented by the use of waveguide Y-structures. The optical input and output may be carried by optical fibers.

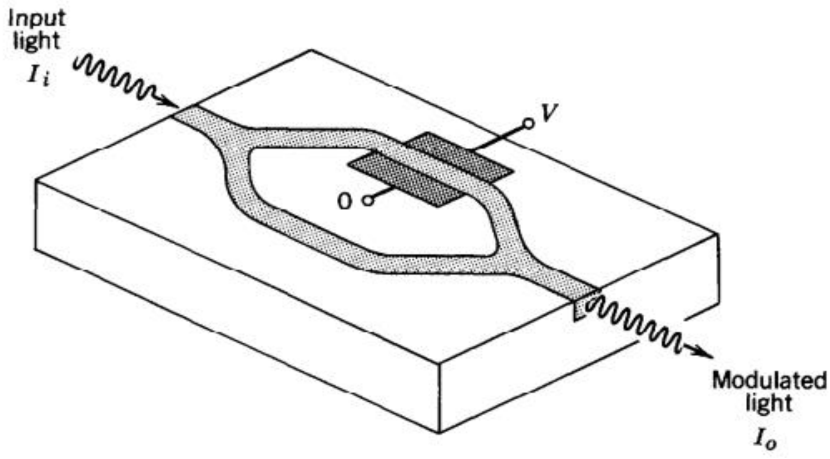


Fig 2.3.2b.Mach-Zehnder intensity modulator

## 2.4) Silicon Photo Detector

Silicon photo detectors in silicon photonics are nothing but integrated photo sensors which work on the basis of photo voltaic effect and can decode received light. Since the digital data modulates the phase, intensity or polarization of the light, the photo detector should be able to detect difference in any of the three or in all of the three mentioned parameters. Photodiode works on the principle of moving the generated free charge carriers under electric field by illumination of light photons [6].

### 2.4.1) Structure and Working

The structure of Silicon photo detector in silicon photonics is similar as that of typical macro semiconductor photo detectors. But the difference lies in the fabrication of the structure in CMOS technology. Based on the structure of photodiode, they are classified into different types. A typical cross sectional view of avalanche photo diode is shown in Fig 2.4.1.a and that of normal silicon photodiode is given in Fig 2.4.1.b

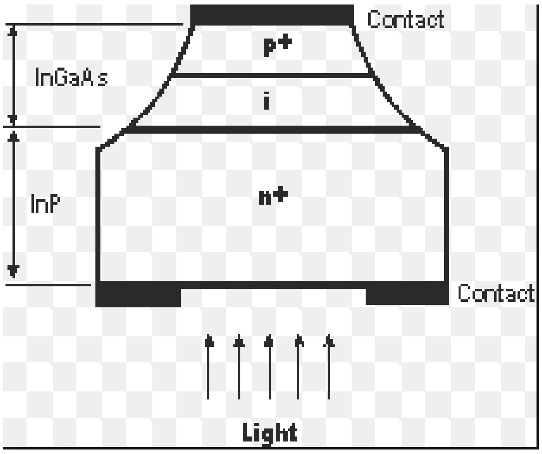


Fig 2.4.1.a.Cross sectional view of avalanche photo diode

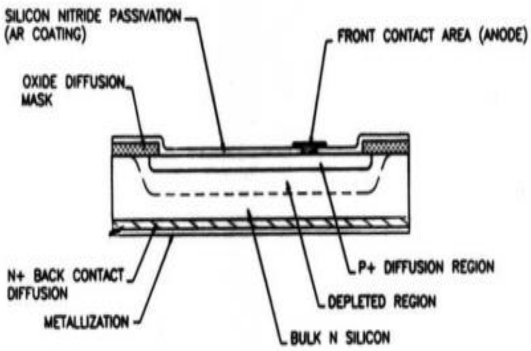


Fig 2.4.1.b.Cross sectional view of normal Silicon photo diode

Between the p-type region and the lightly doped n-type region there is a depletion region which is free from mobile charges. The width of this region depends upon the resistivity of the silicon and the applied voltage; even with no externally applied bias the diffusion of electrons and holes across the junction creates a depletion region with an electric field across it which is known as the "built-in" field. When a photon is absorbed in a semiconductor an electron-hole pair is formed. Photocurrent results when photon-generated electron-hole pairs are separated, electrons passing to the n-region and holes to the p-region. Alternatively, holes and electrons may recombine, thereby causing no charge displacement and thus no contribution to photocurrent. There is a greater probability of separation of a photon-generated electron-hole pair when it is formed within the depletion region where the strongest electric field exists.

## 2.4.2) Characteristics Properties

There some characteristics defined for optical photo detectors based on which the quality of photo detector is estimated, given by;

- Quantum efficiency
- Responsivity
- Response time

## 2.4.2.1) Quantum Efficiency

'Quantum efficiency' is nothing but Probability of detecting an incident photon by generating an electron/hole pair that contributes to the photocurrent. It can be calculated by Ratio of the generated carriers to incident flux of photons (i.e.: ratio of the photocurrent to the incident light power). The spectral response is governed by the spectral character of the quantum efficiency. Quantum efficiency depends on the following properties of the material;

- Reflectance on the surface
- Absorption

Let $I_0$ be the incident light intensity on a substance of absorption coefficient α and length of longitudinal section L as shown in Fig 2.4.2.1.a, then absorbed light intensity ($I_{abs}$) and output light intensity ($I_{out}$) are given by;

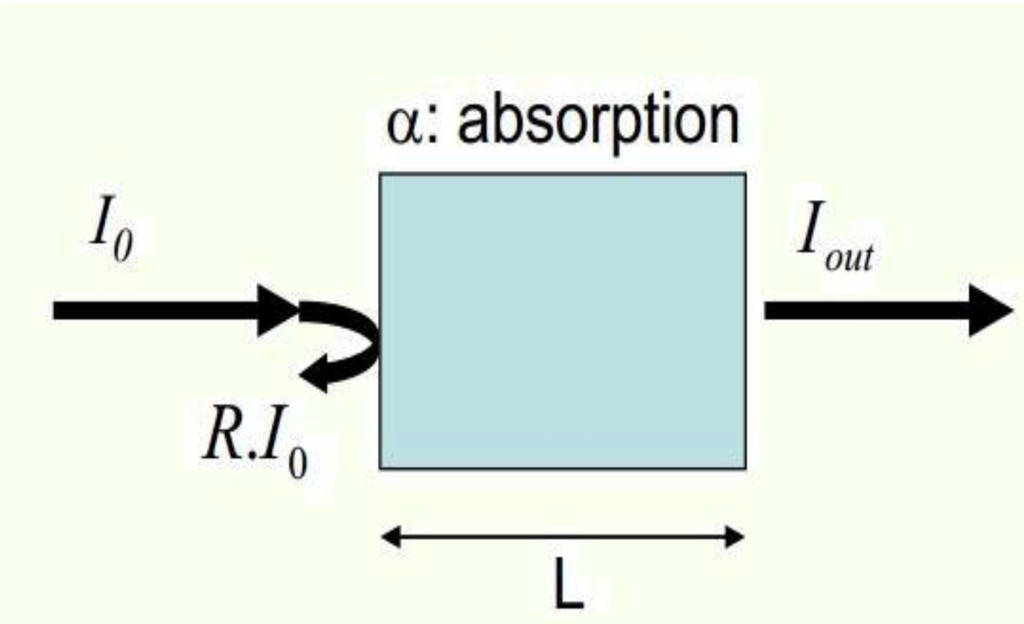


Fig 2.4.2.1.a.Pictorial representation of reflection and absorption coefficient of a typical material

$$I_{out} = I_0(1 - R)\exp(-\alpha L) \qquad (2.4.2.1.1)$$

$$I_{abs} = 1 - I_{out} = I_0(1 - R)[1 - \exp(-\alpha L)] \qquad (2.4.2.1.2)$$

Similar to the above scenario, the output current will be also dependant on the absorption coefficient and reflection parameters of the material.

### 2.4.2.2) Responsivity

Responsivity (R) is often more useful to characterize the response of photo detectors. Responsivity is typically linear with wavelength but real photo detectors exhibit a deviation from the ideal behaviour due to photo generated carrier trapping.

$$\text{Responsivity, } R = \frac{q\eta}{hv}$$

where q is the charge of an electron, η is quantum efficiency of material , h is plank's constant and v is the frequency of incident light [12].

As Responsivity increases, the detector will become more efficient.

### 2.4.2.3) Response Time

The overall response time of photo detector depends on the internal and external response times of the photo diode. The internal response time is function of both transit and diffusion times of the carriers. Transit time of carriers depends on the velocity of carriers in SC (varies with the doping level and the material) and diffusion time of carriers: diffusion of carrier to be collected. Mainly depends on the structure of the photo diode [12].

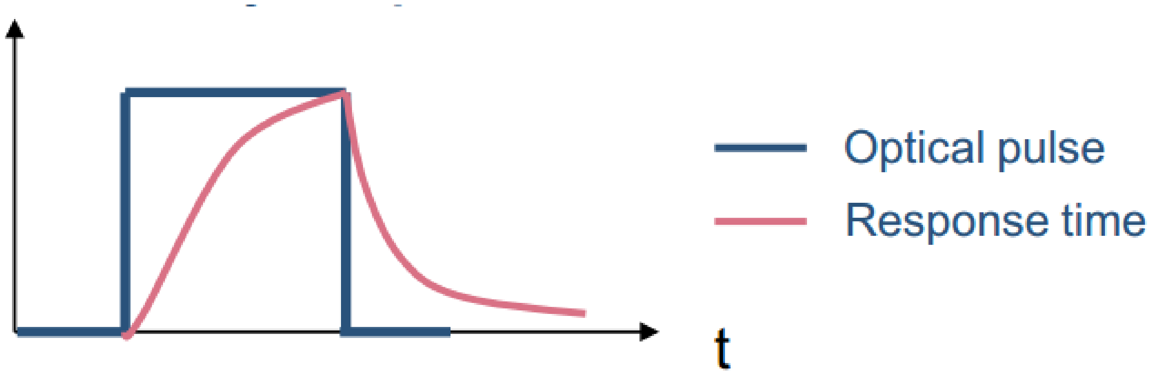


Fig 2.4.2.3.a. Effect of internal response time

The external response time of the photo diode depends on the contact resistances and the parasitic capacitances. The equivalent diagram of photo detector incorporated with additional capacitances and resistances are shown in Fig 2.4.2.3.b,

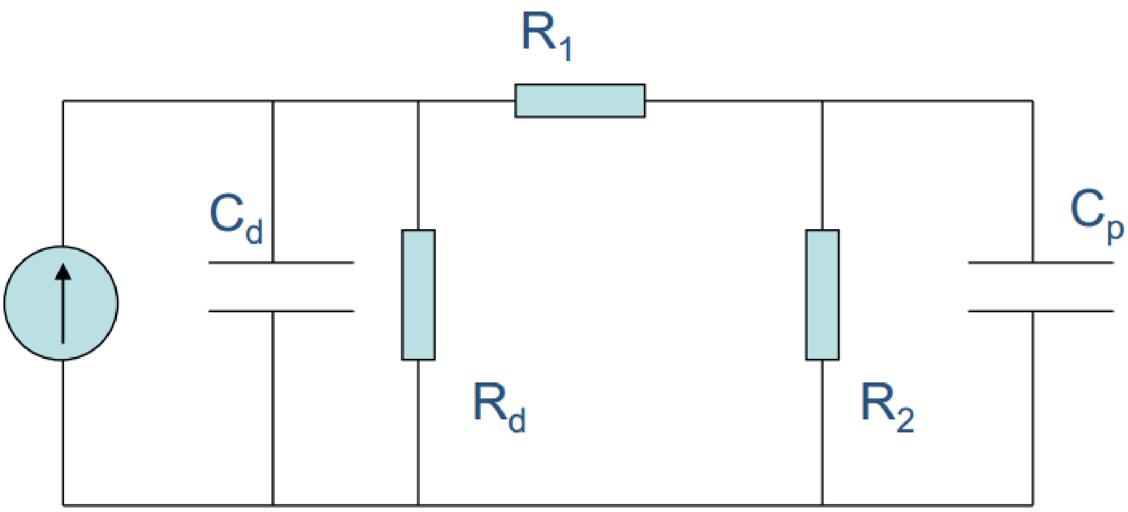

Fig 2.4.2.3.b.Equivalent analog circuit of Photo detector

The External Response time is then calculated as “R2 ($C_P$ + $C_d$)”, since experimental analysis shows that $R_d$ is of very high value and $R_1$ of very low value.

# Chapter 3

## Recent Developments

The synchronous optical network and gigabit Ethernet is the first platform for silicon photonics, acting as the transceivers or WDM. One example is the high speed transmitter developed in Intel Corporation. The multiplexer array of eight high-speed MZI modulators and demultiplexer are monolithically integrated on the same SOI substrate. The chip is packaged with RF connectors and DC controls for test purpose. It has been suggested that this integrated transmitter has the capability of sending data at an aggregate rate of 200 Gb/s over a signal fibre. One transceiver chip developed by Luxtera is regarded as the world's first CMOS Photonics product and may also become an example of silicon photonic product for the next generation. Based on 90 nm SOI CMOS processes, all of 10 Gbps silicon modulator, high-performance WDM, and Ge detectors with bandwidth of 18 GHz and responsivity of 0.54 A/W at 1554 nm are integrated monolithically onto one chip. Three-dimensional integration for nano photonics has also been proposed as an excellent way to improve the performance of silicon photonics these years [11].

# Chapter 4

# Conclusion

In this report, we have seen how silicon photonic communication system works and how it differs from normal optical communication system coupled with macro transmitter and receiver systems. We also had a peripheral insight into the sections of silicon photonic communication systems. Our study had also familiarized with the difficulties and drawbacks of present technologies in achieving reliable silicon photonics communication.

We are living in world, thriving for more and more rapidness in communication and analysis. The analysis speed of the computers and servers that we use are almost enough for our present requirements. But the bottleneck for our requirements is the speed of communication inside and outside the processing device. Since, silicon photonics is capable of communicating at more than 10Gbps at present experimental scenario, we are left with a huge possibility of increasing the processing and communication speed even with the largest possible speed that can be achieved on the basis of Einstein's relativity theory.

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