

A Review on Silicon-Based Photodetectors

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ABSTRACT: Photodetectors are widely used in the optical communication at the transmission end of the photonic system which convert the incident light to current. So, it is needed to make photodetectors with high quantum efficiency for better detection of light and efficient working of the photonics system. Silicon based photodetectors are famous because of their low cost and it is easy to integrate with optoelectronic devices. However there are materials like InGaAs, GaAs and Ge based detectors which have large responsivity and low dark current. It is a challenging task to design detectors with high performance for optical communication system, so there is need for balance between absorption efficiency, wavelength ranges and cost which can be overcome with a particular designing of the detector. There is a need to study about the various parameters of the photodetectors and improve these parameters by modelling of Si based photodetectors, their compatibility with different materials. This paper tends to review all the types of detectors which are Si based and analysis of their characteristics.

KEYWORDS: APD, PIN, photodetector, Silicon based, dark current, quantum efficiency, responsivity, waveguide.

I. INTRODUCTION

The word Photonics is the word used in order with the goals to describe the field of optics, optoelectronics and their applications. In photonics basically the photons are used to carry out the process which uses electrons and other charged particles. Photonics is not only used in the field of communications but it has a significant applications in sensing on a specific wavelength range, optical imaging, instrumentation and material processing etc. A photodiode is a semiconductor device that converts light into current. The photon incident on the active area of the photodiode gets absorbed which lead to electron hole pair generation which further lead to photocurrent. Photodiodes may contain optical filters, built-in lenses, and may have large or small surface areas. As the surface area increases, it results in slower response time. The solar cell which are used to generate electrical solar power is generally a large area photodiode [2]. The INTEL proposed Silicon photonics system is shown in Figure 1.1.

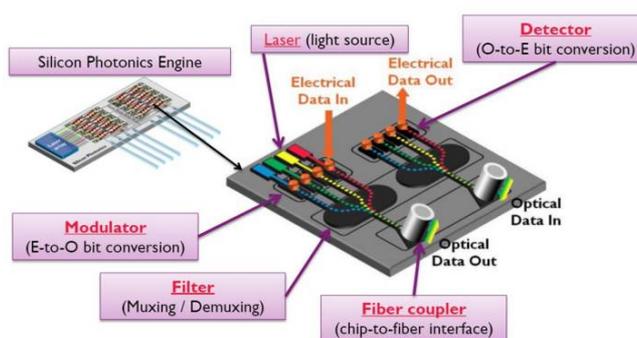


Fig.1 On chip Silicon based photonics system

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Photodetectors are transducers that amend one of their characteristics when light energy falls on them. Photodetectors which generates more amount of current even if little amount of light falls on it and have fast response time are desirable and it is necessary to investigate the applications for high-speed optical communications. These includes avalanche photodiodes (APDs) and positive intrinsic negative photodiodes (PINs) [1]. In waveguide photodetectors, photon flux and carrier flux are perpendicular to each other, which enables high data-rate applications since thin absorption layers allow for short transit times of the generated carriers [2]. The detection efficiency can be increased with the use of long waveguides. There are two types of WGPD i.e. Normal incidence waveguide photodetector and Lateral incidence waveguide photodetector. In these waveguide photodetectors light strike on the waveguide and the material of the waveguide act as absorption layer which further create electron-hole pairs by the absorbed photon and thus lead to photocurrent.

II. PHOTODETECTORS

Photodetectors are the devices that convert light energy into electrical energy. To increase the speed of response of a photodiode PIN junction is preferred over the p-n junction. A photodiode operates in reverse bias condition. The basic principle in the functioning of photodetector is that the photons which are incident on the active layer of photodiode which gets absorbed and create electron-hole pair. This electron-hole pair is being driven by the electric field in the region which generates photocurrent.

A. Photodetector Characteristics

There are various parameters which characterises a photodetector and its applications in different fields, which are spectral response, responsivity, dark current, quantum efficiency, forward-biased noise, noise equivalent power, capacitance, timing response (rise time and fall time), bandwidth, and cut-off frequency.

- Spectral response- is the parameter which shows the current produced on particular wavelengths, and it is assumed that all wavelengths are at the same level of light.
- Photosensitivity- It is the ratio of light energy to the current produced due to the incident light on the active region.
- Quantum efficiency- It is the number of generated electron-hole pairs (i.e., current) divided by the number of photons.
- Dark current- When diode is in reverse bias and the electron hole pair is generated in absence of light (like leakage current). This is a source of noise when the diode is reverse-biased.
- Forward bias noise- It is a (current) source of noise that is related to the shunt resistance of the device. The shunt resistance is defined as the ratio of applied voltage (near 0V) to the amount of current generated. This is also called shunt resistance noise.
- Noise equivalent power- It is defined as the amount of light (of a given wavelength) that is equivalent to the noise level of the device.
- Terminal capacitance- It is the capacitance created between the p-n junction of the diode and the connectors of the device; it limits the response of the photodetector.
- Timing response- It is the time for the output signal to climb from 10% to 90% of its amplitude (rise time) and to drop from 90% to 10% (fall time).
- Frequency bandwidth- It is the frequency (or wavelength) range in which the photodetector is sensitive.
- Cutoff frequency- It is the highest frequency at which the photodetector shows its sensitivity or it can be the smallest wavelength.

B. Types of photodiodes

- **PIN photodiode**-The p-i-n photodiode is a semiconductor device that consists of an intrinsic region which is lightly doped that is sandwiched between a p-type and an n-type layer. When reverse bias is applied to the device, it shows an almost infinite internal impedance i.e. of an open circuit, and generates an output current. The output current is proportional to the input optical power which is defined by responsivity R and a quantum efficiency η as given by equation 1 below:

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$$R = \frac{\text{output current } I}{\text{input optical power } P} \text{ (amperes/watts)}$$

$$\eta = \frac{\text{number of output electrons}}{\text{number of input photons}} \tag{1}$$

The relation between R and η is shown below:

$$R = \frac{e\eta}{hv}$$

where e is the electron charge, η is the efficiency, h is Planck's constant, and v is the frequency of light³. When a photon generates an electron-hole pair, the device generates a current pulse with duration and shape that is basically dependent on the response time of the device. The frequency response of the PIN device is determined by the RC time constant. The capacitance which is created in the reverse-bias PIN photodiode act as a restricting factor to its response and switching speed. As the switching speed increases to very high frequencies, parasitic inductance becomes significant and causes "shot noise," which is estimated as

$$2e(I_s + I_{\text{dark}}) \tag{2}$$

where I_s is the signal current and I_{dark} the current that flows in the absence of light incident, or dark current. The p-i-n diode consist of a heavily doped p-type and n-type regions with an intrinsic region between them, which is basically the absorption layer. In reverse bias condition, it acts like a constant capacitance and in forward bias condition, it acts as a resistor. The forward resistance of the intrinsic region decreases with increasing current. The forward resistance can be changed by changing the bias condition. Also, this device can be used as modulating device and in microwave switching applications. The photocurrent produced in pin diode is generally more than that of p-n diode, and pin diode is used more in high frequency operations than that of p-n diode. Figure 2 shows the p-i-n photodiode with given bias voltage.

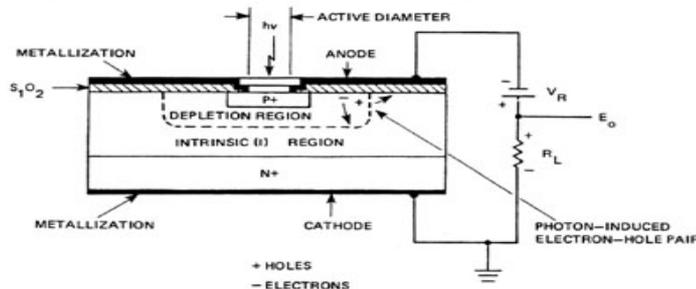


Fig.2 PIN photodiode.

- **APD photodiode-** The APD is a semiconductor device, when reverse bias is applied to the device due to which a strong electric field is created in the junction region. When an electron hole pair is created which flow inside the depletion region, by the incident photon. Now these electron gain energy and they strike at other electrons creating further more electron hole pairs. This multiplication of electron hole pair leads to more current produced in the circuitry. This multiplication process is known as avalanche process where large amount of current is generated with few photons incident on it. The gain M of an APD is expressed by

$$M = \frac{I_{APD}}{I_{\text{primary}}} \tag{3}$$

where I_{APD} is the output current of an avalanche diode and I_{primary} is the current produced due to photon electrons conversion and during this multiplication process, shot noise is also multiplied, and is estimated as

$$2eIM^2F \tag{3}$$

where F is the noise factor of avalanche photodiode. If τ is the effective transit time through the avalanche region, the APD bandwidth is approximated as:

$$B_{APD} = \frac{1}{2pM\tau} \tag{4}$$

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- *MSM photodetectors*- In MSM (metal semiconductor metal) photodetectors there are two metal electrodes on the material which are also known as schottky contacts. The light falls on the active region of the material between these contacts which generates charge carriers in the electric field between the contacts which leads to generation of photocurrent [3]. Figure 3 shows the MSM photodetector with schottky diode.

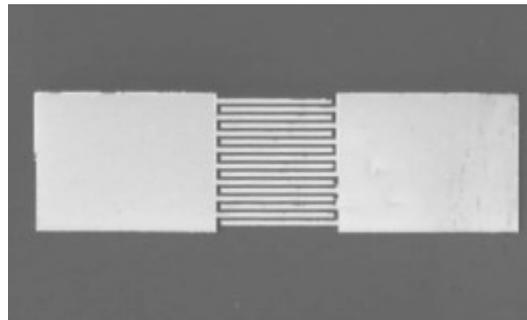


Fig.3 MSM photodetectors with schottky barrier.

- *Waveguide Photodetectors*- In waveguide photodetectors, photon flux and carrier flux are perpendicular to each other, which enables high data-rate applications since thin absorption layers allow for short transit times of the generated carriers [2]. In these photodetectors the light incident inside the waveguide and absorbed by the absorption layer of the PD. A very thin active layer is required in this kind of photodetector but it has less efficiency than normal incidence p-i-n photodetector. The InP waveguide photodetector is shown in Figure 4.

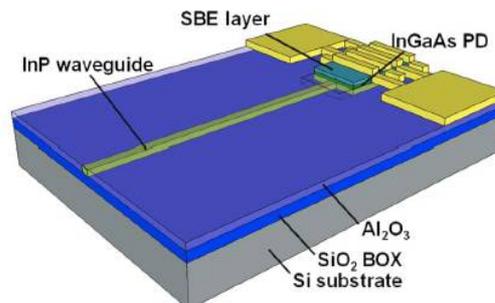


Fig.4 InGaAs waveguide photodetector integrated with CMOS technology.

Waveguide is integrated with the photodetectors to increase the coupling efficiency and for implementation on chip photonics system. In WGPD the light is incident on the waveguide which acts as an absorption layer in the photodetector, thus the generated electron pair travel to through the material of the waveguide and then generate current at the end of the waveguide on the lateral side of the photodetector. Figure 5 shows a waveguide photodetector with SiGeC allow material between SiO₂ layers [4].

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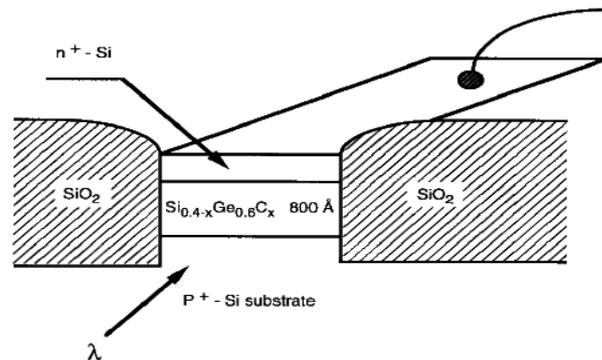


Fig.5 Schematic of SiGeC-Si pin waveguide photodiode on a Si substrate

Similarly Figure 6 shows a cross section of germanium wrap around photodetector on SOI substrate. It a waveguide coupling scheme where a germanium diode grown via rapid melt growth is wrapped around a silicon waveguide. The basic design imagines a lateral PIN photodiode where the intrinsic region is ‘wrapped’ around a single mode silicon waveguide. The central idea being that the germanium will absorb the light from the waveguide evanescently over its length, and by moving the contacts away from the optical mode, overall quantum efficiency will be improved. Due to relying on evanescent coupling, this particular arrangement also allows the photodiode itself to be very thin, reducing the overall capacitance in a lateral junction arrangement [5].

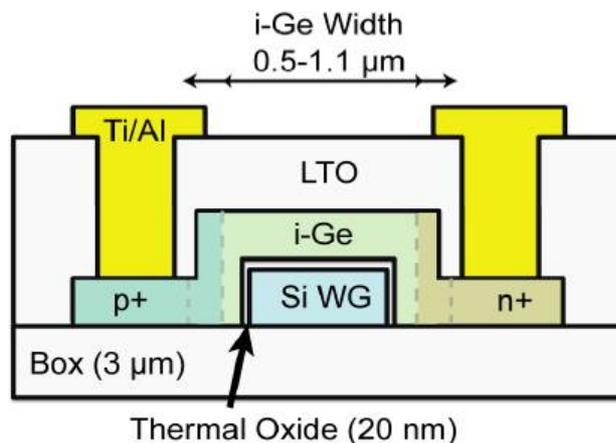


Fig.6 A cross section of a wraparound photodiode showing the lateral doping scheme.

III. MATERIALS USED

The p-i-n photodetector can be made using different materials which are direct band, indirect band gap materials etc. For IR applications many other materials like HgCdTe or InAsSb etc. can be used to work in MIR and LWIR regions. Various materials which are popular for photodetectors are Ge, Si, GaAs, InGaAs, AlGaAs. Some alloys are also used to integrate with silicon for photodetectors like SiGeC layer is used for creating a waveguide photodetector (Ge on silicon). The materials and their characteristics are shown in the Table I.

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TABLE I. Materials used for photo detection and their parameter values [1], [6].

Material	Dark current (at 300K and -2V bias)	Maximum light current (0 to -5V)	Maximum sensitivity	Cutoff frequency(3dB)
Si	1.08pA	50nA at 0.65μm	λ= 0.7 μm	1GHz
Ge	11.5pA	49nA at 0.65μm	λ= 0.66 μm	0.25Ghz
InP	0.4aA	71nA at 0.95μm	λ= 0.92 μm	0.25GHz
ZnSe	0.1aA	54nA at 0.7 μm	λ= 0.71 μm	0.1GHz
GaAs	11.89fA	67nA at 0.9 μm	λ= 0.87 μm	2GHz
Al _{0.4} Ga _{0.6} As	10aA	50nA at 0.65μm	λ= 0.72 μm	2GHz
Al _{0.6} Ga _{0.8} As	1aA	38nA at 0.58μm	λ= 0.57 μm	2GHz
AlAs	1aA	35nA at 0.49μm	λ= 0.41 μm	2GHz
HgCdTe	6.2pA (at 10v & 77K)	-	λ= 1 to 4 μm	-

IV. COMPARISON

The different materials show different values of parameters in different conditions which can be favourable for particular applications. A comparative analysis of related work is given in Table II. Among all types of photodetector PIN photodetector is the best because in PIN photodiode there is intrinsic material in between the p type and n type which leads to wider depletion layer at both the junctions i.e. between the intrinsic material and n type or p type material. Due to this the active area for the incident photons increases, which results in more absorption and further more creation of the charge carriers. This basically increase the photocurrent in the device which is the basic requirement for an efficient photodetector. In APD photodiode a charge carrier is created which collides and leads to more generation of carriers. This multiplication process leads to random noise which is not desirable. APD diodes are costly and even they need high reverse bias voltage (For ex. 38-40 V). Other MSM and schottky diodes have various disadvantages but the major disadvantage is that they contain schottky barriers. The schottky contacts are very closely packed in the structure which further creates noise and effects the response of the photodetector. Different materials are used for PIN photodetectors which have different absorption coefficients like Silicon has good absorption coefficient for shorter wavelengths but have very low absorption near 1.55 μm where major optoelectronic applications are performed. InGaAs on the other hand has better absorption coefficient in this region and for IR region HgCdTe material is used for photodetectors because it can work in MIR, LWIR region as well as in SIR region where Silicon photodetectors cannot work.

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TABLE II. Comparison of different materials and their parameters analyzed.

Research Paper	Photodetectors	Responsivity (A/W)	Dark current(A)	Dynamic resistance(Ω)	Quantum efficiency	Wavelength
P. Chakrabarti, IEEE 2007	LWIR PD (HgCdTe)	-	10^{-6}	6×10^5	-	at 10.6 μm
P. Chakrabarti, IEEE 2008	MWIR PD (HgCdTe)	-	-	-	60%	at 3.8 μm
N.R Das,2009	Si with bipolar technology	0.5	-	-	-	at 0.82 μm
N.R Das,2009	Si with CMOS technology	-	300pA	-	82%	at 850 nm
N.R Das,2009	SiGe	6.5mA/W	-	-	33%	at 1.3 μm
N.R Das,2009	Ge-on-Si(a thin buffer layer over Si)	0.38	0.37mA/cm ² (dark current density)	-	60%	at 1.3 μm
N.R Das,2009	APD	0.55	-	-	-	at 1.3 μm
Yan Gao,2012	InGaAs /InP Pin photodiode	0.5	0.2 μA	-	>30%	at 1.5 μm
F.E Ejeckam,2015	InGaAs On Si photodiode	1	0.29nA	-	>80%	at 1.5 μm
Artur Koblowski,2014	MWIR PD(HgCdTe)	2A/W	0.066 mA/cm ²	-	60-80 %	2.5 to 3.5 μm

V. CONCLUSION

Semiconducting materials incorporated into electronic devices are generally required to be highly perfect, single crystals to perform their functions. The development of the Si microelectronics industry has virtually perfected the quality of single crystal Si wafers and reduced their cost far below any other single crystalline wafer material. The techniques to grow high-quality optoelectronic materials on Si would lead to significant economic development, as well as increasing the availability of critical technologies for healthcare and national security. Si-photodetectors are cost

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effective and are easy to integrate but have lower absorption coefficient. However, for shorter wavelength (0.4 to 1.1 μm) Si-photodetectors have a high responsivity and quantum efficiency. But they don't work well in C and L wavelength bands. Thus, several other materials are being integrated to Si for increasing the operating wavelength ranges for various applications.

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