A Review of BJT Based Phototransistor

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***Abstract*— This literature survey prospects the performances of photo-transistors using different directions of illumination of the device and tends to find the optimized direction in-terms of conversion gain, optical gain and injection efficiency. The choice of materials for fabrication of phototransistors has also been discussed and make a small comparison in solar-cell, photo-diode and phototransistor with the basic parameters used in optical devices.. In addition, a comparative study is done in between homo-junction and hetero-junction BJT based phototransistors which help in understanding the basic phenomena of different performance parameters, like optical gain, spectral range, and efficiency**

Keywords- BJT, AlGaAs, GaAs, Hetero-junction Photo-transistor, Homo-junction Photo-transistor.

I. INTRODUCTION

Optical devices are used to convert optical energy (light) into electrical energy. For applications with weak optical signals, the use of photo-detectors with built-in amplification are used, those photo-detectors are called phototransistor. A phototransistor is a semiconductor device that is highly sensitive to light striking it by generating an electric current. These devices respond to light over a broad range of wavelength from the near UV, through the visible and into the near IR part of spectrum. For a given light source illumination level, the output of a BJT based phototransistor is defined by the area of the exposed collector-Base junction and the DC current Gain of the transistor.

The collector-Base junction of the phototransistor works as a photodiode generating a photocurrent which is fed into the Base of the transistor. Thus, like the case for a photodiode, doubling the size of the Base region doubles the amount of generated Base photocurrent, but phototransistor has much lower noise level as compared to photodiode, we will focus on the photo-bipolar junction transistor (photo-BJT) because of the large current gain of such devices as compare to other optical devices with same physical phenomenon. The main performance matrices parameters of any optical devices are:

Quantum efficiency: It refers to the percentage of absorbed photons that produce electron-hole pair [3]. QE is inversely proportional to the wavelength of incident photon.

Sensitivity: The sensitivity of a phototransistor relates the electric current flowing in the device circuit to the optical power incident on it. The sensitivity is linearly proportional to both the QE and the free-space wavelength.

Optical Gain: optical Gain is caused by photo-induced transitions of electron from the conduction band to the valance band.

Linearity: An output signal that is proportional to the intensity of light falling on the detector.

Power dissipation: Power dissipation is defined as the power that is converted to heat and then conducted or radiated away from device.

Comparisons of optical devices on the basis of these parameters are shown in table I.

TABLE I: Comparison in between optical devices

Parameters	Photo-diode	Photo-transistor
Sensitivity	0.6-0.8 A/W at 900nm	100-500 times as compared to photodiode
Linearity	Excellent	Good
Response time	0.01 µs	5 µs
SNR	2dB/1dB	Same as photodiode
Power Dissipation	≅50 mW (PIN photodiode)	≅150mW (T_{amb} = 25° C, Si photo-transistor)
Performance-to-cost-ratio	Good	excellent
Optical Gain	Less than phototransistor	196%
Efficiency	31-41%	38%
Available wavelength (µm)	0.2-1.1	1.0-2.2

Solar cell was discovered in 1839 by Alexandre-Edmond Becquerel and it was based on the photovoltaic effect. It was earliest optical device having major drawbacks like: nonlinearity, less efficiency (15-25%), shorter spectral range (0.4-1.2 nm) and response time (25ns). Due to all these reasons photodiodes and phototransistors are preferred over solar cell.

II. MATERIALS USED FOR FABRICATION OF BJT BASED PHOTO-TRANSISTOR

A photodiode material should be chosen with a band gap energy slightly less than the photon energy corresponding to the longest operating wavelength. This gives sufficiently high absorption coefficient to ensure a good response, and yet limits the number of thermally generated carriers in order to attain a low "dark current" (i.e. current generated with no incident light). A group-III nitride quaternary material system and method is disclosed for used in semiconductor structures, including LASER diodes, transistors, and photo-detectors, III-V compound materials are suitable for fabricating optoelectronic devices in the near and mid-infrared wavelength range.

Ge photodiodes and photo-transistors have relatively large dark current due to their narrowband gaps in comparison to other semiconductor materials. This is a major shortcoming with the use of Ge photodiodes, especially at shorter wavelength (1.1 μm). The III-V semiconductors based on group III or Boron group and group V or Nitrogen. These are the most compounds for photovoltaic application in terms of their band gaps and lattice constant as reported in the range of sources [8-11]. The physical structure can be optimized to allow higher levels of light exposure by using an offset configuration.

The availability of binary substrates, such as GaAs, InAs, InP and GaSb, allows growth of multilayer homo and hetero-structures. The chosen materials and composition pay a role in the sensitivity of the phototransistor.

The characteristics of the semiconductor material determine the spectral window for large quantum efficiency. For sufficiently short wavelength, QE also decreases because most photons are absorbed near the surface, so that the photo carriers recombine before being collected.

TABLE II: Band gap energy and applicable spectral range for various materials used in the construction of photo-transistors [4]

Material	Si	Ge	GaAs	InP	$In_xGa_{1-x}As$ X=0.53	$In_xGa_{1-x}As_yP_{1-y}$ X=0.73 y=0.60
E_g (eV)	1.12	0.67	1.43	1.34	0.75	0.89
Λ (μm)	0.5-0.9	0.9-1.3	0.75-0.85	0.9-1.0	1.3-1.65	1.0-1.2

Direct band gap III-V compound semiconductors can be better material choices than Ge for the longer wavelength region. Their band gaps can be tailored to the desired wavelength by changing the relative concentrations of their constituents (resulting in lower dark currents).

The band gap energy and the applicable spectral range for the materials used in phototransistor fabrication are shown in table II.

III. BJT PHOTOTRANSISTOR

The invention of phototransistor was done by John N. Shive on the 30th March, 1950. BJT phototransistor can be PNP or NPN type it is similar to an ordinary transistor, except that the bases usually left floating. The Base of the phototransistor would only be used to bias the transistor so that additional collector current was flowing.

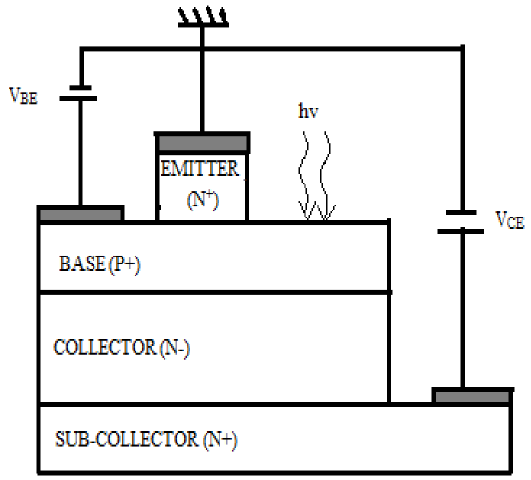

Fig 1: Cross-section view of BJT based Photo-transistor

There is a transparent window in the encapsulation so that light can fall on the transistor. There is an overlap between the region of light absorption and the high electric field depletion region as shown in Fig 1. To make the best use of performance of a transistor, different approaches have been vertical illumination, lateral illumination, and rear face illumination. An idealize case is when light is assumed to be so adjusted that it generates Hole-electron pairs uniformly everywhere in the transistor.

A. VERTICAL SURFACE ILLUMINATION

The first silicon phototransistor were surface illuminated which is the traditional situation in which the light is incident on the base region. This vertical illumination allows easy coupling between the optical fiber and the phototransistor making the integration of the device easier. The incident light flux crosses the emitter without being absorbed and the electron-hole pairs are created in the active base region. If a base contact is removed (base floating), the optical flux directly illuminates the base and the collector extrinsic region of the phototransistor. Optical gain of vertical BJT is 30dB. Fig 2(a) shows the cross section view of vertical illuminated phototransistor.

B. REAR –FACE ILLUMINATION

In the rear face illumination the creation of photo carriers in the active region of the transistor without modifying the Emitter contact. In the rear face illumination the absorption of light takes place on collector. Furthermore, the response coefficient is improved because the metallic contact of the emitter acts as a mirror [4]. Fig 2(b) shows the cross section view of BJT based rear face illumination.

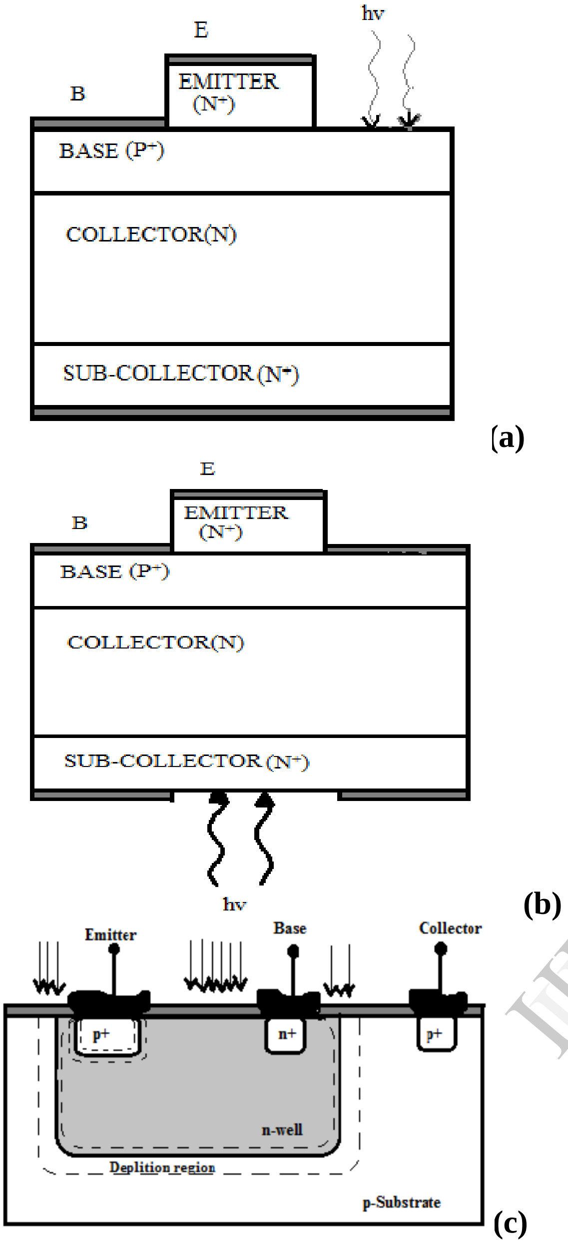

Fig 2: Cross section of Photo-transistor (a) Front face (vertical) illumination, and (b) Rear face illumination (c) lateral illumination

C. LATERAL ILLUMINATION

Lateral illumination (parallel to the layer) requires a face very vertical to the Base-Collector Island, in order to obtain the best possible injection efficiency. The photons and charge carrier no longer propagate in the same direction as in vertical illumination. Base bias is provided when incident photons create electron-hole pairs. This improves the QE and speed performance (high operating frequencies) as compared to vertical or rear face illuminated phototransistor. Injection efficiency of lateral BJT is 50-90%. Fig 2(c) shows the cross section view of lateral illuminated phototransistor.

In edge incidence geometry, the absorption volume is increased and each photon will have the possibility to interact with several Si atoms. Therefore, a lateral illuminated bipolar transistor usually suffers from a lower current gain and lower collector efficiency than the vertical illuminated bipolar devices.

TABLE III: Comparison in vertically, rear face and laterally illuminated photo-transistor

Parameters	**Vertically illuminated Photo-transistor**	**Rear-face illuminated photo-transistor**	**Laterally illuminated photo-transistor**
Quantum efficiency (optical-electrical conversion gain)	21% 1.3um and 16% 1.5um	--	Better than rear-face and Vertical BJT

From the Fig 3 we observed that the lateral illumination gives better frequency response and current gain than the vertical and rear face illumination.

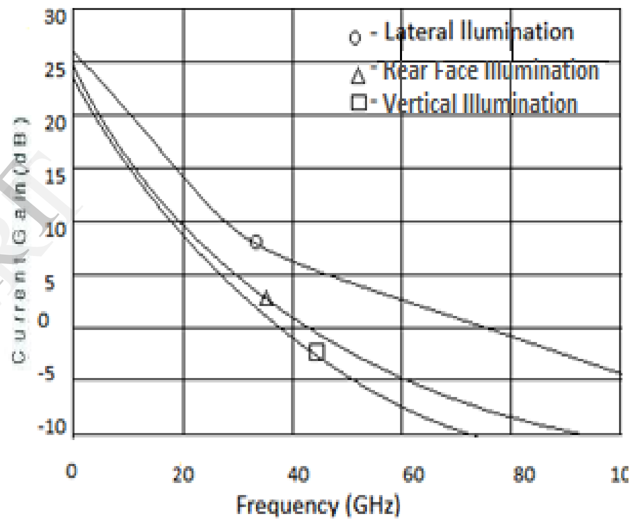

Fig 3: Optical current gain vs frequency for different directions of illumination [6]

IV. CATEGORIES OF PHOTOTRANSISTOR

On the basis of internal structure and material used, BJT phototransistors are categorized into Homo-junction and Hetero-junction phototransistor.

A. HOMO-JUNCTION PHOTOTRANSISTOR

A homo-junction is a semiconductor interface that occurs between layers of similar semiconductor material, these materials have equal band gaps but different doping. Early phototransistors used Ge or Si throughout the device giving a homo-junction structure.

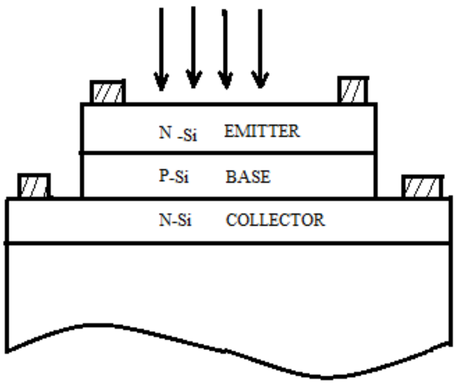

Fig 4: Cross section View of Homojunction phototransistor

IV characteristics of homojunction bipolar phototransistor under different intensity shows that output photocurrent depends in a non-linear fashion on the incident radiation intensity.

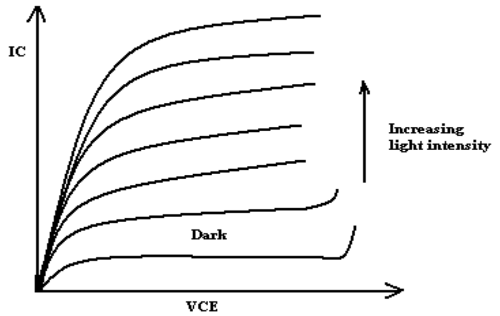

Fig 5: I-V curve of homo-junction [1]

B. HETERO-JUNCTION PHOTOTRANSISTOR

The hetero-junction BJT is a type of BJT which uses different semiconductor material for the Emitter and Base region, creating a hetero-junction. HBTs extend the advantages of silicon
bipolar transistors to significantly higher frequencies[7] . Material that can be used for making HBT are Si, GaAs, AlGaAs, InP, InGaAs, Si-SiGe alloys etc. HBT can provide faster switching speed, and show better performance in term of Emitter injection Efficiency, Base resistance, cutoff frequency, linearity, low phase noise and power added efficiency.

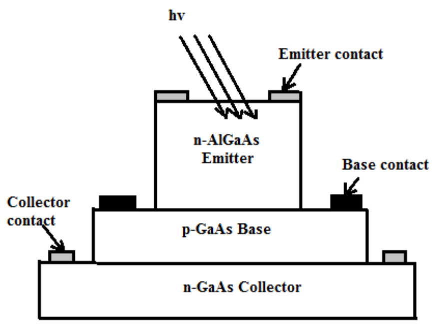

Fig 6: Cross-section view of Hetero-junction Phototransistor [5]

IV curve of HBT showing saturation, active and cutoff region is given below. Active region of HBT is larger than active region of homojunction Bipolar phototransistor as can be seen by Fig-7.

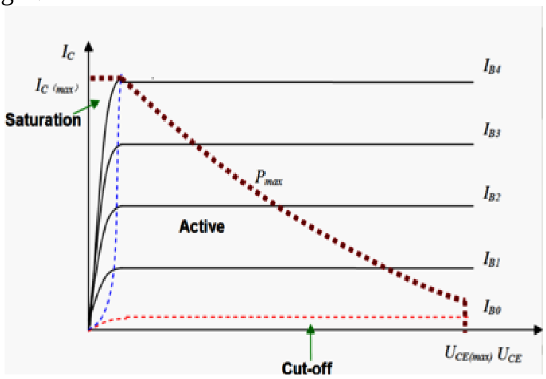

Fig 7: IV curve of HBT [2]

V. COMPARISON OF HOMO-JUNCTION AND HETERO-JUNCTION PHOTOTRANSISTOR

Table 3: Comparison of Hetero-junction (AlGaAs/GaAs) and Homo-junction bipolar transistor (Si)

Parameters	**Homo-junction Photo-transistor (Si)**	**Hetero-junction Photo-transistor (AlGaAs/GaAs)**
Optical Gain	50 to few hundreds	Upto 10,000
Spectral Range	Shorter than HBT	1-1.55μm
Bandwidth	poor	Very high
Response time	12ps	4ps
Operating Frequency	250KHz	>200 GHz

In spite of having high level of gain, the hetero structure devices are not widely used because they are considerably more costly to manufacture.

CONCLUSION

In this paper, we compared Solar cell, Photo-diode and photo-transistor on the basis of their performance parameters. We found that the photo-transistor is the best choice among these three optical devices at some extent.

We have also compared BJT photo-transistor on the basis of material used, structure and direction of illumination. We conclude that hetero-junction phototransistors made by using group III-V material are best on the basis of structure and on the basis of direction of illumination, lateral illuminated phototransistor is better than vertical and Rear face illuminated phototransistor.

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