

Lecture 18: Photodetectors

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1 Introduction

Light emitting diodes and lasers are examples of devices where an electrical current is converted into an optical output (light). There are also optoelectronic devices that do the reverse i.e. convert an optical signal into current. This conversion process can be divided into three major steps

1. The incident light on the semiconductor generates the carriers
2. The carriers are transported through the semiconductor to the electrodes. Usually, some sort of amplification is also present, esp. for photodetectors.
3. Extraction of the generated carriers are current in the external circuit.

2 Photodetector principle

Photodetectors are of many types but they can be divided into two main classes

1. *Thermal* - thermal detectors detect light by a rise in temperature when the light is absorbed. The work mostly in the far IR region.
2. *Photon* - photon detectors work by creating electron-hole pairs on absorption of the incident radiation. The carrier concentration is proportional to the intensity of the incident radiation.

The focus, in this chapter, will be on the photon based detectors. If λ is the wavelength of the incident radiation, then it can be ‘detected’ if

$$\lambda \leq \frac{hc}{\Delta E} \quad (1)$$

where ΔE is the energy of the *relevant transition* within the active region of the device. Different kinds of transitions are possible

1. **Interband** - from the valence band to the conduction band
2. **Interband impurity** - from an impurity level in the band gap to either the valence or conduction band. These impurity states are typically shallow states located close to the opposite band edge
3. **Barrier height** - transition across a Schottky junction from metal to semiconductor

Photodetectors are usually wavelength specific i.e. the material and device are chosen to work over a specific wavelength region. Solar cells, on the other hand, are designed to work with the solar spectrum, which extends from the IR region to the visible and then UV.

An important factor in choosing the photodetector is the absorption coefficient of the semiconductor material. Optical absorption coefficients for different semiconductor materials are shown in figure 1. The absorption coefficient decides the *penetration depth* of the radiation into the device. This is given by Beer-Lambert law, and the penetration depth is the inverse of the absorption coefficient. If α is very large then most of the absorption will be close to the surface. On the other hand, if α is very small, then most of the light will pass through without absorption. The absorption coefficient, and through it the penetration depth, determines the working wavelength range of the photodetector, especially the lower limit. The upper wavelength limit

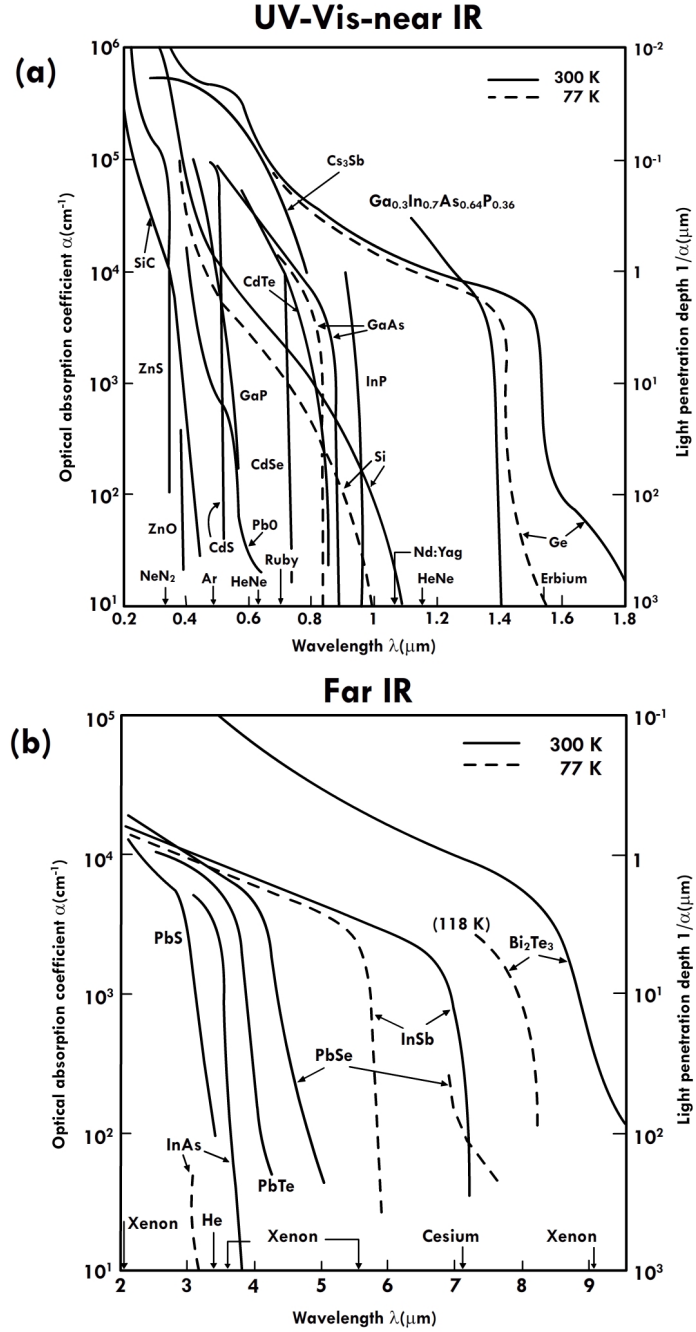


Figure 1: Optical absorption coefficients for different semiconductors as a function of wavelength (a) UV-Vis-near IR region (b) Far IR region. Both room temperature and liquid N₂ temperature data are included. At low temperature the band gap increases and the absorption shifts to lower energy values. Adapted from *Physics of semiconductor devices* - S.M. Sze.

Table 1: Response time and gain of different photodetectors. Adapted from *Physics of semiconductor devices - S.M. Sze*.

Photodetector		Gain	Response time (s)
Photoconductor		$1-10^6$	$10^{-8} - 10^{-3}$
Photodiodes	<i>pn</i> junction	1	10^{-11}
	<i>pin</i> junction	1	$10^{-10} - 10^{-8}$
	Schottky diode	1	10^{-11}
CCD		1	$10^{-11} - 10^{-4}$
Avalanche photodiode		$10^2 - 10^4$	10^{-10}
Phototransistor		$\approx 10^2$	10^{-6}

is determined by equation 1.

Another factor in photodetectors is the *response time*, especially when the radiation arrives in the form of pulses. The device speed is determined by the carrier generation rate. Also, the carrier generation and detection should be faster than the arrival rate of the of the next pulse. Carrier detection is related to the lifetime and also the distance the carries have to travel before reaching the electrodes. One way to reduce the transit time is to reduce the size of the device, esp. in the active region. For a *pn* junction based photodetector, the active region is the depletion region, and this can be made smaller by increasing the doping concentration. But a smaller depletion region will also lead to a lower sensitivity, since the amount of light absorbed will be smaller.

The basic metric of the photodetector is the *quantum efficiency* (η). This is defined as the *number of carriers generated per photon*.

$$\eta = \frac{I_{ph}}{e\phi} = \frac{I_{ph}}{e} \left(\frac{h\nu}{P_{ot}} \right) \quad (2)$$

where I_{ph} is the photocurrent generated from the photon flux, ϕ , and this is related to the optical power P_{ot} . There is also an internal gain mechanism (signal amplification) within the photodetector that can increase the photocurrent. This depends on the type of the detector. The response time is also different for the different detectors. Some typical values for the different detectors are summarized in table 1.

3 Photoconductor

The simplest type of photodetector is a photoconductor. This is a slab of Si, with electrodes at either end. These are usually metals that form an *ohmic*

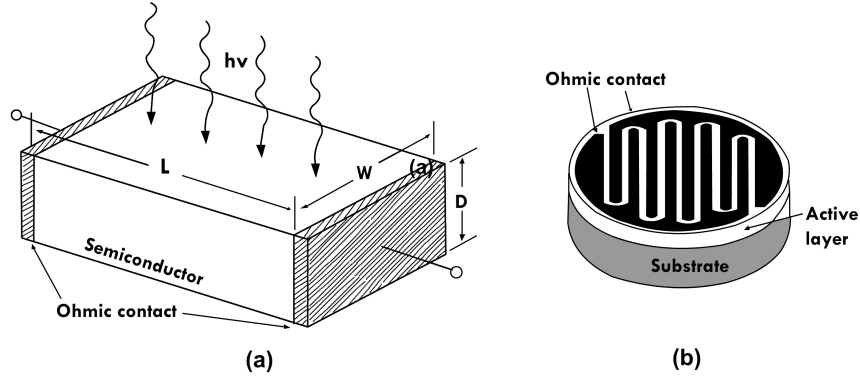


Figure 2: (a) Schematic of the photoconductor showing the absorption of light in the bulk of the semiconductor. (b) A practical design where serpentine Ohmic contacts are used in the top, through which light is incident on the semiconductor. There is another Ohmic contact on the bottom. Adapted from *Physics of semiconductor devices* - S.M. Sze.

contact with the semiconductor. The schematic of the photoconductor device is shown in figure 2. When light falls on the semiconductor material, excess carriers are generated, that form the current. The gain is given by

$$Gain = \tau \left(\frac{1}{t_{rn}} + \frac{1}{t_{rp}} \right) \quad (3)$$

where t_{rn} and t_{rp} are the transit times for the electrons and holes to reach the electrodes. This depends on the electric field (E_x), the carrier mobilities (μ_e and μ_h), and the length (L) of the semiconductor.

$$\begin{aligned} t_{rn} &= \frac{L}{\mu_e E_x} \\ t_{rp} &= \frac{L}{\mu_h E_x} \end{aligned} \quad (4)$$

The photoexcitation process can be intrinsic (band to band) or extrinsic (impurity to band), as shown in figure 3. The carrier mobilities depend on the presence of impurities in the semiconductor. A high mobility is required for a large gain. The choice of the material depends on the region of interest. Sometimes, the device is cooled for reducing thermal noise and increasing sensitivity.

Photoconductors are not only used for detecting radiation in the UV-Visible-near IR region but can also be used for detecting X-rays. This is especially

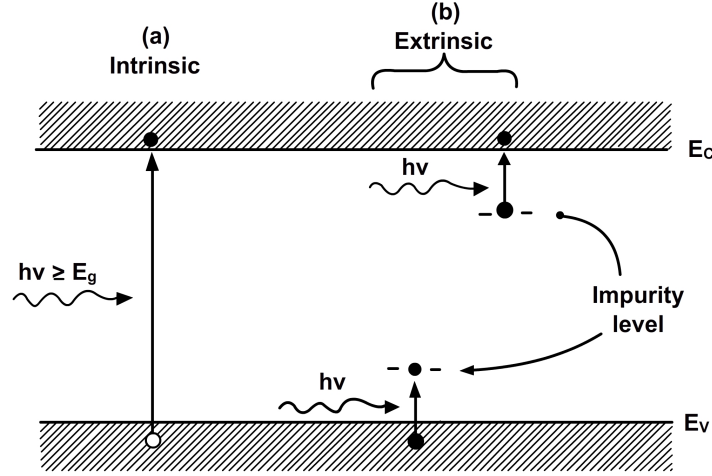


Figure 3: Excitation transition in a photoconductor. This can be (a) band-to-band transitions or (b) Impurity to band transitions. These impurity levels are shallow states that are close to the band edges. Deep states can also take part in photoexcitation but carriers get trapped there and reduce the photocurrent. Adapted from *Physics of semiconductor devices* - S.M. Sze.

useful in energy dispersive spectroscopy (EDS) for chemical identification in electron microscopy systems. Detectors for EDS are made of Si, lightly doped with Li. These detectors are cooled to liquid N₂ temperatures to minimize noise. Cooled Si and Ge detectors are also used for detection in photoluminescence measurements. Ge has the advantage of detecting light further into the IR region due to its lower band gap compared to Si.

4 Photodiodes

A photodiode is based on a simple *pn* or *pin* junction. In the case of the *pn* junction diode, carriers are generated in the depletion region. By applying a high reverse bias, the generated electrons and holes are separated and the current is measured. The disadvantage of the *pn* junction photodiode is that the depletion width is small and depends on the doping concentrations in the semiconductor. It is not possible to tailor the depletion region over a wide range. This can be overcome by using the *pin* photodiode, which is a special case of the *pn* junction photodiode. The schematic of the *pin* device and its band structure is shown in figure 4. The carriers are generated in the intrinsic region and then extracted by application of reverse bias. Electrons

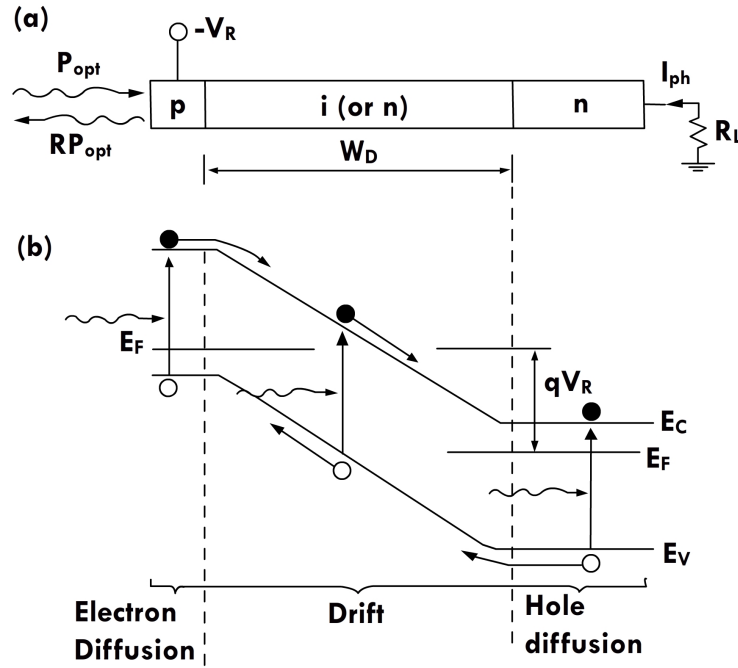


Figure 4: *pin* photodiode. (a) The design shows that the *p* and *n* regions are thin and most of the absorption is in the intrinsic region. Instead of intrinsic a lightly doped *n* region can also be used. (b) Energy band diagram showing the creation of electron-hole pairs and their separation due to the applied external field. A reverse bias is applied so that the electrical field is higher at the junction. Adapted from *Physics of semiconductor devices* - *S.M. Sze*.

that are generated, move to the n side, while holes move to the p side. The advantage of the pin structure is that the quantum efficiency, sensitivity, and gain of the device can be controlled by the thickness of the intrinsic region while a thin p and n regions can be maintained.

Let α be the absorption coefficient in the intrinsic region. This is wavelength specific. Let w_D the width of the intrinsic region. For high quantum efficiency, the product $\alpha w_D \gg 1$. The trade off is that the device length is longer and this increases carrier transit time and hence the response time. A Si based pin photodiode and its behavior is summarized in figure 5.

4.1 Heterojunction photodiode

For a homojunction based pin diode, the p and n regions (or atleast one of them) should be thin to minimize optical absorption. But practical implementation is difficult so that there is a loss of device sensitivity. To improve the sensitivity, a heterojunction photodiode can be used. Here, the p and n regions are made of a higher band gap material, so that their absorption coefficient is lower in the wavelength range of interest. This also means that the quantum efficiency does not depend on the depth of the junction from the surface. Two examples of InP based heterojunction devices are shown in figure 6. The InP region has a band gap of 1.27 eV while the active region of i -InGaAs has a band gap of 0.73 eV. So light of energy less than the band gap of InP can easily reach the intrinsic region. The InP also acts as a filter to remove the higher energy radiation improving device sensitivity. In the case of heterojunction diodes, the choice of material and substrates are limited since interfaces without defects have to be grown. Defect states in the interface can trap the carriers and again reduce the device efficiency.

4.2 Metal-semiconductor photodiode

Metal-semiconductor junctions are either of the Ohmic or the Schottky variety. Schottky junctions can be used for photodiodes since it has a depletion region that can be used for carrier generation (Ohmic junctions have an accumulation region instead). There are two main modes of operation

1. $h\nu > E_g$ - here electron-hole pairs are generated in the semiconductor and contribute to the current.
2. $\phi_B < h\nu < E_g$ - a photon is excited from the metal and moves to the semiconductor. This happens when the photon energy is greater than the barrier potential. This process is called *internal photoemission*.

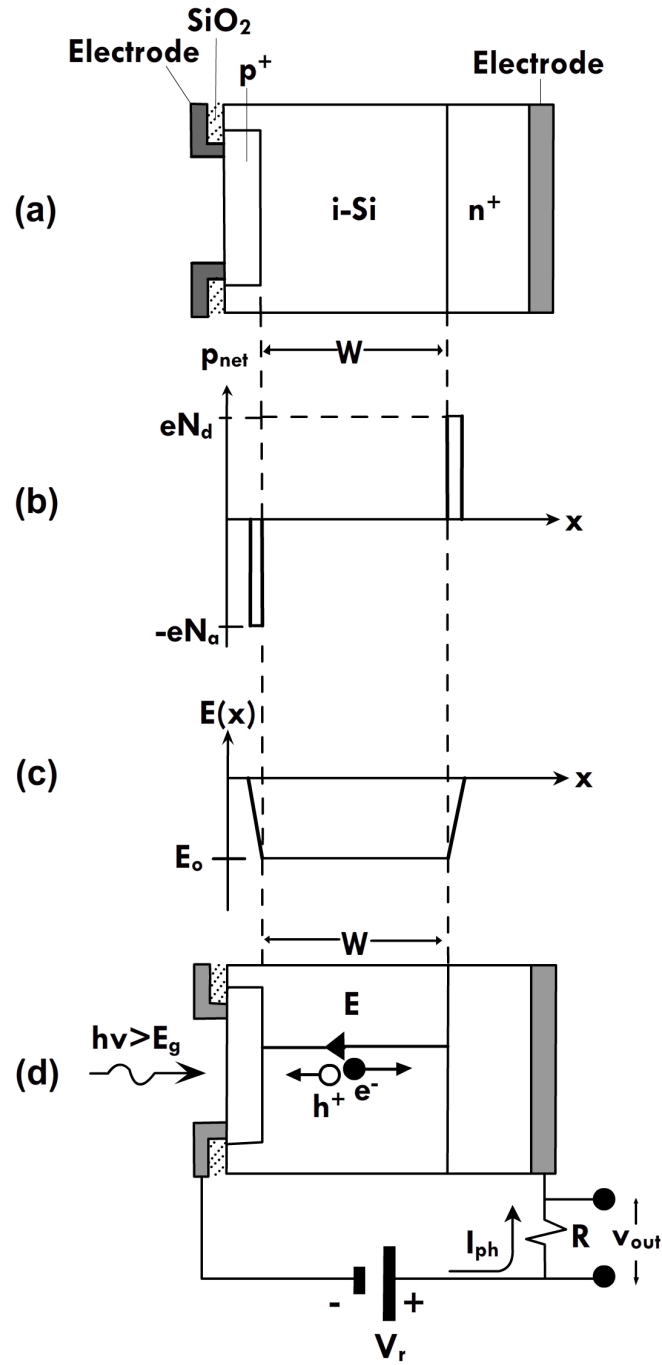


Figure 5: The working of a Si based *pin* photodiode. (a) *pin* design. (b) charge distribution across the device. (c) Electric field. (d) Drift current under illumination and external reverse bias. The bias helps in charge separation. Adapted from *Principles of electronic materials* - S.O. Kasap

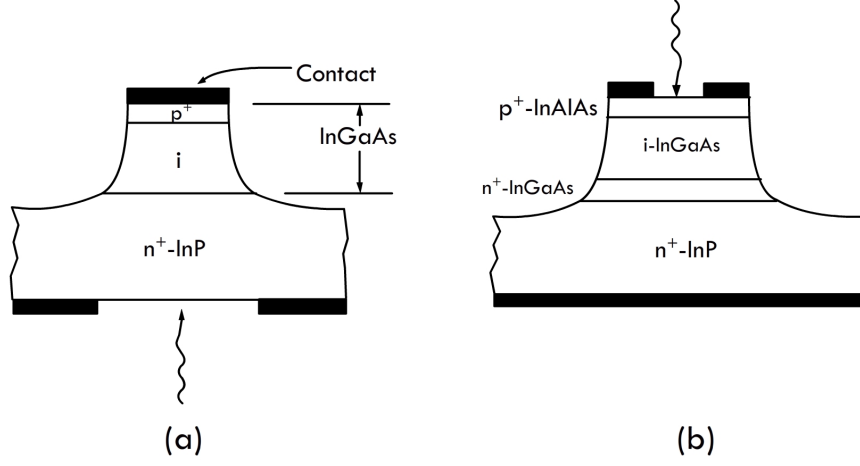


Figure 6: InP based heterojunction *pin* photodiode with (a) substrate and (b) top illumination. In both cases the intrinsic region, is where the carriers are generated. The *p* and *n* regions have a higher band gap than the intrinsic region so that their absorption coefficient, in the region of interest, is low. These can also be used to filter the high energy radiation that would show up as noise. Adapted from *Physics of semiconductor devices - S.M. Sze*.

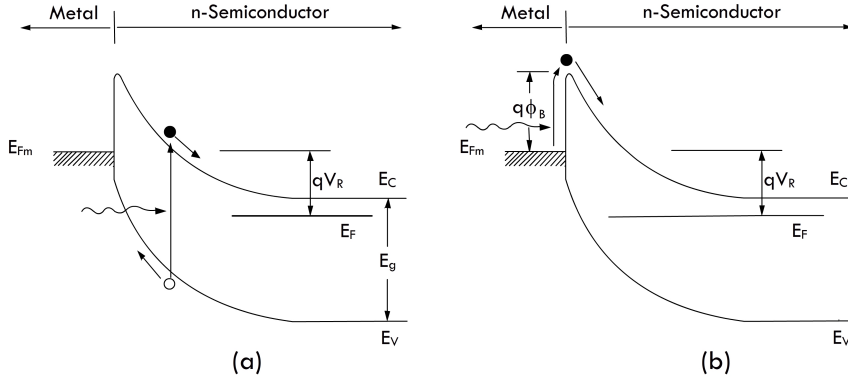


Figure 7: Metal semiconductor junction based photodiode. (a) Short wavelengths are absorbed by the semiconductor directly creating electron-hole pairs. These electron and holes are separated by the external bias, forming a current (b) Internal photoemission occurs when the light causes excitation of electron from metal to the semiconductor. Adapted from *Physics of semiconductor devices - S.M. Sze*.

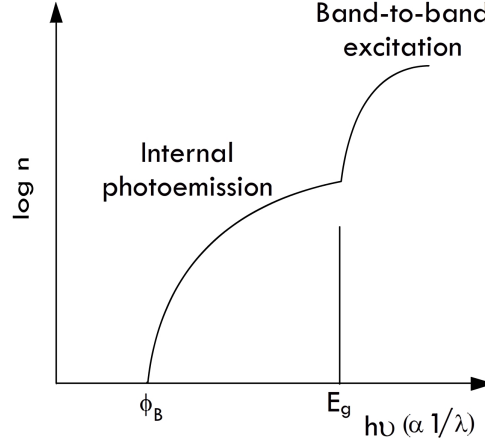


Figure 8: Metal semiconductor junction quantum efficiency. There are two regimes, corresponding to band excitation and internal photoemission. Band excitation has a higher efficiency but internal photoemission increased the upper limit of wavelength range of the detector Adapted from *Physics of semiconductor devices* - S.M. Sze.

Both processes are summarized in figure 7. The metal-semiconductor junction is in reverse bias to separate the electrons and holes. The quantum efficiency of the device depends on which of the process are active, shown in figure 8.

Sometimes instead of metals, silicides are used to form the junction. For example, PtSi, Pd₂Si or IrSi is used to form the junction with Si. Consider the photodiode formed between PtSi and Si. The Schottky barrier height is given by the difference between the work function of PtSi and electron affinity of Si. For this junction, the barrier height is 0.92 eV. Si band gap is 1.12 eV. For wavelength less than 1100 nm (1.1 μm) the excitation is due to band absorption in Si. For wavelength between 1320 - 1100 nm the excitation is due to the internal photoemission process (from PtSi to Si). Wavelengths longer than 1320 nm are not absorbed. Thus, the higher wavelength range has been shifted from 1100 nm to 1320 nm, by using the process of internal photoemission.

One drawback of the metal-semiconductor photodiode is that the metal layer has to be very thin since absorption coefficients for metals is very high. To give a figure of comparison, at a wavelength of 1000 nm, Si has a α of 10^4 m^{-1} , while Pt has a α of $7 \times 10^7 \text{ m}^{-1}$. Turning this into a penetration depth, a Pt layer only 10 nm thick can reduce the intensity by half!

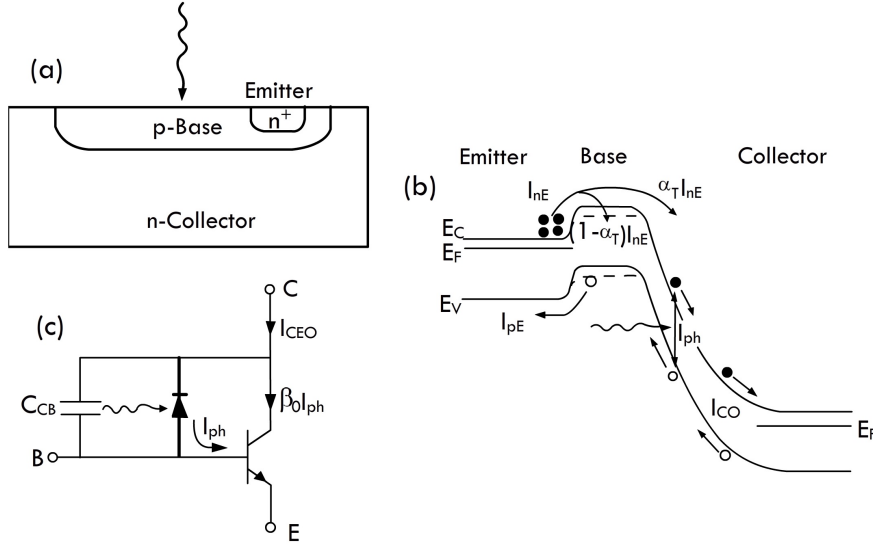


Figure 9: BJT based phototransistor. (a) Schematic of the device. Light emission is from the top into the collector region. The base and emitter are thin so that absorption in them can be neglected (b) Band diagram showing electron-hole generation in the collector and separation. (c) Common base configuration. There is an increase in gain due to the photocurrent. Adapted from *Physics of semiconductor devices* - S.M. Sze.

5 Phototransistor

The phototransistor uses the transistor gain action in conjunction with the carrier generation due to light absorption. Consider the schematic of a bipolar junction transistor (BJT) based device shown in figure 9. The transistor has a large base area (lightly doped) to collect the photons, at the base and collector depletion region. This is unlike a conventional BJT, where the base is usually thin to prevent carrier loss due to recombination (when the carriers move from emitter to collector). This accumulation of carriers at the base lowers the potential and increases the efficiency of transfer of carriers from the emitter to the collector. Instead of a regular transistor, a heterojunction transistor can also be used. The emitter material has a larger band gap than the base, to minimize absorption. Typical devices include AlGaAs/GaAs and CdS/Si based devices. These have a higher injection efficiency than the regular phototransistors because they are transparent to the wavelength of interest.