3.1 Introduction

When a p-type and an n-type semiconductor are brought together in close contact, the boundary of the interface where the two types meet is called the ***p-n junction.***

A useful p-n junction cannot be constructed merely by welding a piece of p-type material against another piece of n-type semiconductor as this will introduce a grain boundary i.e., a discontinuity across the junction. There are two principal techniques of fabricating a p-n junction : (i) *grown junction* and (ii) *fused junction*, into the details of which we shall not enter. The p-n junctions are created by doping one side of a single crystal semiconductor with acceptors and the other side with donors. A p-n junction is thus a two-terminal device and is known as a ***junction diode.*** Most of the semiconductor devices contain one or more p-n junctions because of its effective role as a control element. So, the p-n junctions are elementary 'building blocks' of almost all the semiconductor devices like transistors, LEDs, ICs, solar cells etc.

3.2 Unbiased p-n junction

In a p-type semiconductor, holes are the majority carriers and in an n-type semiconductor electrons are the majority carriers. When a p-n junction is formed (Fig 3.1(a)), electrons from n-region diffuse into p-region and holes from p-region diffuse into n-region due to the difference in carrier concentration. During the process of diffusion, the electrons recombine with the holes in the p-side after crossing the junction, leaving behind the positively charged immobile donor ions in n-region. The hole in their turn cross the junction to recombine with the electrons in the n-region, leaving behind the negatively charged immobile acceptor ions in the p-region.

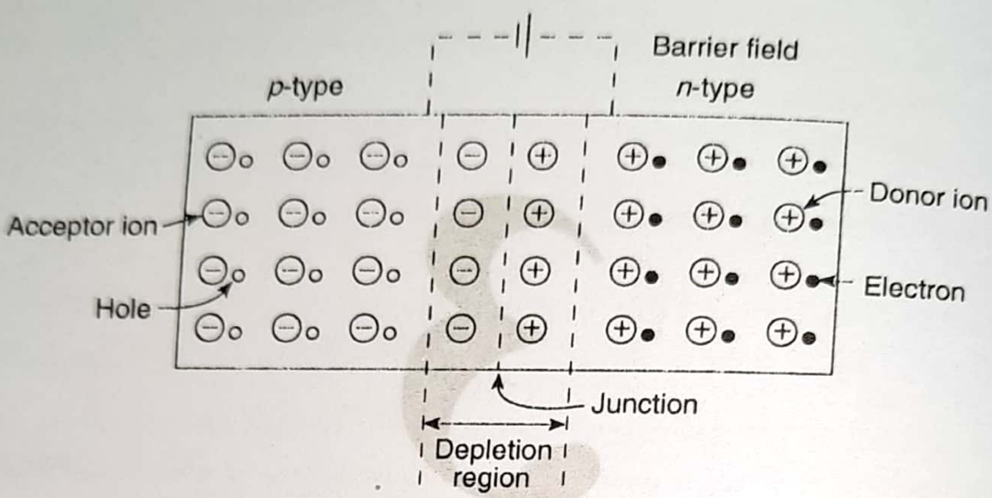
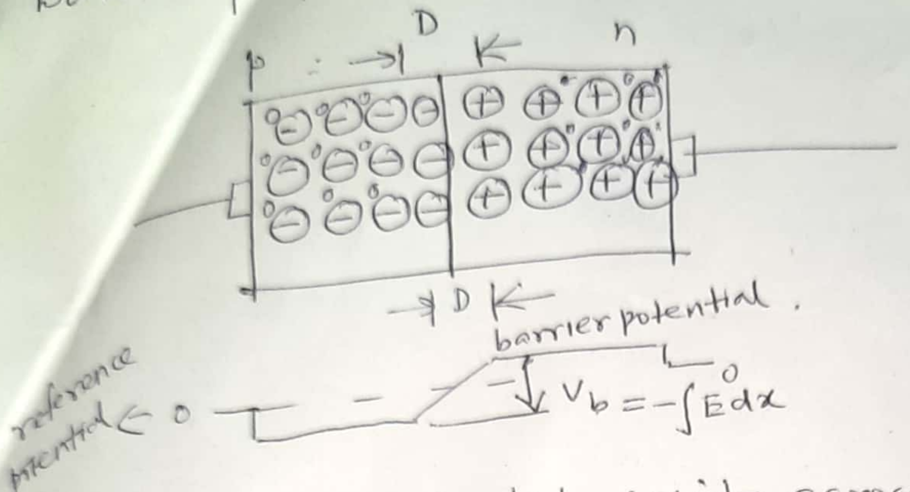


Fig. 3.1 Schematic diagram of a p-n junction

As a consequence of the diffusion and recombination, non-neutralized ions are left in the neighbourhood of the junction. Since the region near the junction becomes deprived of the mobile charge carriers (electrons or holes) and contains only the immobile ions, it is called the ***depletion region*** or *the space charge region*. It is also called *transition region*. The thickness of depletion region is $\sim 10^{-6}$ m. The non-neutralized positive and negative charges produce an electric field across the junction directed from n-side to the p-side. This field is called *potential barrier* or ***barrier field*** which opposes further diffusion of electrons and holes through the junction. In equilibrium, the internal barrier field is just sufficient to prevent diffusion of majority charge carriers. However, it is to be noted that the field helps the minority carriers to move across the junction and a very small amount of current flows. The potential barrier V_b acts as a *fictitious* battery connected respectively with its positive terminal to n-side and negative terminal to p-side. The circuit symbol of a p-n junction diode is shown in Fig. 3.2 where the arrowhead is in the direction of current flow when the p-side and the n-side are connected respectively to the positive and negative pole of a battery.

(1) Why we can not measure ~~electric field~~ barrier potential of a p-n junction.



• → e^-
o → holes
⊖ immobile -vely charged acceptor ion
⊕ immobile +vely charged donor ion
D → depletion region

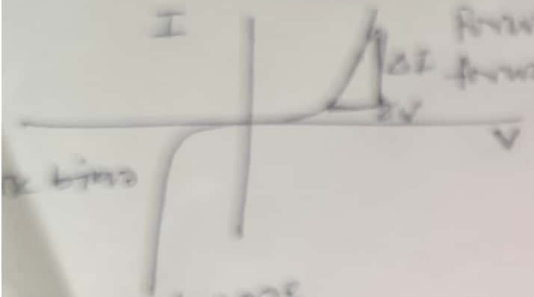
- barrier potential exists across the depletion region & not across the diode, so the region of existence of electric field lines is limited to the depletion region only. voltmeter / multimeter is connected across the terminals of p & n junctions. The unbiased p & n regions between voltmeter probe & depletion region acts as insulator & prevents field lines to reach the voltmeter ~~pro~~ probes..

- To measure potential, slightest of current should move within the voltmeter. ~~If the~~ In the biased or unbiased p-n junction the ohmic contact forming p-n diodes at the semiconductor metal junction which hides the barrier potential drop.

diodes at the semiconductor metal junction which
wides the barrier potential drop.

(2) Diode current & voltage measurement

diode characteristics curve

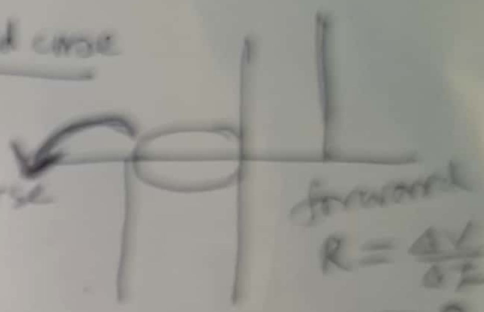


forward bias
forward resistance
finite

$R = \frac{\Delta V}{\Delta I}$

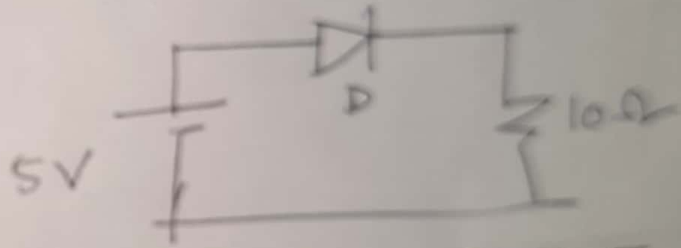
non ideal case

idealized case



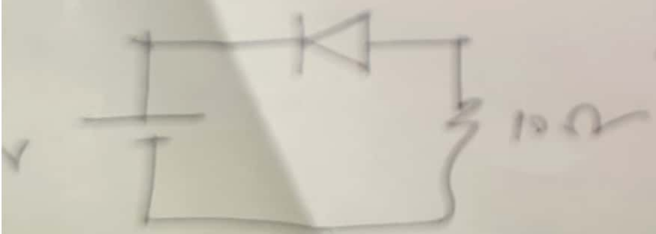
Reverse
$R = \infty$

forward
$R = \frac{\Delta V}{\Delta I} = 0$



$\because (R_d = 0)$ $I = \frac{5}{10} = 0.5A$

V_d = voltage drop at D
$= 0$ $(\because R_d = 0)$



D will behave as $R = \infty$ or open circuit

$\therefore V_d = 5V$ & V at $10\Omega = 0$

3.7 Characteristics of a Zener diode

A Zener diode exhibits almost the same properties as that of a p-n junction diode. The I-V characteristic of a Zener diode is shown in Fig. 3.11.

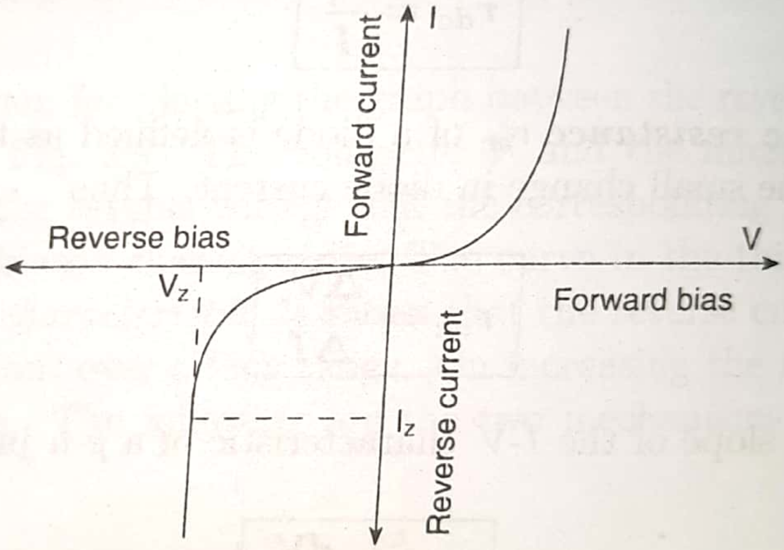


Fig. 3.11 I-V characteristics of a Zener diode

The forward biased characteristic is similar to that of an ordinary p-n junction diode. Under reverse bias, the I-V characteristic is similar to an ordinary p-n junction diode up to the breakdown voltage. In Zener diodes, the doping is controlled in such a way that the breakdown voltage is sharp and distinct. Beyond the breakdown voltage, the reverse current increases sharply to high value which indicates that the voltage across the diode is almost independent of the diode current in this region. This breakdown voltage is known as *Zener voltage* V_z and the corresponding current is *Zener current* I_z. Clearly, V_z remains constant even when I_z increases rapidly. This makes a Zener diode extremely useful as a *voltage regulator device* or reference diode.

Moreover, Zener diode is prepared as highly doped p-type and n-type semiconductor and the power rating is so high that it is not damaged by the large reverse current. So, Zener diodes are used as *voltage regulator*. The circuit diagram of a simple Zener voltage regulator is shown in Fig. 3.12.

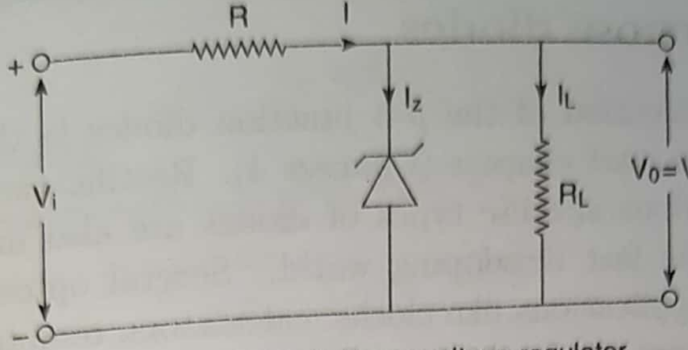


Fig. 3.12 Simple Zener voltage regulator

The unregulated dc supply voltage V_i ($> V_z$) and the series resistance R are so chosen that the diode operates in the reverse breakdown region. The Zener diode keeps a constant output voltage $V_0 = V_z$ across the load resistance R_L, although the input voltage V_i or the load resistance R_L, may vary over a wide range.

Let I and I_L be the supply current and the load current respectively. From Fig. 3.12, we get, by applying the KCL and the KVL

$$I = I_z + I_L \tag{3.8.1}$$

$$V_z = V_i - IR \tag{3.8.2}$$

$$V_z = V_0 = I_L R_L \tag{3.8.3}$$

The output voltage V_0 may be varied (i) by varying the load resistance R_L and (ii) by variation of the input voltage V_i.

(A) Load regulation—In this case, the supply voltage V_i is kept *constant* and the load current I_L is changed by changing R_L. For an ideal case, V_z is *constant*. So, $\Delta V_z = 0$ and $\Delta V_i = 0$.

∴ Eq. (3.8.2) gives,

$$\Delta I = 0$$

$$\text{i.e.,}\quad \Delta I_z + \Delta I_L = 0, \quad \text{using (3.8.1)}$$

$$\text{or,}\quad \Delta I_z = -\Delta I_L \tag{3.8.4}$$

Thus, if the load resistance is increased, keeping the supply voltage constant, the load current decreases with an equal increase in Zener current so that the output remains constant at V_z.

(B) Line regulation—When the load resistance R_L is kept fixed and the supply voltage V_i is varied, we get from (3.8.2)

$$\Delta V_i = \Delta I \cdot R \tag{3.8.5}$$

since $\Delta V_z = \Delta V_0 = 0$ and I_L is constant. From (3.8.1), therefore,

$$\Delta I = \Delta I_z \tag{3.8.6}$$

Some of them are descr...

3.9.1 Light Emitting Diode (LED)

Light emitting diode (abbreviated as LED) is a special type semiconducting *p-n* junction diode which emits light under forward biased condition.

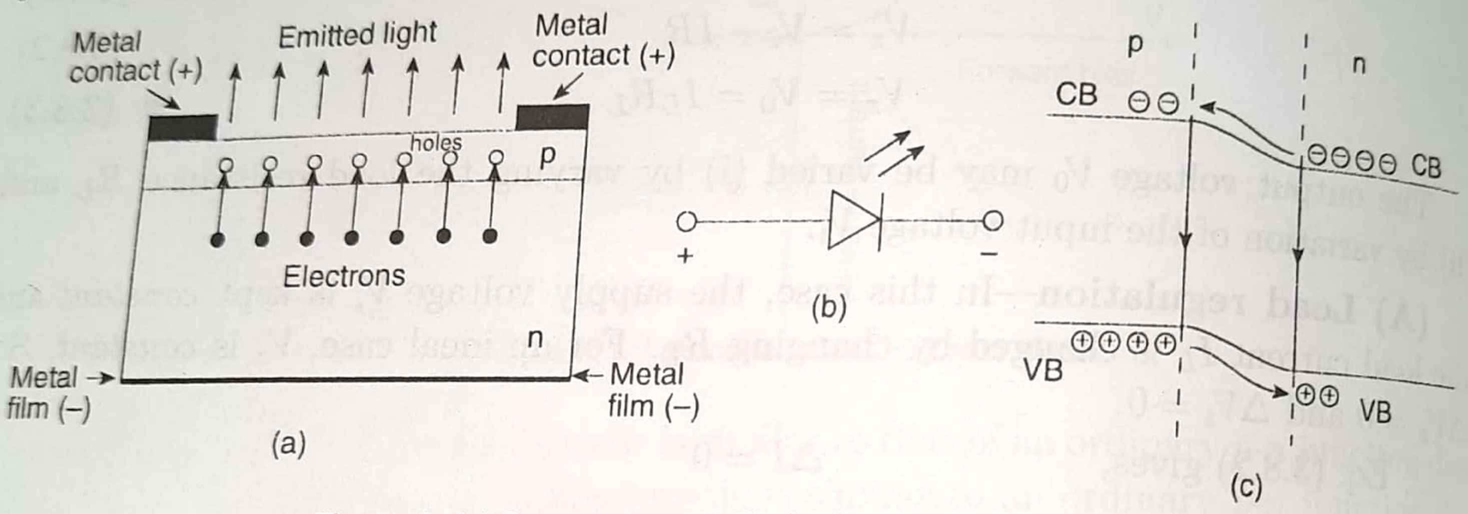


Fig. 3.13 (a) Construction of LED (b) Symbol of LED
(c) Electron-hole recombination and emission of light

Construction—The construction of a typical LED can be followed from Fig. 3.13(a). First, one *n*-type layer of gallium arsenide (GaAs) or gallium arsenide phosphide (GaAsP) or some other suitable semiconducting material is grown on a substrate. Then, a *p*-type layer of very small thickness is deposited onto it by diffusion so that light energy may emit from the depletion region after travelling a very short distance. The metal anode connection is made at the *p*-layer so as to allow more surface area for light emission and the cathode connection is made at the bottom of the substrate coated with metal film. Most of the LEDs contain a domed lens that gathers and intensifies light. Fig. 3.13(b) shows the symbol of a LED.

Principle of working—The principle underlying the operation of a LED is the emission of radiation due to recombination of holes and electrons. When a *p-n* junction is forward biased, the barrier height decreases and electrons from the n-side and the holes from the p-side move towards the narrow depleted region. This results in the electron-hole recombination. Since the electrons make transition from conduction band to valence band during this process, energy is released as a photon of frequency ν given by

$$E_g = h\nu$$

where E_g = band gap energy.

The corresponding wavelength λ is given by

$$\lambda = \frac{hc}{E_g} \quad (\because \nu = c/\lambda)$$

The downward transition of electrons from the conduction band to the valence band and subsequent emission of photons due to recombination is shown in Fig. 3.13(c). The intensity of emitted light depends on the number of photons which in turn depends on the number of recombination that occurs.

For GaAsP, the band gap energy $E_g = 1.9\,\text{eV}$. So we have

$$\lambda = \frac{hc}{E_g} = \frac{6.62 \times 10^{-34} \times 3 \times 10^8}{1.9 \times 1.6 \times 10^{-19}}\ \text{m} = 6533\ \text{Å (reddish)}$$

Uses and advantages of LED—The applications of LED are rather too many. Some of the uses are as under:

1. LEDs are mainly used in signal lamps and display devices, in digital watches, in TV remotes, in calculators and multimeters, in telephone switchboards, etc.
2. The infrared LEDs are used in optical fibre communication and alarm systems where invisible signals are essential.
3. LED can also be used as a laser, known as Injection Junction Laser.

Advantages—LEDs have the following advantages over the traditional lamps with filaments.

1. LEDs consume relatively much smaller power for their operation.
2. They have also quite long life span (~ 100,000 hours)
3. They are very fast in action, small in size and cheap in price.
4. They are available to emit light of all colours.

... Solar cell ... that it can *directly* convert a ... absorbed

The first solar cells were developed in USA in 1954 and were made of silicon. Silicon cells are the only ones, even to-day, that enjoy the commercial status.

Construction—A solar cell is basically an unbiased *p-n* junction diode made of silicon. Fig. 3.14(a) shows schematically the constructional details of a typical solar cell

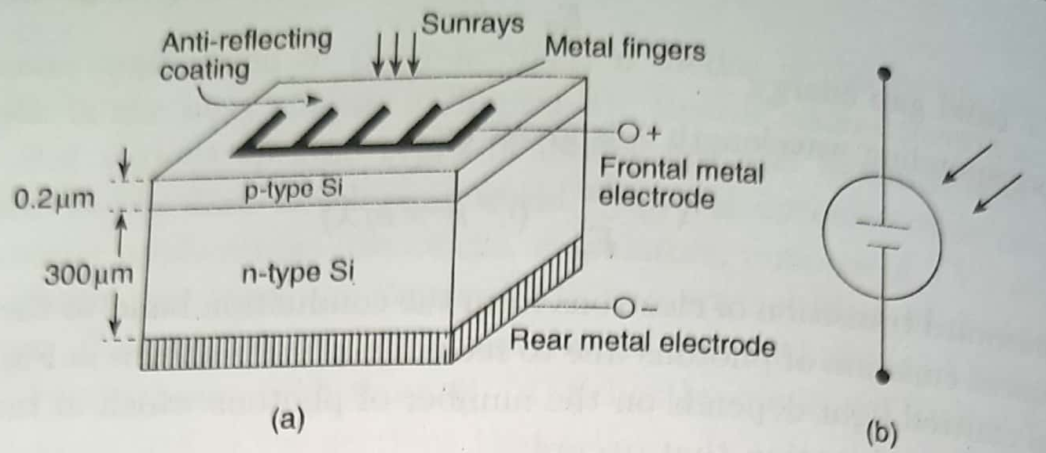


Fig. 3.14 (a) Construction of solar cell (b) Symbol of solar cell

and Fig. 3.14(b) gives its symbolic representation. The upper electrode of the cell is in the form of a ring or a grid with fingers so that sunlight may easily pass through it. To prevent the loss of light by reflection, the upper surface is coated by an anti-reflecting layer. The *p*-layer of the junction diode is much thinner compared to the *n*-layer for an easy diffusion of majority carriers before recombination. The lower electrode (metal) completely covers the surface. Both the *p* and the *n*-regions are heavily doped to obtain a large amount of photovoltage.

Principle of working—The schematic diagram of a *p-n* junction solar cell with a load resistance R_L is shown in Fig. 3.15(a). Since the band gap for silicon is 1.1 eV, the photons of sunlight incident on the diode, if absorbed, can produce electron-hole pairs in both the *p* and *n*-side of the junction. The electrons and holes produced near the depletion layer reach finally the depletion region *W* by diffusion and are separated by

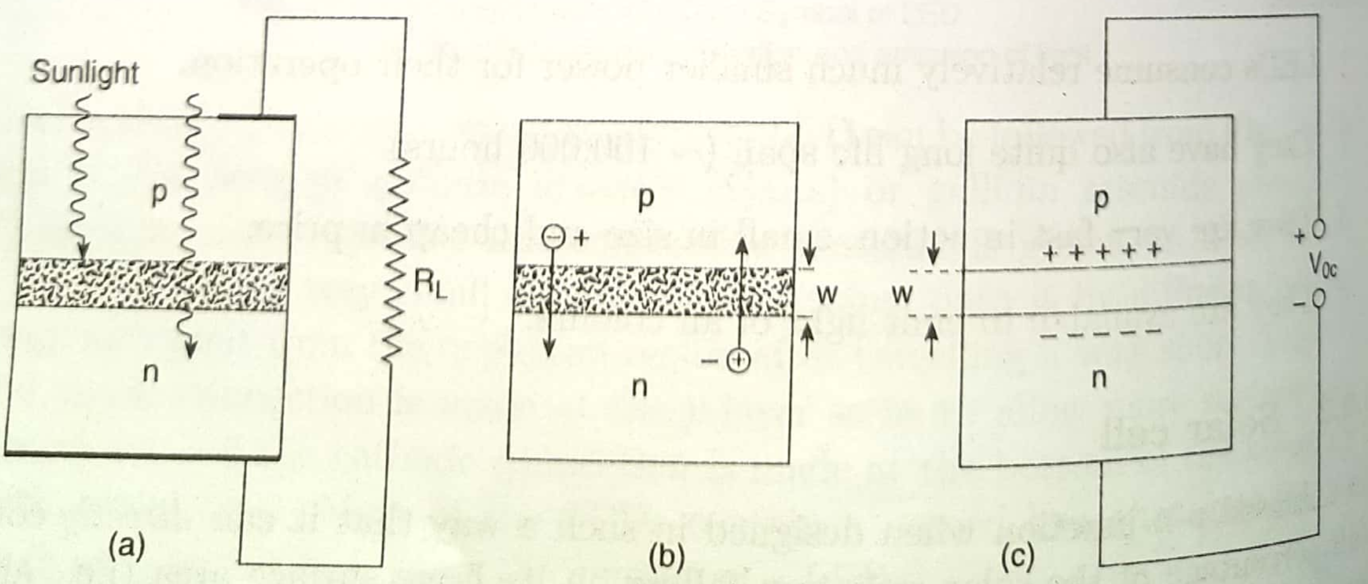


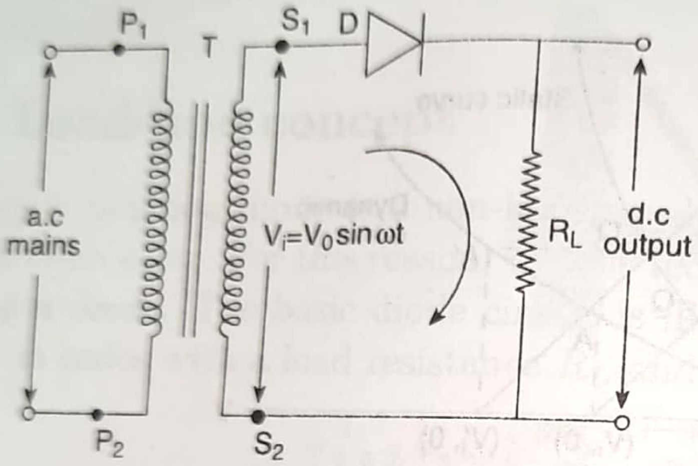
Fig. 3.15 (a) Incident photons (b) absorption of photons and creation of e-h pairs (c) deposition of charges

strong barrier field that exists there. The electrons in the p-side and the holes in the n-side are swept away in the depletion region (Fig. 3.15(b)) and are deposited at the edge of the depletion layer producing an open circuit voltage V_{oc}(Fig. 3.15(c)). When a load s connected, a current flows through the load so long the diode is exposed to sunlight. The open circuit voltage is quite low (~ 0.5 V) and the maximum value of current i.e., he short circuit current is $\sim 10^{-3}$ A. So, for practical applications, a large number of olar cells are to be combined in series and parallel to produce appreciable amount of oltage or current. Such a combination of solar cells is known as a ***solar panel.***

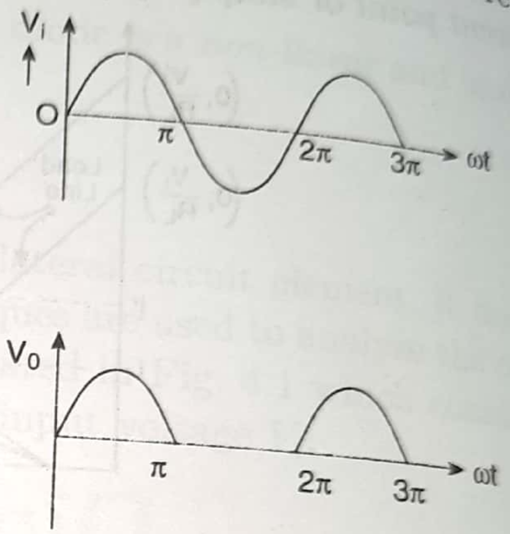
Uses of solar cells—Solar cells have already a number of applications and they e on the increase. Some are enumerated below.

1. Solar cells are extensively used to recharge the storage batteries in satellites and communication equipments.
2. They are used to power watches and calculators.
3. They are also capable of detecting very low level of light intensity.
4. They are being increasingly used to provide domestic and commercial electricity in an eco-friendly way, particularly in areas where the sunshine is plentiful.

wave, it is called *half-wave rectifier*. The basic circuit diagram of a half-wave rectifier is illustrated in Fig. 4.3(a).



(a) Half-wave rectifier



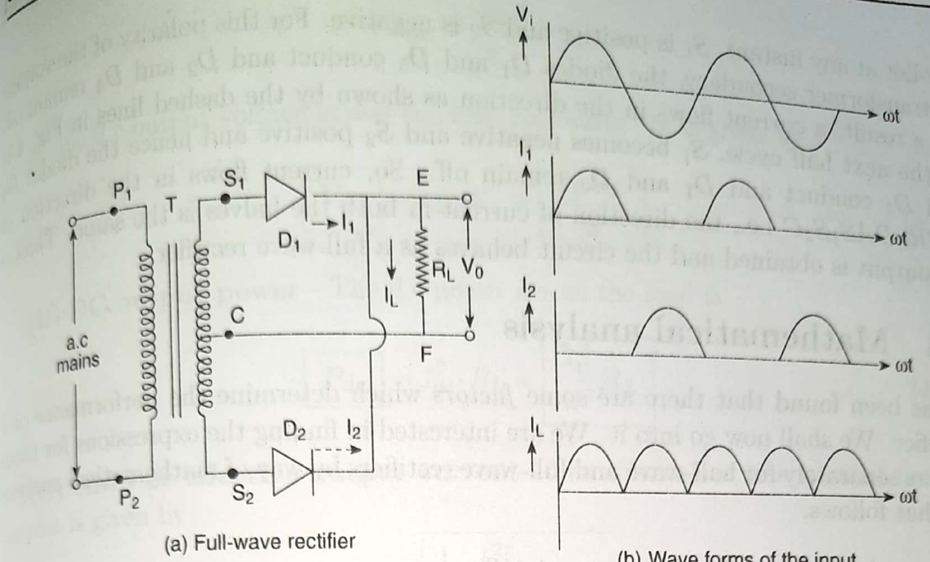
(b) Wave forms of the input and output voltages

Fig. 4.3

An alternating input voltage if fed to the primary P_1P_2 of a transformer T, which may be a step up or a step down transformer, an alternating voltage is induced at the secondary S_1S_2 due to mutual induction. The *p-n* junction diode D is connected across the secondary in series with a load resistance R_L. When the D is forward biased i.e., S_1 is positive and S_2 is negative, the current flows through the load resistance R_L in the direction of arrows (Fig. 4.3(a)) and an output voltage is obtained across the load. During the next half cycle, S_1 becomes negative and S_2 positive so that the diode is reverse biased. In this case, no output current and hence no output voltage is obtained. Fig. 4.3(b) shows the a.c input and the unidirectional pulsating output voltages.

4.3.2 Full-wave rectifier

A full



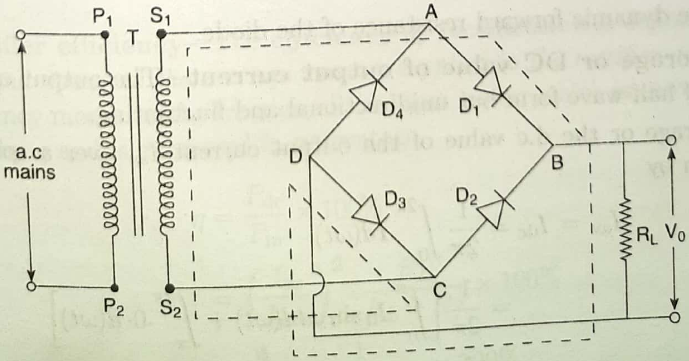
(a) Full-wave rectifier

(b) Wave forms of the input and output signals

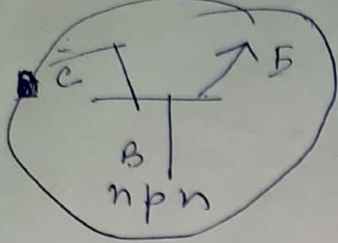
Fig. 4.4

biased and D_2 is reverse biased. So, only the diode D_1 conducts current I_L through the load resistance R_L from E to F producing an output voltage $V_0 = V_L = I_L R_L$. During the next half cycle, D_2 conducts and D_1 remains off. In this case, the current-flow is also in the same direction i.e., from E to F. Since the load current I_L is the sum of the currents through D_1 and D_2, an unidirectional current through the load resistance R_L is obtained by utilizing the full signal and the above circuit behaves as a full-wave rectifier. The wave forms for the input and output signals are shown in Fig. 4.4(b).

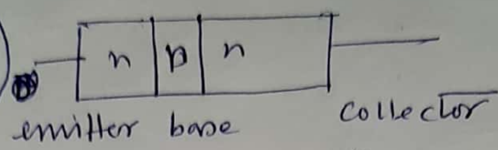
(ii) **Bridge rectifier**—The full-wave rectifier circuit, consisting of four diodes arranged in the form of a Wheatstone Bridge network, is known as ***bridge rectifier***. This rectifier is widely used in power circuits and rectifier type a.c meters. The circuit diagram of the bridge rectifier is shown in Fig. 4.5.



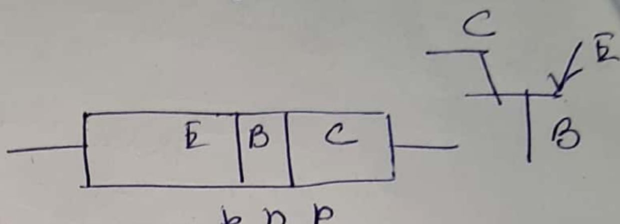
Transistor



circuit



schematic diagram



pnp

Note the sizes of Emitter, base & collector.

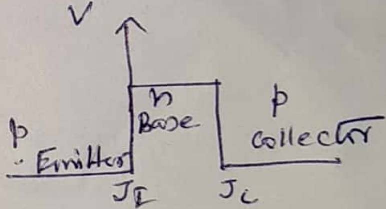
The size of collector is largest. Base is smallest.

Doping of collector is intermediate between that of emitter & base.

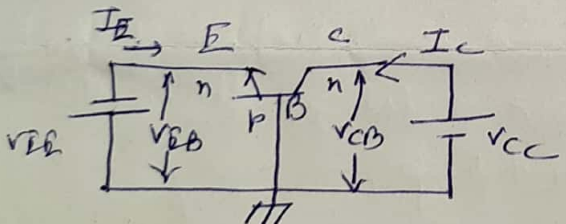
As the doping of base is ~~too~~ least, the depletion regions at the emitter-base junction & collector-base junction extends into the base, making effective width of base very small.

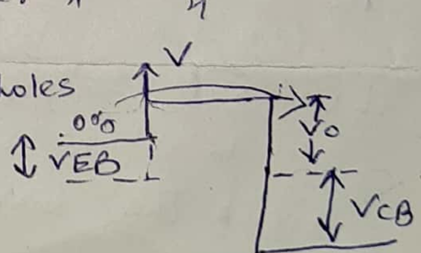
Effective base width $\sim 10^{-6}$ m

potential barrier in a pnp transistor

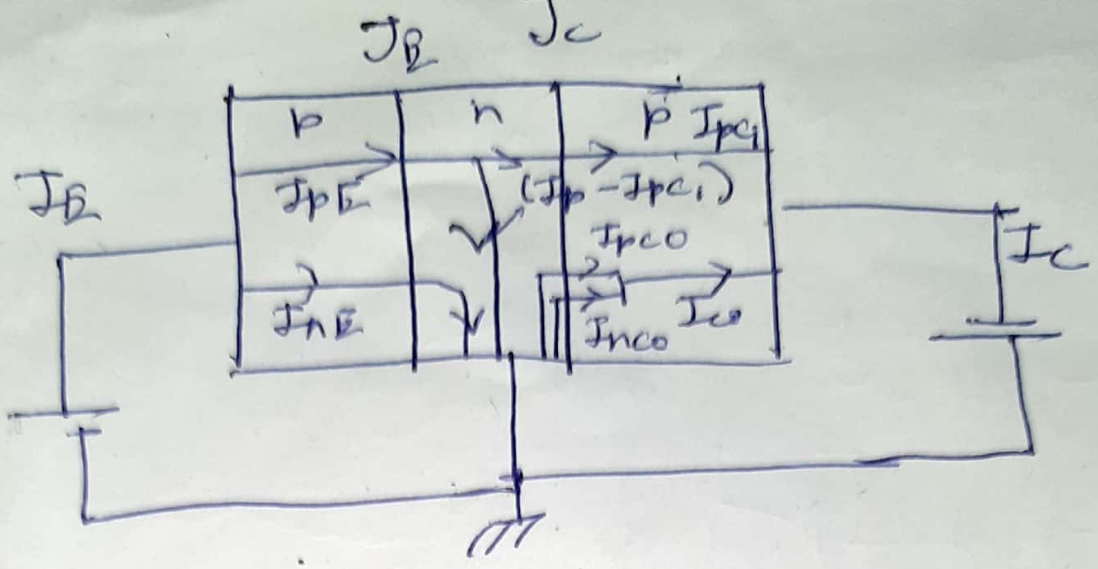


Active region – Reverse bias of collector base junction
Forward " " Emitter " "





For a pnp transistor at active region due to forward bias, the extra voltage V_{EB} pushes the holes ~~o~~ upward & the holes are attracted by reverse bias V_{CB}. Therefore a large current pass through due to holes falling down potential hill. As base width is small, recombination of holes at base is very less probable.



probable.

$$I_E = I_{pE} + I_{nE}$$

I_{pE} = current due to diffusion of holes from emitter to base

I_{nE} = current due to diffusion of electrons from base to emitter.

$$I_{co} = I_{nco} + I_{pco}$$

reverse saturation current = drift of holes from base to collector + drift of e^- from collector to base

$\therefore$ total collector current

$$I_C = I_{pC_1} + I_{co} = \alpha I_E + I_{co}$$

$$\boxed{\alpha = \frac{I_C - I_{co}}{I_E}}$$

large signal current gain in CB mode

$I_C = \alpha I_E + I_{CO}$ $\qquad I_E = I_B + I_C$

$= \alpha (I_B + I_C) + I_{CO}$

or $I_C = \frac{\alpha I_B}{1-\alpha} + \frac{I_{CO}}{1-\alpha}$ $\qquad \beta = \frac{\alpha}{1-\alpha}$

$= \beta I_B + (1+\beta) I_{CO}$

Active region

β is large signal current gain in CE mode

$(1+\beta) I_{CO} = I_{CEO}$

$0.9 \le \alpha \le 0.95$

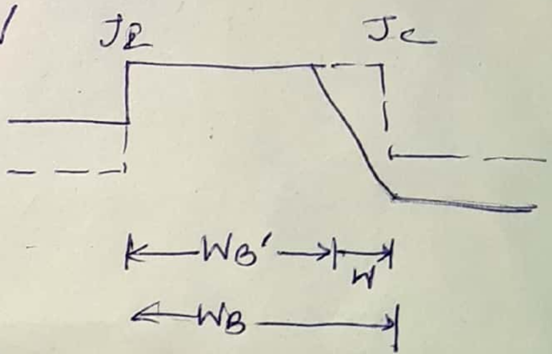
Early effect

Width of depletion region decreases with increase in doping concentrations & amount of reverse bias in CB junction.

effective base width $W_B' = W_B - W$

W = width of depletion region in base side.

→ base width modulation



Early effect result

i) recombination is less in base

ii) As reverse V_{CB} increases, I_E increases.

iii) for large reverse V_{CB}, $W_B' \simeq 0$

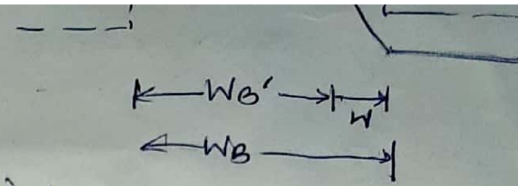
voltage breakdown in transistor

→ punch through / reach through

CB –

$V_{CB} = 12V$

Base width modulation



Early effect

result

i) recombination is less in base
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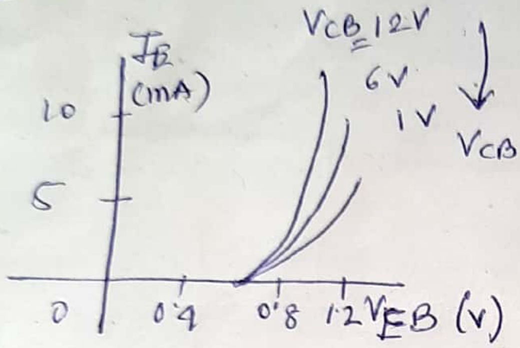
voltage breakdown in transistor
→ punch through / reach through

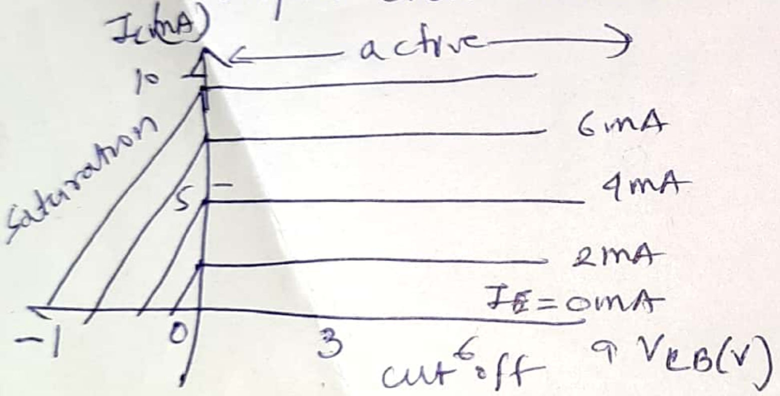
CB



Input characteristics

cutoff ⇒ $I_C = 0$
Both emitter & collector junctions are reverse biased
Only I_{CO} flows through the collector.

Saturation ⇒
Both emitter & collector junctions are forward biased
I_C very high



output charac.

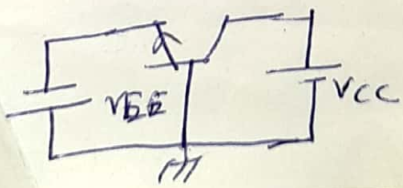
active ⇒
use eqn

$I_C = \alpha I_E + I_{CO}$
or, $= \alpha I_E + I_{CBO}$

I_{CBO} means I_C at common base reverse saturation.

$$\alpha_{dc} = \frac{I_C}{I_E} \qquad \alpha_{ac} = \frac{\Delta I_C}{\Delta I_E}\Big|_{V_{CB} = \text{const}}$$

Circuit



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