Completed

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P-II

UNIT-4

SOLID STATE DEVICES

Lect 32

Drift and Diffusion Current

When a battery is connected across semiconductor, the electrons experience a force towards the positive terminal of the battery and holes towards negative terminal. The random motion of of electrons and holes gets modified. Over and above the random motion there also occurs a net movement called drift. The electric current flows through the semiconductor in the same direction as in which holes are moving. Since electrons are negatively charged, the direction of electric current is opposite to the direction of motion.

When the flow of carriers is due to an applied voltage the resultant current is called drift current. A second type of current may also exist in a semiconductor. This current is called diffusion current and it flows as a result of a gradient of carrier concentration. A gradient of carrier concentration arises near the boundary of a PN junction. The diffusion current is also due to motion of both electron and holes.

<u>**Drift Current**</u> :— Under the action of an electric field, the charge carriers, namely electrons and holes produce two drift currents components.

The electron drifts in conduction band produces a component J_e is given by

$$J_e\,(\text{Drift}) = n e \mu_e E \quad -(1)$$

The holes drifts in valence band hence

$$J_h\,(\text{drift}) = P e \mu_h E \quad -(2)$$

Although electrons and holes flow in opposite direction, the direction of conventional current due to both carriers is in same direction. Hence total drift current density is given by

$$J(drift) = J_e(drift) + J_h(drift)$$
$$J(drift) = e(n\mu_e + p\mu_h)E$$

Diffusion Current:

In a semiconductor, the transport of charge carriers can occure without the assistance of an external field. The driving force for carrier transport is the spatial variation of concentration of carriers. The directional movement of charge carriers due to their concentration diffusion current.

Suppose an external agent such as light or temp. acts momentarily at one end of p-type semiconductor.

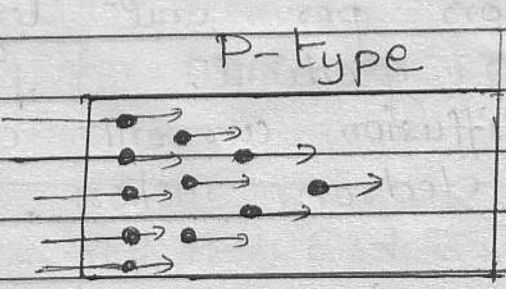

fig 4.1

The action of external agen[t] such as generates additional electron-hole pairs leading to a sudden increase in the concentration of charge carriers in the rest of the material is not disturbed and is at equilibrium value. The difference in concentration causes migration of carriers from the region of higher concentration to the region of lower of concentration in order to restore the equilibrium condition. Such migration of carrier is known as <u>diffusion</u>. As the carriers are charged particles their ~~additional~~ directional movement produces a current flow which is called <u>diffusion</u> current. The diffusion current is ~~called~~ proportional to the rate of change of carrier concentration per unit length. ie concentration gradient.

The diffusion current component due to electron motion is given b[y]

$$I_e(\text{diff}) = eD_e \frac{dn}{dx}$$

If we consider. The hole diffusion current will be given by

$$J_h\,(diff) = -e D_h \frac{dP}{dx}$$

Where D_e and D_h are known as diffusion constant for electrons and holes respectively.

The drift and diffusion current coexist in semiconductor. The total current density due to drift and diffusion of e^- may be written as

$$J_e = J_e\,(drift) + J_e\,(diff)$$

$$\boxed{J_e = e\left(n \mu_e E + D_e \frac{dn}{dx}\right)}$$

Similarly for holes we can write

$$\boxed{J_h = e\left(P \mu_h E + D_h \frac{dP}{dx}\right)}$$

3. ## PHOTOCONDUCTIVITY :—

Conductivity of a semiconductor is proportional to th concentration p and n of charg carriers. Accordingly σ may be increased by increasing either p and n of charge. This increa in electron density n or hole dens p may be achieved by following two ways —

(1) By increasing temperature

(2) By illuminating the semiconductor.

(3) Both these methods results in generation of new electron-hole pai The corresponding devices are reffere as thermistors and photoconductors.

Thermistors :

The conductivity of an intrinsic germanium (silicon) increases about 6% (8%) per degree centigrade rise in temperature. This tempetature dependence has been utilized in Thermistors. Thermistor found popular applicat in

(i) Thermometry.
(ii) measurement of microwave.
(iii) Thermal relay etc.

Photoconductor :-

when radiation is incident on semiconductor, its conductivity increases, the effect is called photoconductivity effect. The energy incident on semiconductor ionizes some of covalent bond resulting in new hole-electron pairs in excess of those generated thermally. This increased number of carriers result in decreased resistivity ie increased conductivity. Such a device is known as photoresistor or photoconductors.

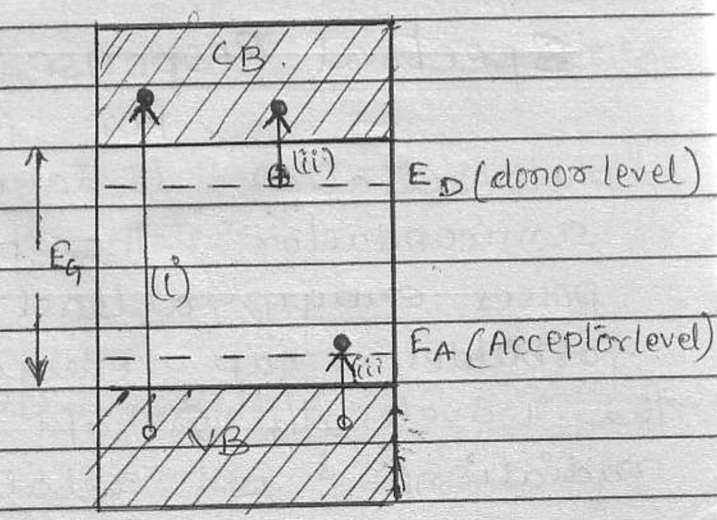

fig 4.2

when photons of adequate energies are incident on specimen photogeneration takes place. It may result–

(i) A high energy photon may cause creation of electron hole pair. Such an excitation is called intrinsic photoexcitation.

(ii) A photo may excite an electron from donor atom to conduction band

(iii) a photon may excite an electron from valence band into an acceptor level. The last two transitions are known as impurity excitation. photoconductivity is caused mainly by intrinsic photoexcitation.

Spectral Response:

For intrinsic photoexcitation to take place in semiconductor, the photon must posses energy atleast equal to forbidden gap energy E_G. But the wavelength λ of light radiation is related to energy translation of an electron from level E_1 to level E_2 by following relation.

$$\lambda = \frac{12,400}{E_2 - E_1}$$

where the wavelength λ is in angstroms and E_1 and E_2 are in electron volt (eV).
Hence the wavelength λ_c of a photon whose energy corresponds to E_G is given by

$$\lambda_c = \frac{12,400}{E_G}.$$

If λ_c is expressed in microns (1 microns $= 10^{-5} m$) then equation becomes

$$\lambda_c = \frac{1.24}{E_G}$$

In case if wavelength of light exceeds λ_c, the energy of photon falls short of E_G and no intrinsic photoexcitation takes place.

The wavelength λ_c is called critical wavelength or cutoff wavelength.

For Ge, $E_G = 0.72\,eV$ and $\lambda_c = 1.73$ micron

For Si, $E_G = 1.1\,eV$ and $\lambda_c = 1.3$ micron

spectral sensitivity curve for Ge and Si are shown in figure.

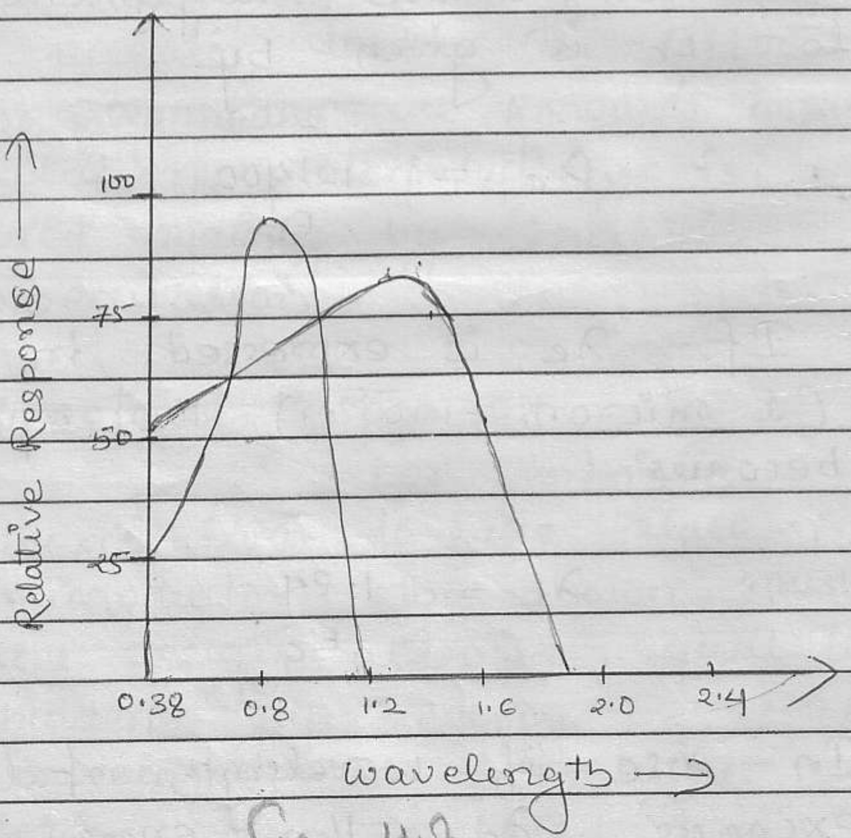

fig 4.3

This implies that for fixed intensity radiation of different wavelength produces different quantities of free carriers. It is called photoelectric response or spectral response.

It may be seen from figure that wavelength λ of radiation is decreased below λ_c ie as frequency 'f' is ~~decreased~~ increased beyond f_c, the response increases and reaches a maximum and then decreases.

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Hall Effect :

If a metal or semiconductor carring a current I is placed in a transverse magnetic field $\vec{B}$, a potential difference is produced in the direction normal to both the current and magnetic field directions. This phenomenon is called Hall effect.

Hall effect measurements showed that it is negative charge carriers namely electrons that are responsible for electrical conduction in metals. It is the Hall effect measurements again which showed that there exists two types of charge carriers in semiconductors. The importance of Hall effect is that it helps in determining —

(1) determines the sign of the charge carriers.

(2) determines charge carrier concentration.

(3) determines mobility of charge carriers if conductivity of material is known.

Let us consider a rectangular plate of P-type semiconductors. When potential difference is applied across its ends, a current of strength I flows through it along x-direction. If holes are charge carriers in P-type semiconductor the current is given by

$$I = PAev_h$$

$p \rightarrow$ concentration of holes.
$A \rightarrow$ area of cross-section.
$e \rightarrow$ charge of holes.
$v_h \rightarrow$ drift velocity of holes.

The current density

$$J_x = \frac{I}{A} = p e v_h$$

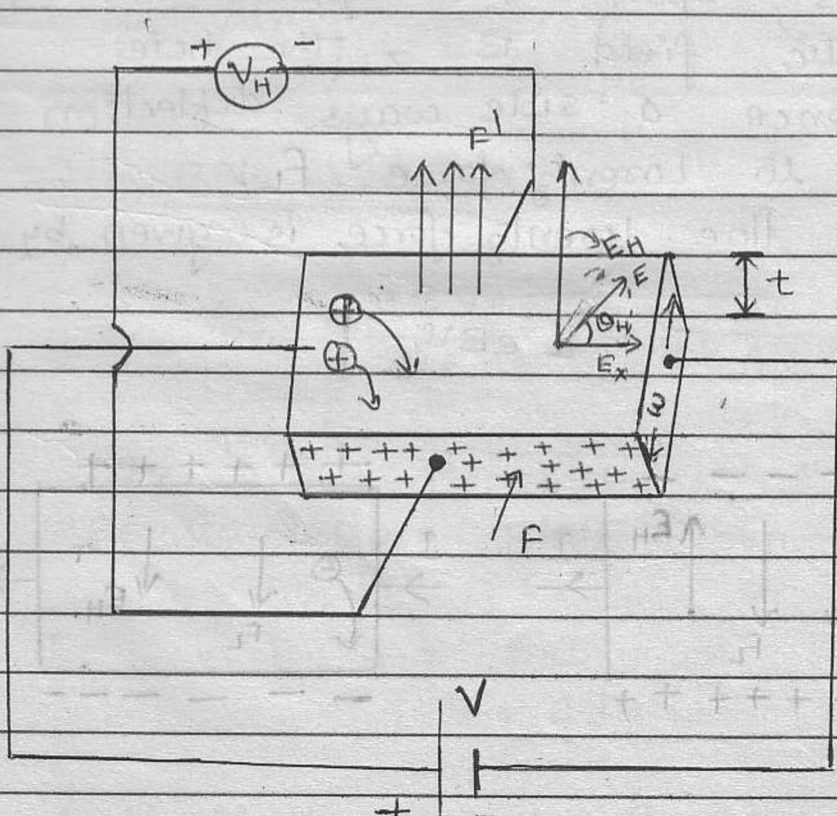

fig 4.4

Any plane perpendicular to current flow direction is an equipotential surface. Therefore potential difference between the front and rear faces F and F' is zero.

If magnetic field $\vec{B}$ is applied normal to crystal surface and also to current flow a transverse potential difference is produced between F and F'. It is called Hall voltage (V_H). The origin of Hall voltage is as follows. Upon the application of magnetic field B, the holes experience a side ways deflection due to Lorentz force F_L.

The Lorentz force is given by

$$F_L = eBv_h$$

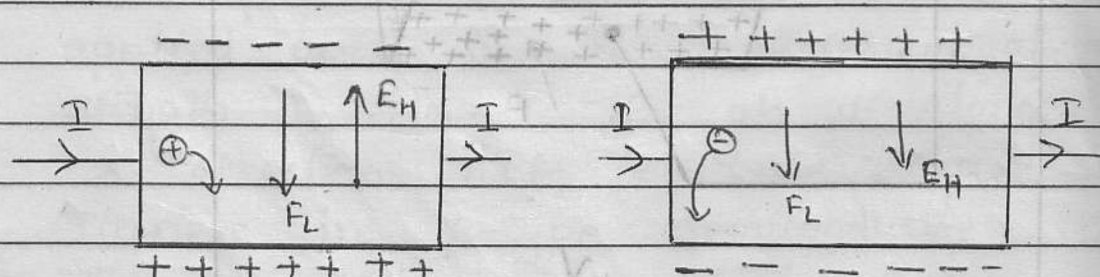

Fig 4.5

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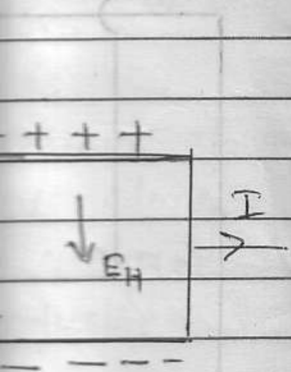

Because of this force holes are deflected towards face F and pile up there, correspondingly equivalent negative charge pile up on rear field is produced between face F and F'. A condition of equillibrium is reached when force F_E due to electric field E_H is balanced by Lorentz force F_L.

$$F_E = F_L$$

$$eE_H = eBv_h$$

$$e\left(\frac{V_H}{w}\right) = eB\left(\frac{J_x}{pe}\right)$$

$$\Rightarrow \frac{eV_H}{w} = \frac{BJ_x}{p}$$

$$\Rightarrow V_H = \frac{wBJ_x}{pe} = \frac{wBI}{peA}$$

If 't' is the thickness of semiconductor plate then $A = wt$.

$$\therefore V_H = \frac{B.I}{p.e.t}$$

Hall field per unit current density

per unit magnetic induction is called Hall coefficient. (R_H)

$$\text{Thus} \quad R_H = \frac{E_H}{J_x B} = \frac{V_H/w}{J_x B}$$

$$R_H = \frac{w B J_x}{w \rho e J_x B}$$

$$\boxed{R_H = \frac{1}{\rho e}}$$

$$\text{but} \quad V_H = \frac{B \cdot I}{\rho e t}$$

$$\therefore \quad V_H = R_H \frac{BI}{t}$$

$$\boxed{R_H = \frac{V_H \cdot t}{B \cdot I}}$$

Hall voltage is real voltage and it can be measured with the help of voltmeter.

Knowing the sign of Hall voltage sign of charge carriers in semiconductor is known. If Hall voltage is negative, Semiconductor is n-type. If Hall voltage is positive semiconductor is p-type.

Knowing Hall coefficient the concentration of charge carriers can be determined using the relation. Carrier concentration is given by

$$p = \frac{1}{R_H e}$$

In case of n-type semiconductor

$$R_H = -\frac{1}{ne}$$

$$n = -\frac{1}{R_H e}$$

In case of semiconductors Hall coefficient drops sharply with a rise in temperature indicating that the concentration of free electrons increases with increase in temperature.

The net electric field E

in semiconductor is vector sum of E_x and E_H, its acts at an angle θ_H to x- axis. θ_H is called <u>Hall voltage.</u>

$$\tan\theta_H = \frac{E_H}{E_x}$$

$$\text{but} \quad E_H = \frac{V_H}{w} = \frac{B J_x}{Pe}$$

$$\text{Also} \quad E_x = \rho J_x$$

$$\therefore \quad \tan\theta_H = \frac{B}{Pe\rho}$$

$$\tan\theta_H = \sigma R_H B$$

The product of $R_H B$ is designated as mobility of holes.

$$\tan\theta_H = \mu_h B$$

$$\theta_H = \tan^{-1}(\mu_h B)$$

where $\boxed{\mu_h = \sigma R_H}$

By determining the conductivity of crystal through a separate experiment and determining the value of R_H from Hall effect measurement, the carrier mobility can be calculated.

P-n Junction:

When P-type material is immetially joined to N-type a P-N junction is formed. P-N junction is formed from piece of semi-conductor by diffusing P-type material to one half side and N-type material to other half side. The plane dividing two zones is known as a junction.

When two pieces are joined together, due to diffusion some electrons from N regions cross over to P region, they combines with holes and become neutral. Similarly some of holes from p-region cross over to N-region where they combines with electrons and become neutral. Thus a layer is formed which is known as depletion region or charged free region or space change region because there are no charge available for conduction. The diffusion of electrons and holes across the junction continues till a potential barrier developed in depletion layer which prevents further diffusion or neutralization. The potential barrier can be increased or decreased by applying external voltage.

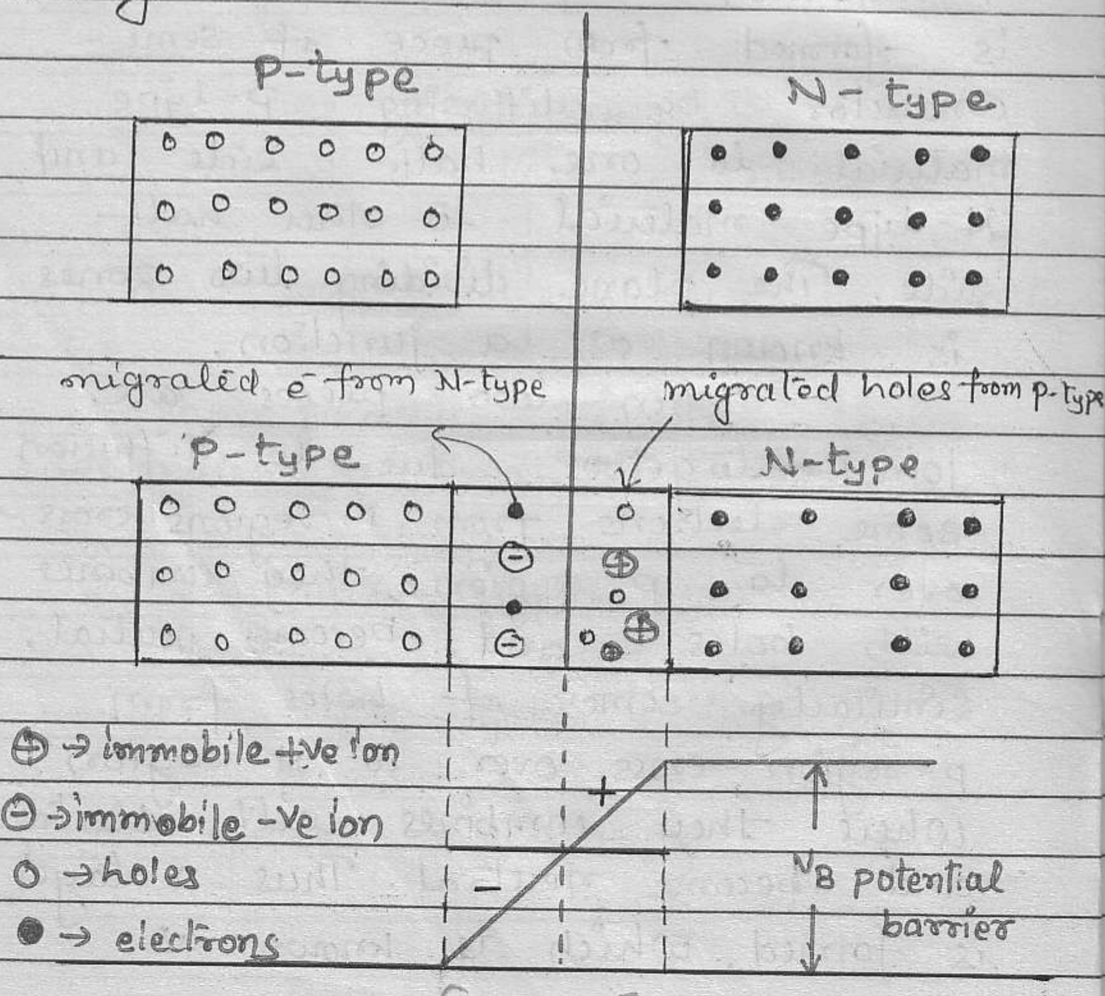

fig 4.6

Junction voltage :-

when depletion layer is formed there are +ve immobile ions in N-region in N-type semiconductor and negative immobile ions in p-type semiconductor. Due to charge separation, a voltage V_B is developed across the junction under equillibrium conditions. This voltage is known as junction voltage or internal voltage.

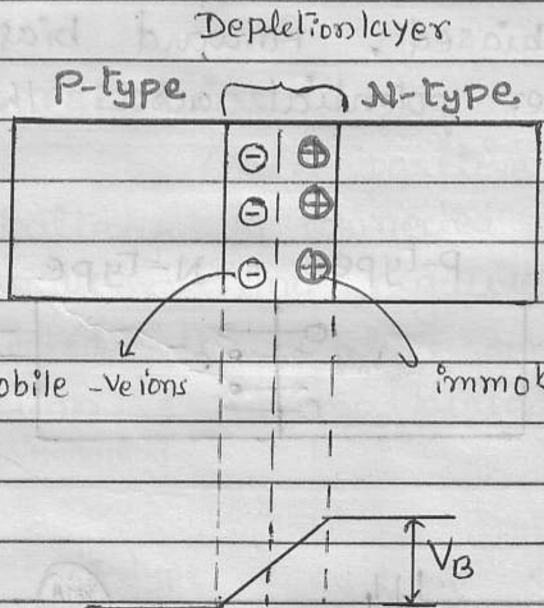

fig 4.7

Rectifying Action:

In order to rectify the depletion layer diode of P-N junction is connected to dc voltage. When dc voltage is connected across a P-N junction junction is said to be biased. A P-N junction can be biased in two ways —

(1) **Forward bias:—**

When positive terminal of a battery is connected to p-type semiconductor and negative terminal is connected to N-type semiconductor, then junction is forward biased. Forward bias lowers the barrier potential across the junction.

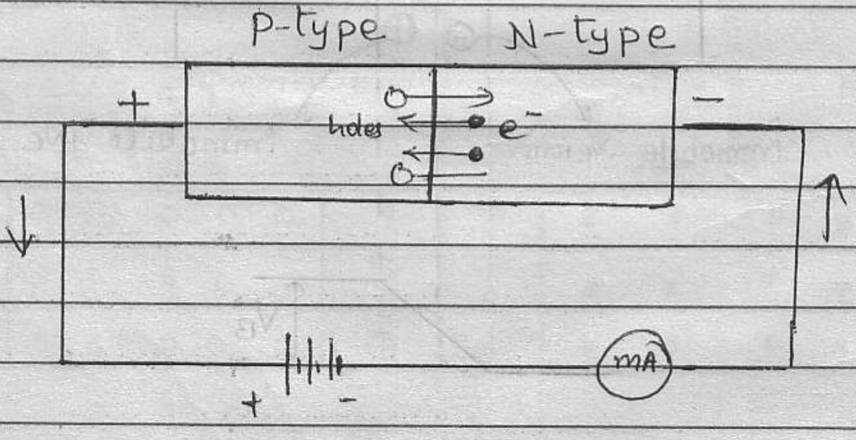

Fig 4.8

In case of forward bias holes from p-region and electrons from N-region are repelled towards the junction. Here the battery ~~of energy~~ voltage should be high enough to impart sufficient energy to these carriers to overcome the potential barrier at the junction. The constant movement of electrons towards the positive terminal and holes towards the negative terminals produces high current.

(ii) **Reverse bias :**

When positive terminal of a battery is connected to N-type semiconductor and negative terminal is connected to P-type semiconductor the junction is reverse biased.

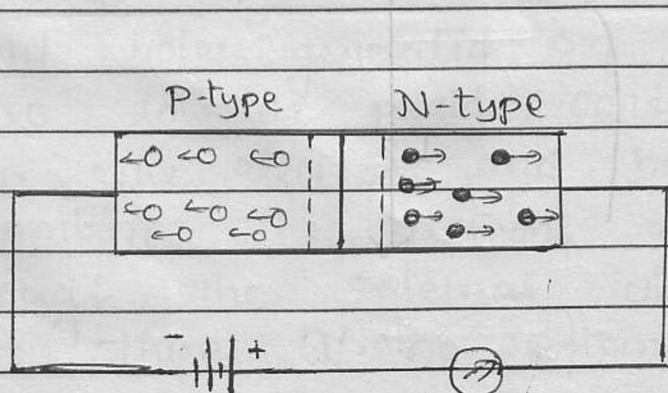

fig. 4.9

The effect of Reverse bias is to increase barrier potential, thus allowing a very little current to flow. When junction is reverse biased the electrons in N-type and holes in p-Type are attracted away from the junction under the action of applied voltage. Hence current is negligibly small ie junction has high resistance.

P-N Junction as a Diode:

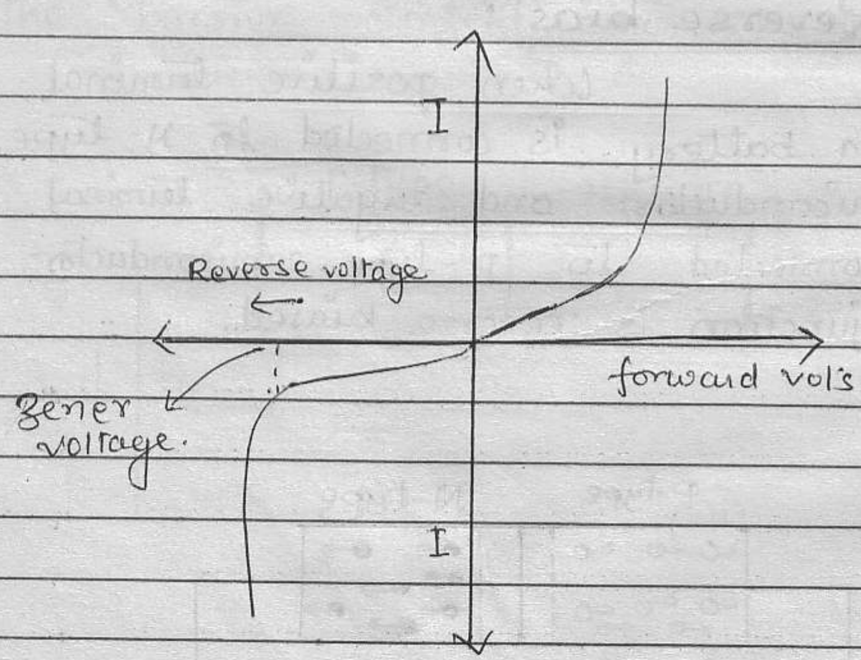

fig 4.10

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PHOTODIODES :

photodiodes converts light energy incident on them to electrical energy and effect is termed as photovoltaic effect. photodiodes are used as sources of power (solar cell) as also as photodetectors.

The principle of photovoltaic effect is absorption of a photon in the region of p-n junction leads to creation of an electron and a hole. Since the field within junction is from n-side to p-side, the excess minority carriers thus generated diffuse to the junction where they are carried across and becomes majority charge carriers — ie electrons generated on p-side move towards n-side and holes generated on n-side move towards p-side. consequently for the electrons and holes to recombine the electrons must go through the external circuit. If there is no external current path, majority carrier excess.

charge will be built up on both sides of junction, with the result in buil- up potential will be ~~result~~ reduced.

If the external circuit is closed, the current will therefore flow in the circuit. The current in circuit will flow so long as the semiconductor region are illuminated

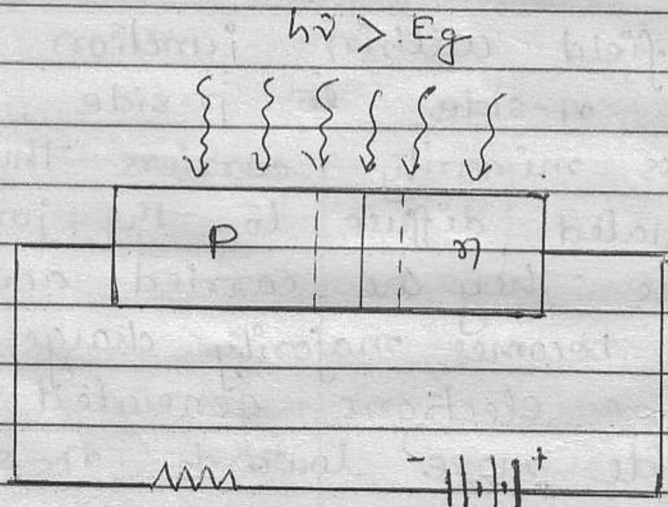

Fig 4.11 (4)

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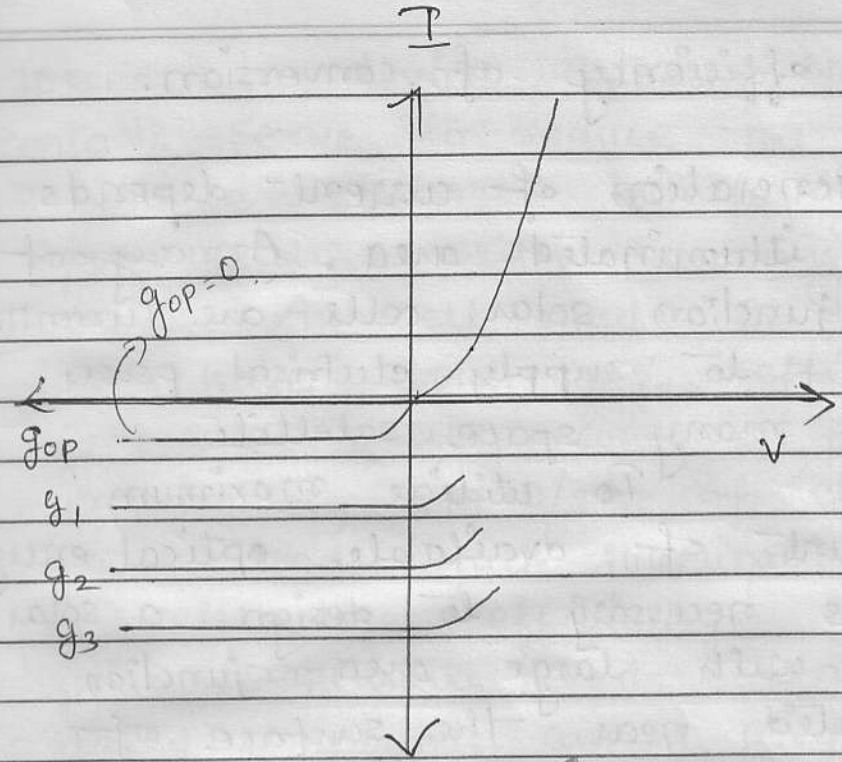

$g_3 > g_2 > g_1$ fig 4.11(b)

$g_{op} \rightarrow$ electron hole generation/cm^3-sec

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Solar Cell:

The ability of illuminated junction ie photodiodes to deliver power is made use of in a solar cells, used to convert solar energy into electrical energy. Consideration involve in operation of solar cell is

(i) power delivered

(ii) efficiency of conversion.

Generation of current depends on illuminated area. Array of p-n junction solar cells are currently used to supply electrical power for many space satellite. To utilize maximum amount of available optical energy, it is necessary to design a solar cell with large area junction located near the surface of the device. The junction depth must be less than the length in n-type material to allow holes generated near surface to diffuse to junction before they recombines. Similarly the thickness of p-region must be such that e^- generated in this region can diffuse to junction before recombination takes place. In order to obtain large photovoltage the doping should be heavy. It is important that series resistance of device be very small so that power is not lost to heat due to ohmic losses in device itself. Narrow contacts serve to reduce the series resistance without interfering appreciably with incoming light.

A well made Si cell can have about 10% efficiency for solar energy conversion, providing approximately 100 W/m² of electrical power under full illumination. Si cells loses efficiency at high temperature, GaAs and related compounds can be used at 100°C or higher.

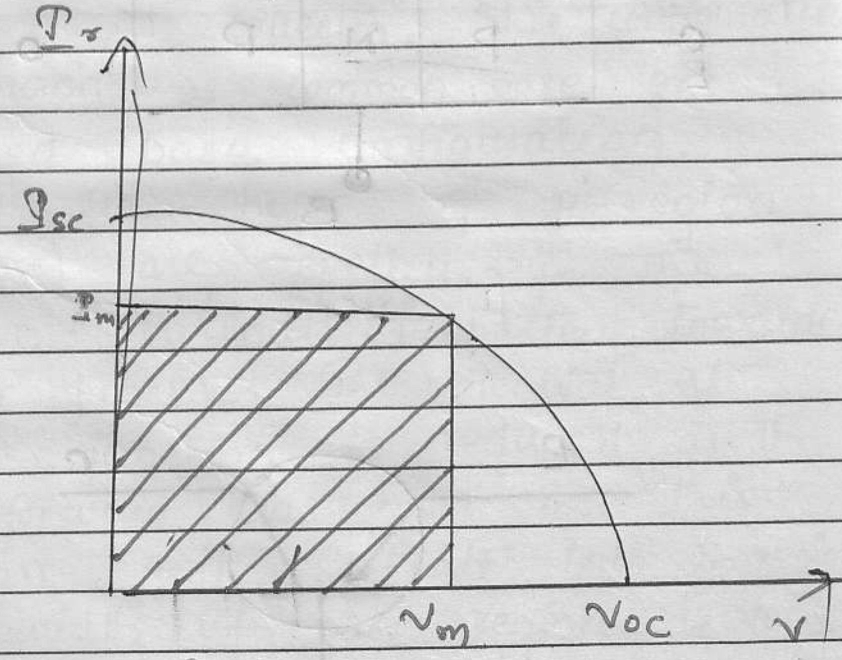


fig 4.12

V-I characteristic of illuminated solar cells.

Transistors :

When two P-N junction diodes are placed back to back, a triode transistor or junction transistors are formed. There are two common types of junction transistors:

(1) PNP Type

(2) NPN Type

Operation of PNP :

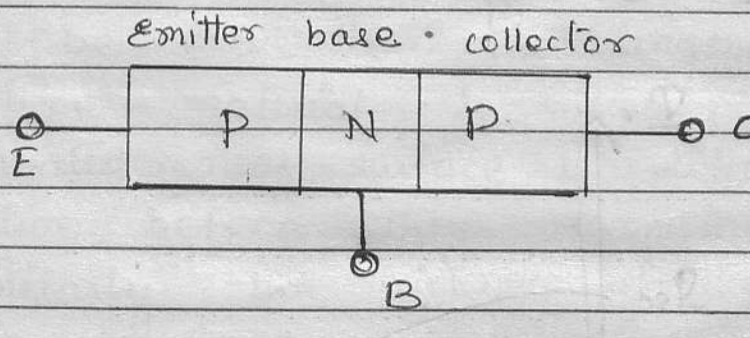
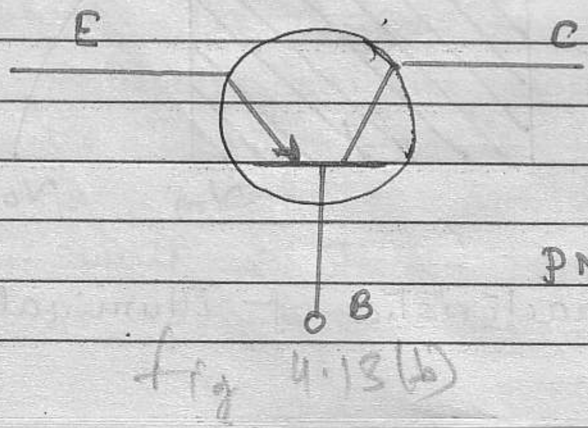


fig 4.13 (a)



PNP-transitor

fig 4.13 (b)

In case of PNP transistor, the P region of left is connected to positive terminal of the battery and N region to negative terminal ie P-N junction is forward biased. The junction that is forward biased in a transistor is always termed as emitter junction. The p-region of right is connected to the negative of a battery and the N-region to the positive terminal ie reverse biased. The junction with reverse bias in a transistor is termed as collector. This configuration is known as common base or grounded base configuration.

The holes of p-region (emitter) are repelled by the positive terminal of battery towards emitter junction. The potential at emitter junction is reduced as it is forward bias holes cross this junction and penetrate into N-region. The width of base region is very thin and it is lightly doped and hence only 2 to 5% holes recombine with free electrons of N-region. This constitute base current which is very small. The remaining holes (95% to 98%) are able to drift across the base and enter into collector region.

As each hole reaches collector electrode an electron is emitted from negative terminal of battery and neutralizes the hole. Now a covalent bond near the emitter electrode breaks down. The liberated electron enters the positive terminal of battery. V_c while hole immediately move towards the emitter junction. The process is repeated again and again.

In PNP transistor following can be observed —

(1) Current conduction within PNP transistor takes place by hole conduction from emitter to collector. The conduction in external circuit is due to electrons.

(2) The collector current is slightly less than the emitter current.

This is due to 2 to 5% of the holes are lost in recombination with electrons in base region. Thus collector current is slightly less than emitter current.

(3) The collector current is function of emitter current.

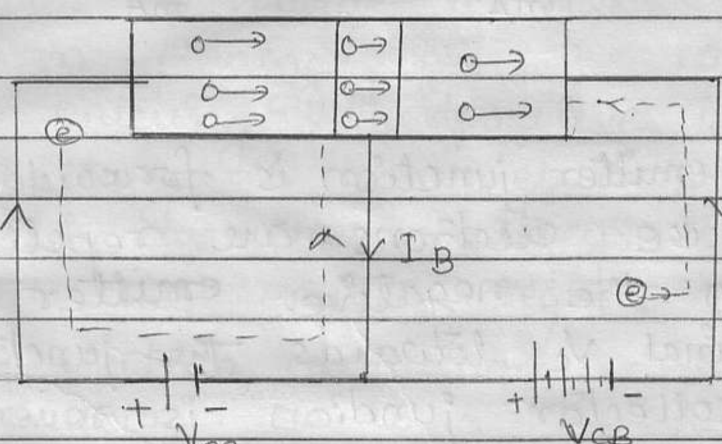


fig 4.14(a)

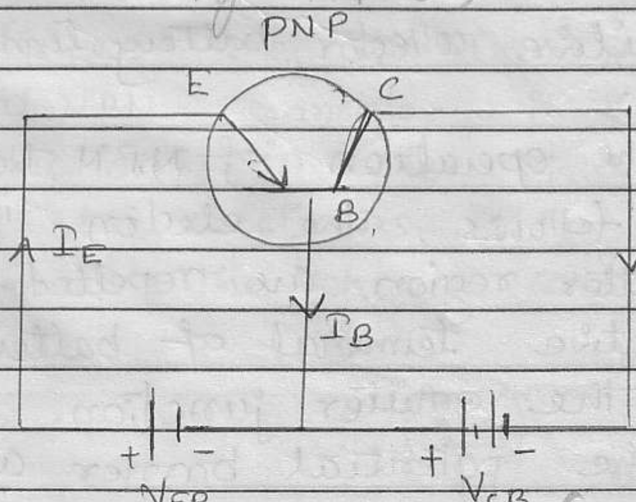


fig 4.14(b)

Operation of NPN transistor

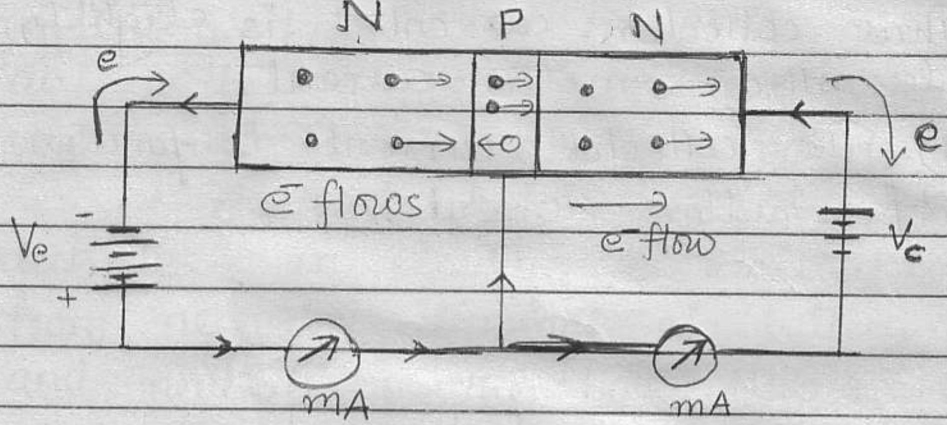
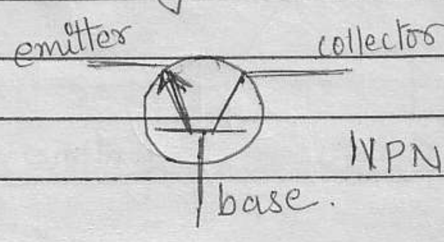


fig 4.15

The emitter junction is forward biased because electrons are repelled from the negative emitter Battery terminal V_e towards the junction. The collector junction is reversed biased because electrons are flowing away from collector junction towards the positive collector battery terminal V_c.

The operation of NPN transistor is as follows, the election in the emitter region are repelled from the negative terminal of battery towards the emitter junction. Since the potential barrier at this junction is reduced due to forward bias and base region is very thin and lightly doped, electrons cross the P-type base region. A few electrons combines with holes in p-region and are lost as charge carrier. Now the electrons in N region (collector region) are readily swept up by positive collector voltage V_c. For every electron flowing out the collector and entering the positive terminal of battery V_c and electron from negative emitter battery terminal enters the emitter region. In this way electron conduction take place continuously so long the junction are properly biased.

The main difference between the operation of PNP and NPN transistor is that current conduction in latter is carried out by electrons while in the former the charge carriers are holes.



NPN transistor

fig 4.16

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Transistor Connections :

There are three leads in a transistor emitter (E), Base (B), collector (C). However when a transistor is to be connected in a circuit we require 4 terminals : 2 for output and 2 for input. Hence in transistor one terminal is made common and input and output are obtained.

Accordingly a transistor can be connected in three different way or modes.

(1) C-E mode (common emitter mode)
(2) C-B mode (common base mode)
(3) C-C mode (common collector mode)

C-E mode:

The input signal is fed between base and emitter.

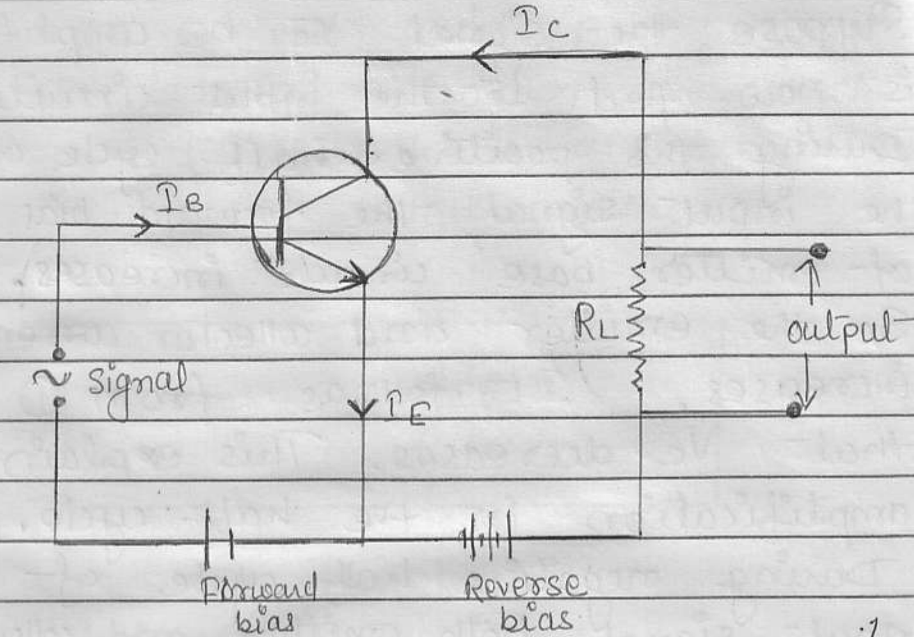

fig 4.17

In common emitter mode, the emitter terminal is common to both input and output circuits. While the input circuit is forward biased and output circuit is reverse biased.

When no AC signal (input signal) is supplied to the input circuit, the collector current I_C flowing through the load resistance R_L will produce a voltage drop $I_C R_L$ across load resistance. This voltage drop is clearly in opposition to the applied voltage V_{CE}

$$\text{net collector voltage } V_C = V_{CE} - I_C R_L \quad —①$$

Suppose the signal to be amplified is now fed to the input circuit. During the positive half cycle of the input signal, the forward bias of emitter base circuit increases. So the emitter and collector current increases. It follows from (1) that V_c decreases. This explain amplification in +ve half cycle.

During negative half cycle of input signal both emitter and collector current decreases. The collector emitter voltage is increased. In other word output signal becomes more positive. The output signal is 180° out of phase with input signal.

Current amplification factor or current gain (β):

(i) Dc current gain: (β_{DC})

It is the ratio of collector current to the base current at constant collector voltage

$$\beta_{DC} = \left(\frac{I_C}{I_B}\right)_{V_C}$$

Dc current gain is much larger than 1.

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(ii) **AC current gain (β_{AC})**

It is the ratio of the change of collector current to the change of base current at constant collector voltage.

$$\beta_{AC} = \left(\frac{\Delta I_C}{\Delta I_B}\right)_{V_C}$$

Voltage gain:

It is the ratio of output voltage across the load resistor to the input signal voltage.
If V_i and V_o represent the input and output voltages respectively, then

$$\text{voltage gain} = \frac{V_o}{V_i}$$

$$= \frac{I_C R_L}{I_B R_i} = \beta \times \frac{R_L}{R_i}$$

power gain :- It is the ratio of output power to input power.

$$\text{power gain} = \frac{\text{output power}}{\text{Input power}}$$

$$= \frac{\text{output current} \times \text{output voltage}}{\text{Input current} \times \text{Input voltage}}$$

$$= \text{current gain} \times \text{voltage gain}$$

$$= \beta \times \beta \times \frac{R_L}{R_i}$$

$$= \beta^2 \frac{R_L}{R_i}$$

Common emitter amplifier gives higher current and higher power gain than common base amplifiers, so common emitter amplifier are more popular than common base amplifier.

Common base (C-B) mode :

Figure shows the experimental arrangment of NPN transistor as common base amplifier. The base terminal is common to both input and output. The input circuit is forward biased and output circuit is reversed biased.

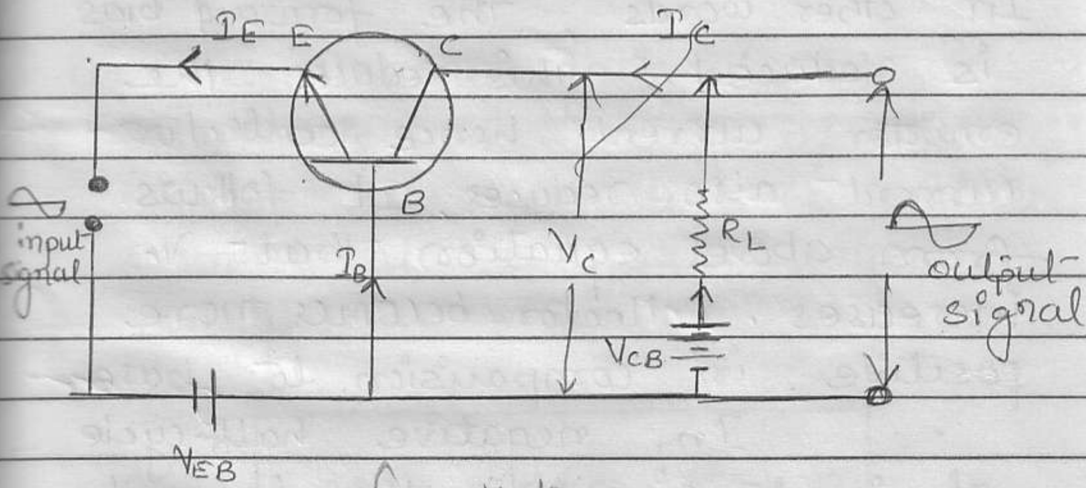


fig 4.18

When no Ac signal (input signal) is supplied to the input circuit the collector current I_c flowing through the load resistance R_L will produce a voltage drop $I_C R_L$

across the load resistance. This voltage drop is clearly in opposition to the applied voltage V_{CB}.

∴ Net collector voltage, $V_C = V_{CB} - I_C R_L$

Suppose the input signal which is to be amplified is now fed to input circuit. During the positive half of the input signal the emitter becomes less negative with respect to base. In other words, the forward bias is reduced. This reduces the emitter current hence collector current also reduces. It follows from above equation that V_C increases. Collector becomes more positive in comparision to base.

In negative half cycle of input signal, the forward bias is increased ie the emitter becomes more negative with respect to base. So the emitter current ~~decreases~~ increases. Consequently collector current I_C also increases. It follows from above equation that V_C is decreased, ie collector becomes less positive or more negative in comparision to base. This explains the amplification of negative half cycle.

The output signal follows exactly all the variations of the input signal. ie output and input are in phase in C-B mode.

Current Amplification factor (α)

(i) DC current gain (α_{DC})

It is the ratio of the collector current to the emitter current at constant collector voltage.

$$\alpha_{DC} = \left(\frac{I_C}{I_E}\right)_{V_C}$$

The DC current gain is always less than one. It's value varies from 0.95 to 0.98.

(ii) AC current gain (α_{AC})

It is the ratio of the change in collector current to the change in emitter current at constant collector voltage.

$$\alpha_{AC} = \left(\frac{\Delta I_C}{\Delta I_E}\right)_{V_C}$$

Voltage gain:

It is the ratio of output voltage cross the load resistor to the input signal voltage. If V_i and V_o represents the input and output voltages then,

$$\text{Voltage gain} = \frac{V_o}{V_i}$$

$$= \frac{I_C R_L}{I_E R_i}$$

$$= \alpha \times \left(\frac{R_L}{R_i}\right)$$

α is approximately equal to one

Relation between α and β

(I) For A.C values:-

In both common base and common emitter circuits, the emitter current is sum of collector current and base current.

$$I_E = I_B + I_C$$

$$\Delta I_E = \Delta I_B + \Delta I_C$$

or $$\Delta I_B = \Delta I_E - \Delta I_C$$

$$\beta_{AC} = \frac{\Delta I_C}{\Delta I_B} = \frac{\Delta I_C}{\Delta I_E - \Delta I_C} = \frac{\Delta I_C / \Delta I_E}{1 - \frac{\Delta I_C}{\Delta I_E}} = \frac{\alpha_{A.C}}{1 - \alpha_{A.C}}$$

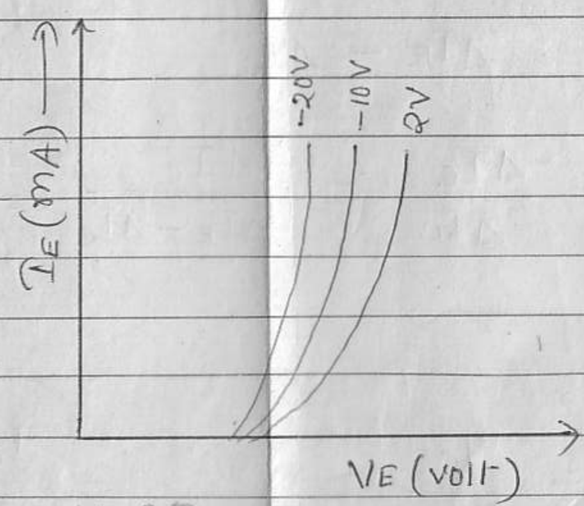
(II) For D.C value:

$$\beta_{dc} = \frac{I_C}{I_B} = \frac{I_C}{I_E - I_C} = \frac{I_C / I_E}{1 - I_C / I_E} = \frac{\alpha_{DC}}{1 - \alpha_{DC}}$$

Transistor characteristics in common base configuration.

Let us consider the case of PNP transistor. The emitter base circuit called input circuit is forward biased. The collector base circuit called output circuit is reverse biased.

Input characteristics:- Input chacteristic is graph between emitter voltage (V_E) and emitter current I_E for a constant value of collector voltage.



(Input characteris

fig 4.28

Input characteristic reveals following:-

(i) For a given value of collector voltage, small increase of emitter voltage brings about rapid increase in emitter current.

(ii) An increase in the magnitude of collector voltage c
the emitter current to increase for a fixed value of

(iii) There exist a voltage below which emitter current is
practically zero. This voltage is called cut-in or threshol
voltage of transistor. It's value is 0.1 V for germanium trans
and 0.5 for silicon transistor.

The reciprocal of the slope of $V_E - I_E$ curve gi
input resistance of transistor.

Output characteristics :—

output characteristic is a graph betw
collector voltage V_C and collector current I_C for a constan
value of emitter current I_E.

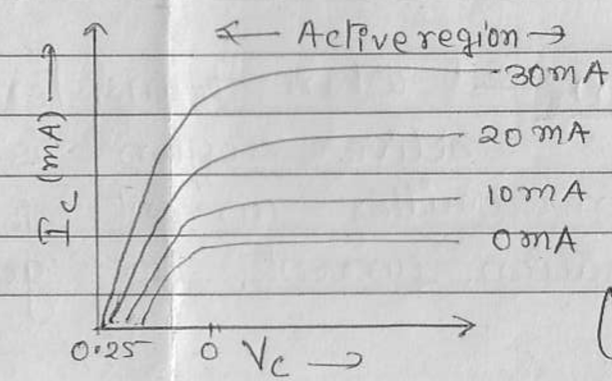
Output characteristics of a typical PNP tr
These characteristics can be divided into following thre
regions.

(i) **Active Region:—** when transistor is used as amplifier, the
active region is normal operating region of
transistor. when emitter current is zero, the collector current
the reverse saturation current. For germanium transistor, the ma

of this current is in the microampere range. For a silicon transist[or] it is in the nanoampere range. In active region collector current is nearly independent of collector voltage. It depends on emitter current. It may be noted that in active region, the output characteristics are almost parallel lines equally spaced for equal increments in emitter current.

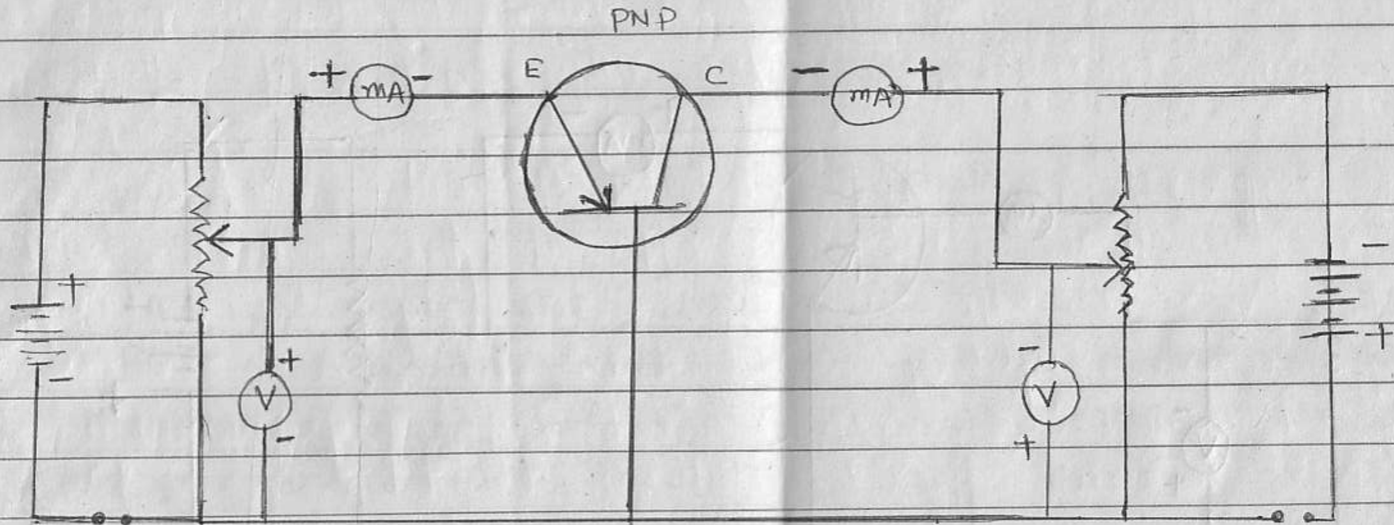
(ii) **Saturation Region:** This region is located to the left of $V_c = 0$ and above the output characteristics of $I_E = 0$. When V_c is slightly positive, the collector-base junction becomes forward-biased. Consequently, the collector current varies exponentially with collector voltage. This explains large variation in I_c with V_c in the saturation region.

(iii) **Cut-off region:** — The region to the right of $V_c = 0$ and before the characteristic for $I_E = 0$ is the cut-off region of the transistor. Both the junctions of transistors are reverse-biased in this region.



(output characteristi[cs])

fig 4.29

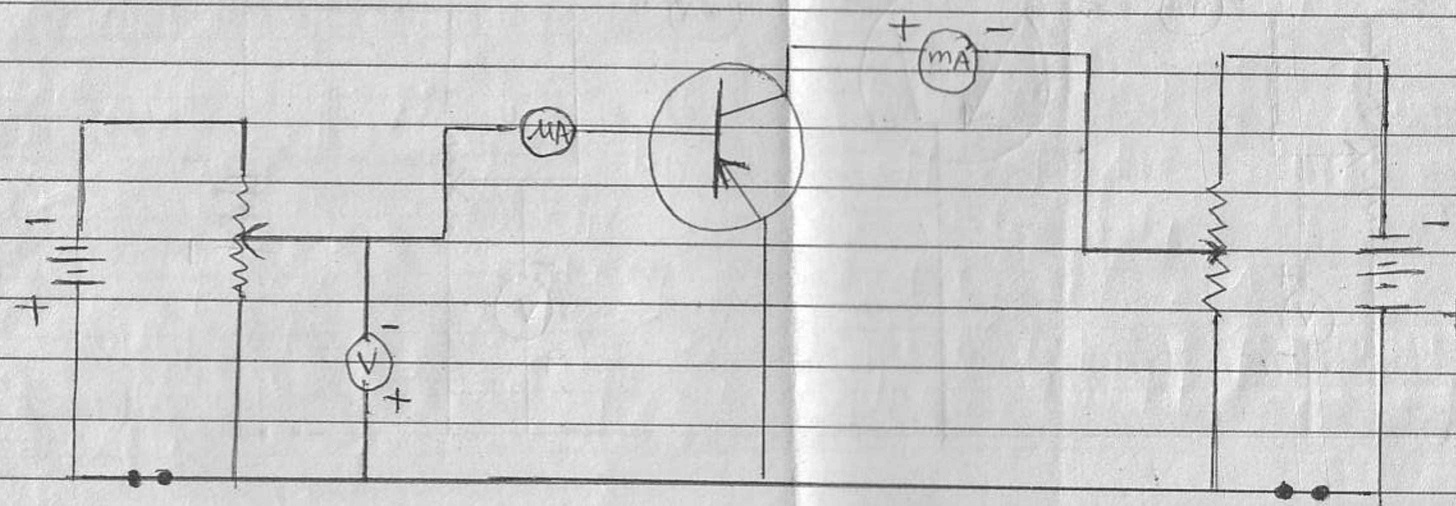


(common base configuration of PNP transistor)

Fig 4.30

Transistor characteristics in common emitter configuration

The emitter base circuite is called the input circuite. The collector- base circuite called output circuite, is reverse biased.



(common emitter configuation of PNP transistor)

fig 4.3)

Input characteristics: These characteristics represent the variation of base current (I_B) with base voltage (V_B), keeping collector voltage (V_C) constant.

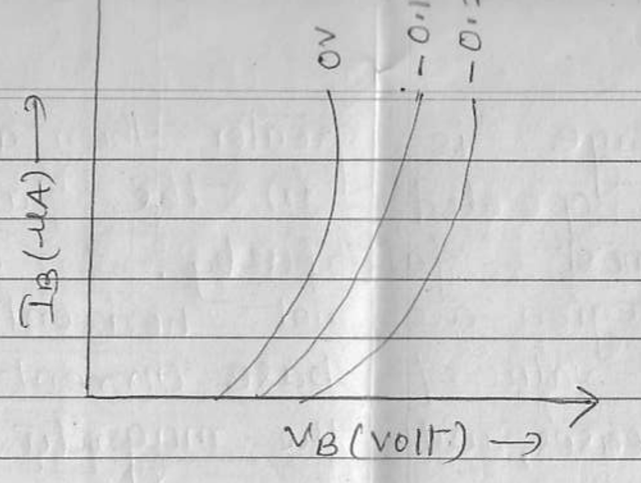


fig 4.32

(Input characteristics)

These characteristics are similar to that of forward-biased diode. For a constant value of V_B, I_B decreases with increas[e] in the magnitude of V_c. This is because with increasin[g] magnitude of V_c, the effective base width and consequentl[y] the recombination base current is reduced.

<u>Output characteristics</u>:- These characteristics represent the variation of collector current I_c with collector voltage V_c, keeping base current I_B constant. The output characteristics can be divided into the following regions -

(1) Active region: this is a region where the magnitude of the base current is greater than zero and magnitude of

of the collector voltage is greater than a few tenth of a volt. When transistor is operated in the active region, it amplifies signals almost faithfully. In output characteristics in the active region are not horizontal lines. This is because for a fixed value of base current, the magnitude of collector current increases with the magnitude of collector voltage.

(ii) **Cut-off region:** by making base current zero, we do not obtain the cut-off of the collector ~~voltage~~ current. The cut-off can be obtained by making the emitter junction slightly reversed-biased. A reverse bias of nearly 0.1 V across emitter junction of a germanium transistor is sufficient to cut-off. For silicon transistor corresponding value is zero.

(iii) **Saturation region:** This region is very close to zero voltage axis. In this region, the collector current becomes almost independent of the base current.

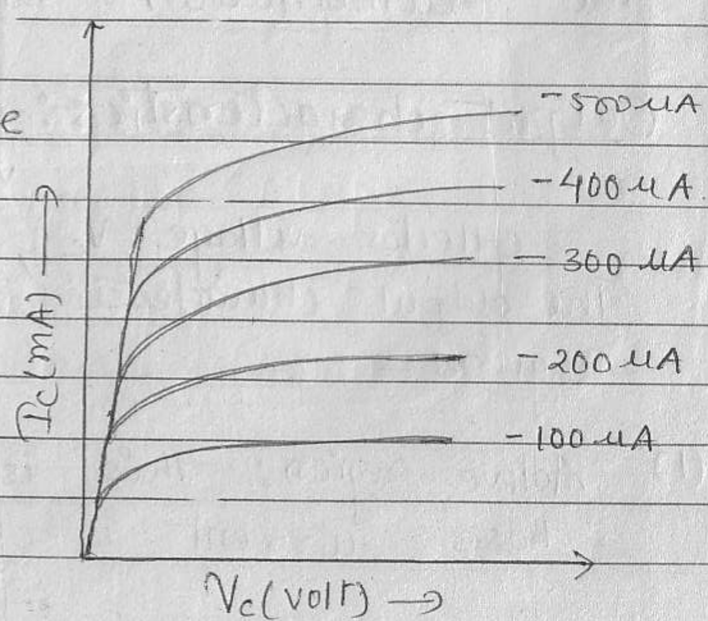


fig 4.33

(output characteristics)

and $R_L >> R_i$, therefore very high voltage gain can be obtained.

power gain:

It is the ratio of output power to the input power.

$$\text{power gain} = \frac{\text{output power}}{\text{Input power}}$$

$$= \frac{\text{Output current} \times \text{output voltage}}{\text{Input current} \times \text{Input voltage}}$$

$$= \text{current gain} \times \text{voltage gain}$$

$$= \alpha \times \alpha \times \frac{R_L}{R_i} = \alpha^2 \frac{R_L}{R_i}$$

Since R_L is large as compared to R_i hence power gain is quite large.

Lect 39

SUPERCONDUCTIVITY

The sudden disappearance of electrical resistance in materials below a certain temperature is known as superconductivity. The materials that exhibits superconductivity and which are in the superconducting state are called superconductors. The temperature at which normal materials turns into a superconductor is called critical temperature T_c.

Every superconductors has its own critical temperature at which it passes over into the superconducting state

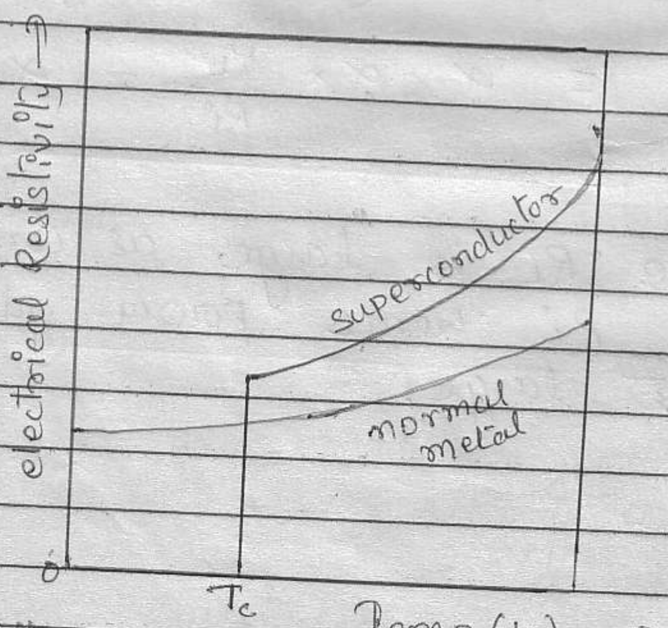


fig 4.1

(fig 2)

The superconducting transition is sharp for a chemically pure and structurally perfect specimen while the transition range is broad in case of specimen containing impurities or specimen which are structurally perfect.

Characteristics of Superconductors

Zero electrical Resistance :-

A superconductor is characterised by zero electrical resistivity. They are the ideal or perfect conductors which does not cause I^2R losses.

persistent Current :

Once a current is started in a closed loop of superconducting material, it will continue to keep flowing of it's own accord around the loop as long as loop is held below the critical temperature. Such a steady current which flows with undiminishing strength is called a persistent current. The persistent current does not need external power to maintain it because there does not exist I^2R losses.

Effect of Temperature (fig 2)

When the temperature of superconducting material is increased the material transforms into a normal material above the critical temperature T_c. The transition is reversible. When material is cooled below T_c, it again goes into superconducting state. The transition is thermodynamic phase transition, just as the order in arrangement of atoms increases in a transition of material from liquid to solid state, a rearrangement of conduction electrons takes place leading to an increase in the order in case of the transition from normal to the superconducting state.

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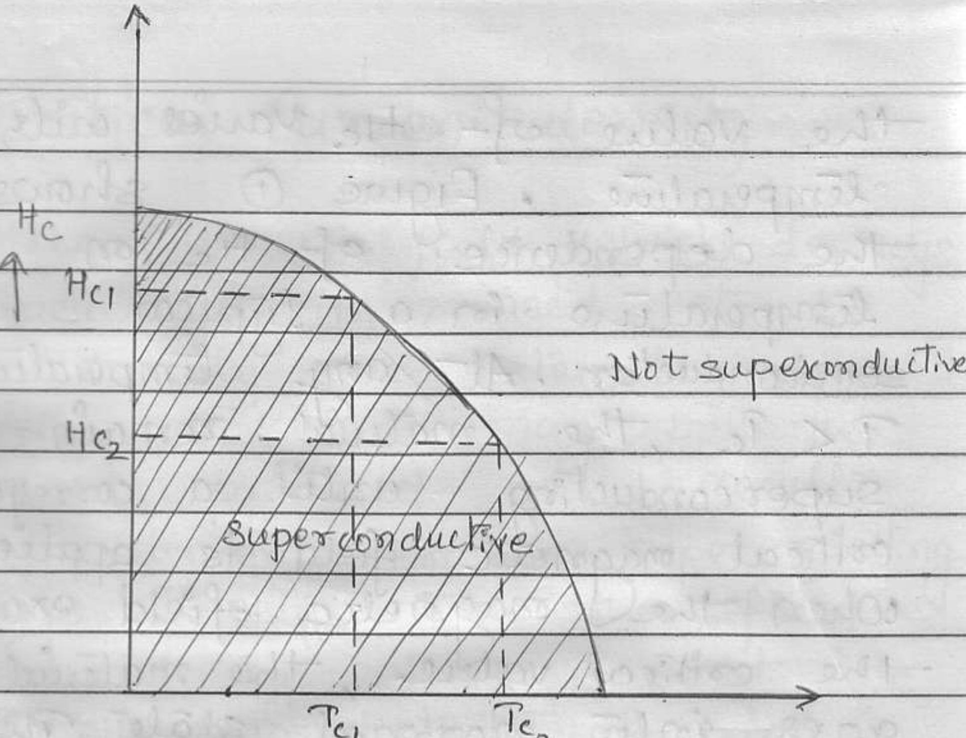


Temperature →

fig (1)

fig 4.20

Effect of External magnetic field

Kammerlingh Onnes observed in 1913 that superconductivity vanishes if a sufficiently strong magnetic field is applied. The minimum magnetic field which is necessary to regain the normal resistivity is called the critical magnetic field, H_c. When applied magnetic field exceeds the critical value H_c, the superconducting state is destroyed and material goes into critical state. Obviously

The value of H_c varies with temperature. Figure ① shows the dependence of H_c on temperature in a typical semiconductor. At any temperature $T < T_c$, the material remains superconducting until a corresponding critical magnetic field is applied. When the magnetic field exceeds the critical value, the material goes into normal state. The critical field required to destroyed the superconducting state decreases progressively with increasing temperature. For example a magnetic field of 0.04T will destroy the superconductivity of mercury at $T \simeq 0K$ where as a field of 0.02 T is sufficient to destroy its conductivity at about 3K. The dependance of critical field on temperature is governed by following relation.

$$H_c(T) = H_c(0)\left[1-\left(\frac{T}{T_c}\right)\right]^2$$

Critical Current density

The magnetic field which destroys superconductivity, need not be necessarily the externally applied field, but it may be the field produced as a result of current flow in superconducting rings it self. Even the field produced by itself exceeds H_c, the superconductivity of ring is destroyed. Thus superconducting material carried a current and of magnetic field produced by this current is equal to H_c, the superconductivity disappears. The maximum current density J at which superconductivity disappear is called critical current density J_c. For any value of $J < J_c$ the current sustained itself where as for the values of $J > J_c$ the current cannot sustain itself. This effect was observed in 1916 by Silsbee and is known as Silsbee effect.

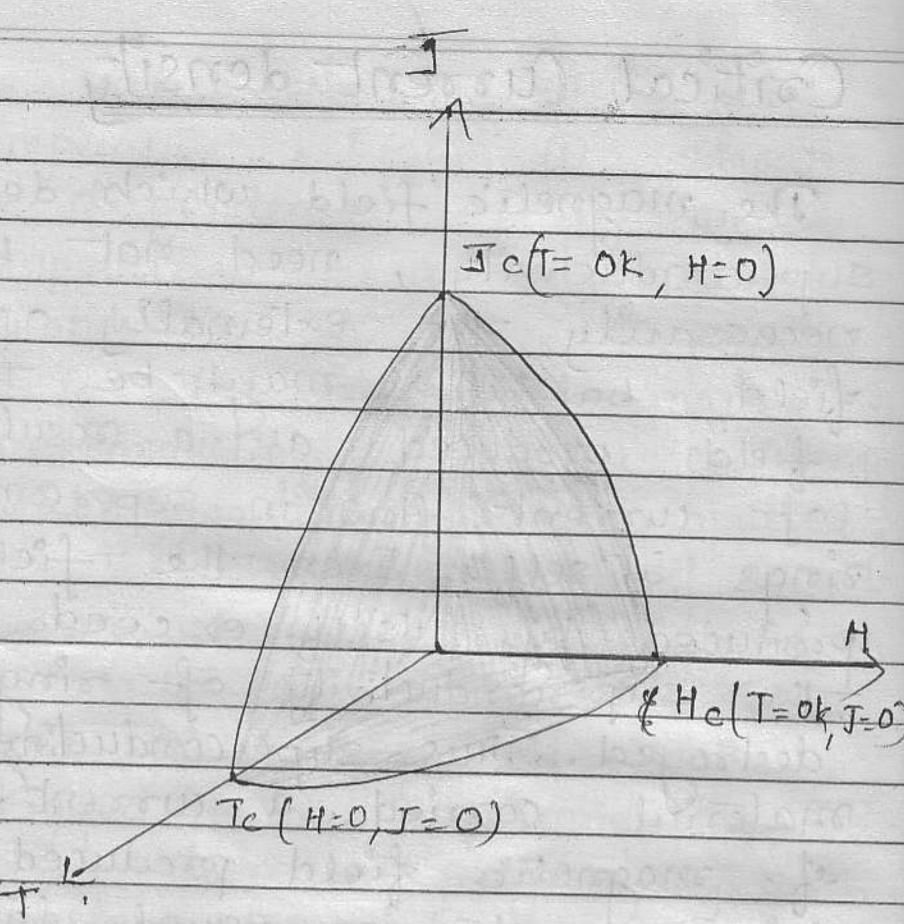


fig (4.2)

MEISSNER EFFECT

In 1933 Meissner and Ochsenfeld showed that if a long cylindrical superconductor is cooled in longitudinal magnetic field below its transition temperature T_c. The lines of induction will pushed out of material due to infinite conductivity.

On the other hand if material is cooled initially below transition temperature and placed in magnetic field a flux will not penetrate the material.

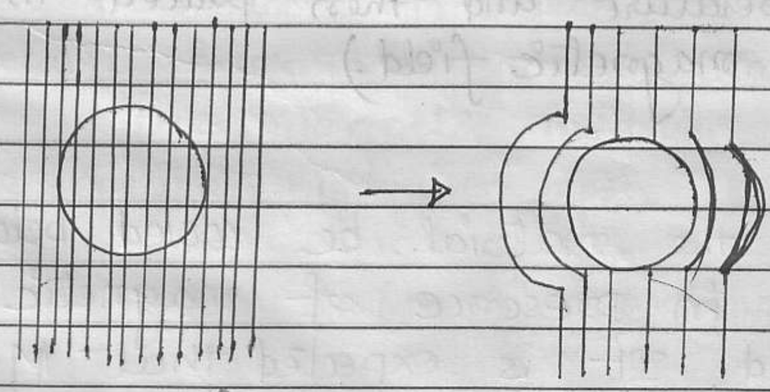
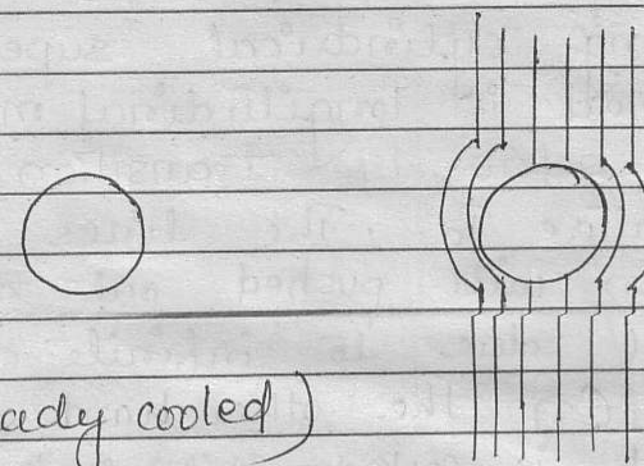


fig 4.22 (a)

Cooled in field — Lines pushed out on cooling

(Meissnor effect in sphere cooled in a const. magnetic field, below T_c lines of induction are ejected from the sphere)



(Already cooled)

(Lines cannot penetrate)

fig 4.22(b)

(Meissener effect for specimen initially cooled below transition temperature and then placed in the magnetic field.)

Let the material be cooled below T_c in presence of magnetic field. It is expected that M.F through material will remain unchanged. However Meissner and Ochsenfeld found that the magnetic flux was totally expelled from sample as it became superconducting. The explusion of magnetic flux during the transition from the normal to the superconducting state is called <u>Meissner effect.</u>

The experiments of Meissner established that as the temperature is lowered, the specimen enters superconducting state at $T = T_c$ and magnetic flux is pushed out of it for all temperatures $T < T_c$. The effect is reversible. When temperature is raised from ~~below~~ above T_c, the flux suddenly starts penetrating the specimen at $T = T_c$ as a result of which material returns back to normal state.

The magnetic induction inside the specimen is given by

$$B = \mu_0 (H + M) \quad \text{(Normal state}$$

where $H \rightarrow$ external applied magnetic field.

$M \rightarrow$ magnetization produced within the specimen.

At $T < T_c$, $B = 0$ and

$$\mu_0 (H + M) = 0 \quad \text{(superconducting state)}$$

$$\therefore \quad M = -H$$

The susceptibility of material is

$$\chi = \frac{M}{H} = -1 \quad \text{(perfect diamagnetism)}$$

Thus, superconducting state is characterised by perfect diamagnetism.

Meissner effect shows that in superconductor not only $\frac{dB}{dt} = 0$ but also $B = 0$.

In other words two mutually independent properties — zero resistivity ($S = 0$ and $E = 0$) and perfect diamagnetism ($B = 0$ & $\chi = -1$) are essential properties that characterize the superconducting state.

Lect 40

Types of Superconductors

Depending upon magnetization behaviour of superconductors in external magnetic field, superconductors can be classified into following two categories —

(1) Type - I or soft superconductors

In type - I superconductors, the transition from superconducting state to normal state in the presence of a magnetic field occurs sharply at the critical value H_c. Type - I superconductors are perfectly diamagnetic below H_c and completly expel the magnetic field from the interior of superconducting phase. upto critical field strength, the magnetization of material grows in proportion to external field and then abruptly drops to zero at the transition to normal conducting state. The magnetic field can peretiate only the surface layer and current can flow in this layer.

Hence Type-I superconductors are poor carrier of current.

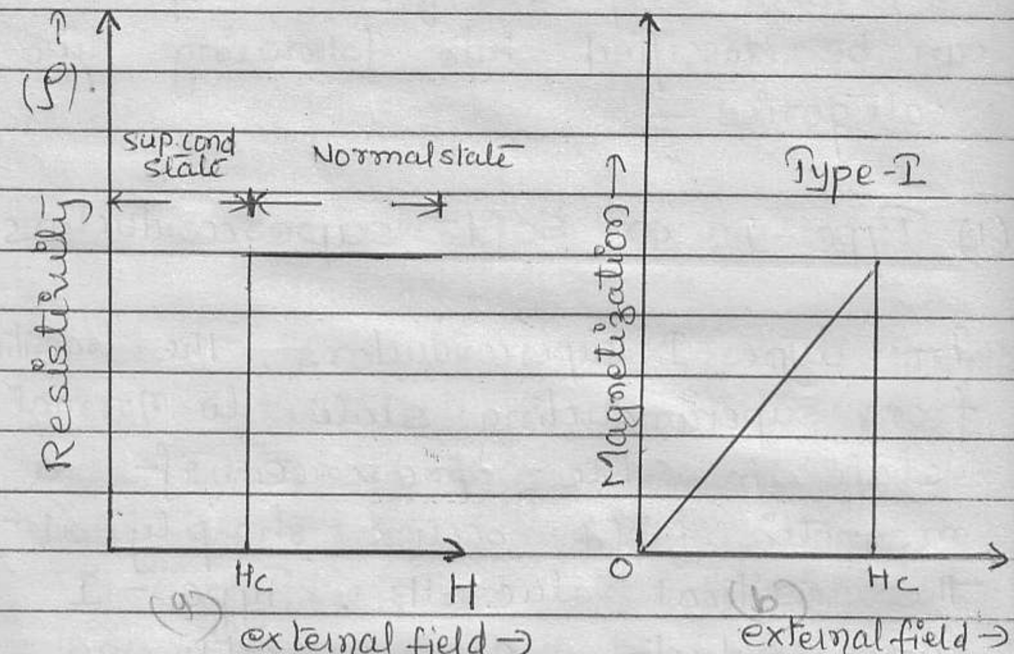


fig 4.23

Following points are to be noted —

(i) Transition is reversible at H_c ie if the magnetic field is reduced below H_c, the material again acquires the property of superconductivity.

(ii) Lead, tin, mercury etc fall into Type-I category.

(iii) Type-I materials are called soft superconductors because superconductivity is destroyed very easily at low H_c values.

(2) Type-II superconductor or Hard Superconductors:

This type of superconductors are characterized by the existence of two critical magnetic field ie lower critical magnetic field H_{c_1} and upper critical field H_{c_2}

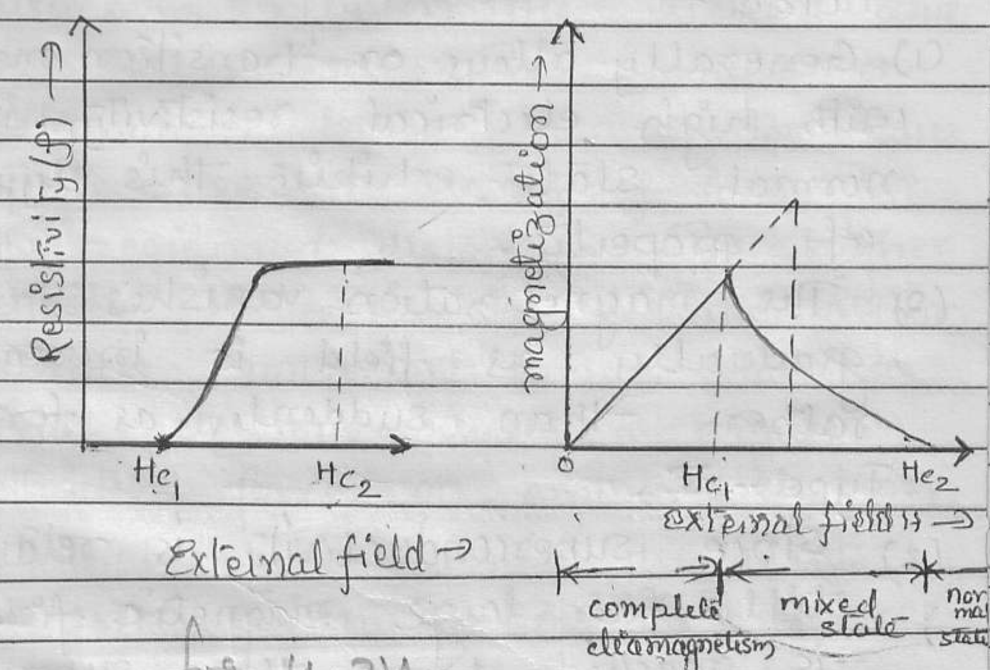


fig 4.24

For this group of semiconductors below H_{c_1} the specimen is superconducting ie diamagnetic because flux is completely excluded. At H_{c_1}, the flux starts penetrating into specimen until the upper critical field H_{c_2} is reached.

The specimen is in the mixed state and exhibits superconducting electrical properties.

Thus between H_{c_1} and H_{c_2} the Meissner effect is not complete. At H_{c_2} the magnetization vanishes and specimen turns to normal conducting state.

The following points are to be noted —

(1) Generally alloys or transition metals with high electrical resistivity in normal state, exhibits this type of property.

(2) The magnetization vanishes gradually as field is increased rather than suddenly as for Type - I.

(3) Since superconductivity is retained till fair large magnetic field is reached, hence these superconductors are called hard superconductors.

(4) Eg. (Nb_3Sn) alloy

Lect 42

THE BCS THEORY

American physics John Bardeen, Leon N. cooper and John Robert Schrieffer developed in 1957 the quantum theory of superconductivity. This theory is based on interaction of two electrons with intermediator phonons.

When electron approaches an ion in lattice, there is a coulomb attraction between the electrons and the lattice ions. This produces a distortion in lattice. The distortion causes an increase in density of ions in the region of distortion. The higher density of ions in distortion region attracts another electrons. Thus a free electrons excerts a small attractive force on another electron through phonons which are quanta of lattice vibration. A pair of free electrons thus coupled through phonon is called cooper pair. At normal temperature the attractive force is very small and pairing of electrons does not takes place. Each Cooper pair consists of two electrons of opposite momenta. At lower temperature, such pairing is energetically advantageous. This dense ~~of~~ cloud of cooper pairs forms collective state where strong correlations arise among the motions of all pairs because of which they drift cooperatively through the material. Thus super-conducting state is an ordered state of conduction electrons. The small velocity of cooper pairs combined with their precise ordering minimizes collision processes. The extremely rare collisions of Cooper pairs with lattice leads to vanishing resistivity.

The BCS theory gives two important results —

Existence of Energy gap:—

The electrons of Cooper pair have a lower energy than two unpaired electrons. Therefore the energy spectrum of electrons exhibits an energy gap. The Cooper pairs occupy the lower state. The energy gap prevents the pairs from breaking apart.

A finite energy 2Δ must be expended to dissociate a Cooper pair. For superconductor at 0K, the width of gap is proportional to critical temperature. Thus

$$2\Delta = 3.52\, k T_c$$

The energy gap is generally of the order of 10^{-3} eV.

Flux quantization:

A closed superconducting loop can enclose magnetic flux only in integral multiples of fundamental quantum of flux. Thus, the magnetic flux enclosed by a superconducting ring ϕ is given by

$$\phi = n \frac{h}{2e}$$

$$\phi = n\phi_0 \quad , \quad n = 1, 2, 3 \ldots$$

where $\phi_0 = \frac{h}{2e}$ is the flux quantum and is called <u>fluxon</u>. The value of flux quantum is

$$\phi_0 = 2.07 \times 10^{-15} \text{ weber.}$$

APPLICATIONS

(1) Electricity is transmitted and distributed through cables. A large amount of power ~~of~~ is lost on way due to I^2R losses. When superconductor will be used as cables, these losses are avoided.

(2) Superconducting coils in transformers and electrical machines generates much stronger magnetic field than magnetic circuits employing ferromagnetic materials do. The size of motors and generators will be drastically reduced. They are lighter and much more efficient.

(3) The Meissner effect can be applied in bearings that would operate without friction losses in all kinds of rotating machines.

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(4) High magnetic fields are required in many area of reasearch and diagnostic equipments in medicine. The electromagnets are Cumbrsome being very big in size, demand large electrical power to maintain the magnetic field and required continuous cooling. Superconducting solenoids produce very strong magnetic fields. They are small in size and does not need power. Thus they are less Cumbersome and less expensive.

(5) The most important application is mag lev or magnetic lavitation trains. Maglev coaches do not slide over steel rails but float on a four inch air Cushion over a strongly magnetized track. Superconducting coils produce the magnetic repulsion in order to levitate the coaches. AS there does not exist mechanical friction, speed upto 500 km/hr can be easily achieved.

(6) The semiconductor logic elements have a speed limit. They operate at speed of nanoseconds. In contrast logic elements based on

Josephson junction can operate at the speed of a few picoseconds. Josephson junctions are therefore expected to increase the speed of ~~superconductors~~. supercomputers.

(7) Several medical diagnostic equipments are now employing SQUIDS which detect very minute changes in magnetic field of a human brain or body.

SQUIDS:

SQUIDS is an acronym of superconducting Quantum Interference Devices. It is basically a superconding loop with a "weak link" to measure magnetic flux changes within the loop. A weak link is a region that has a much lower critical current the rest of superconducting ring. When current in the link exceeds the critical current, the link becomes normal. It allows fluxon to penetrate the link. When fluxons penetrate the link, the current fall to critical value and the link revert to superconducting state. The weak link thus acts as gate. It can be prepared such that it allows single fluxon.

The critical current in the weak link varies periodically as total flux through area enclosed by superconducting loop changes as shown

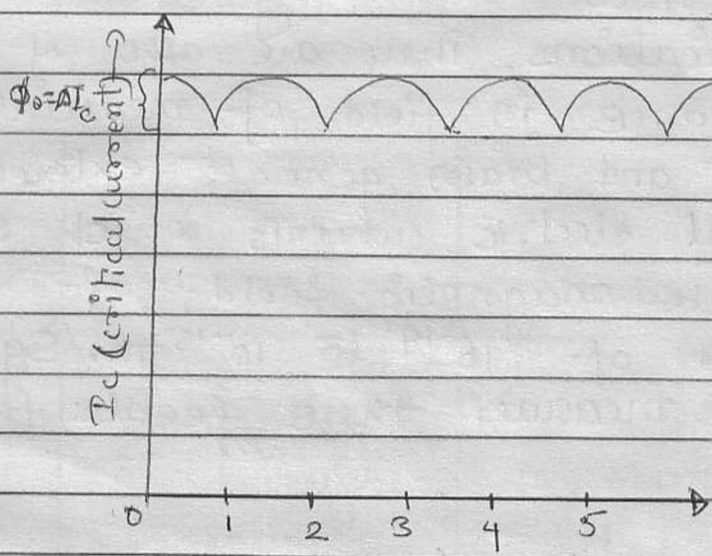


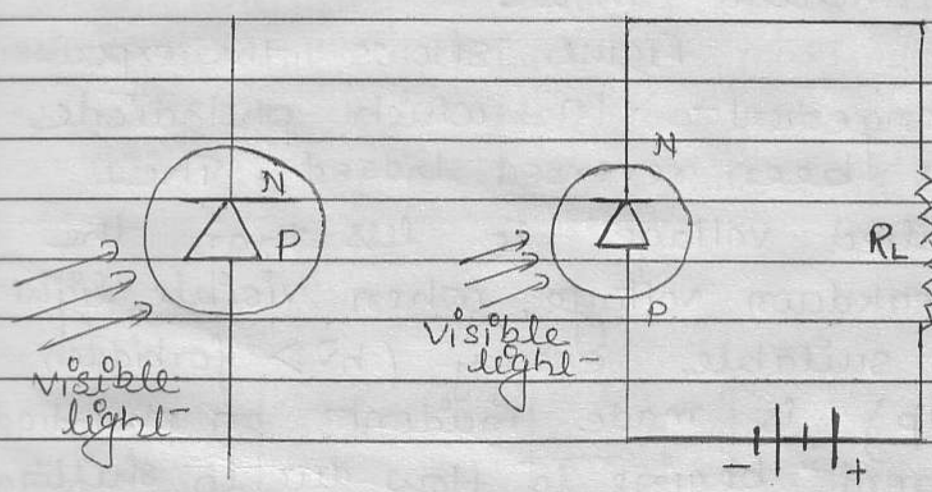
fig 4.25

(periodic variation of critical current I_c with total flux through the area of SQUID)

The current executes one cycle each time the flux changes by one fluxon ϕ_0. The periodic variation in squid current can be sensed by nearby coil. The changing magnetic field due to change in Squid current induces emf and current in sensing coil. The emf induced in the coil. The emf induced in the coil may be used to drive the electronic counting circuits. SQUIDS acts as extremely sensitive magnetometers. These are used in variety of electrical and magnetic measurement applications. They are also of great assistance in field of medicine. The heart and brain generate extremely small electric currents which set up weak magnetic fields of the order of 10^{-14} to 10^{-15} T. Squids can measure these feeble fields.

PHOTO DIODE

A PN junction diode made of photosensitive semiconductor is called photodiode. In this type of diode provision is made for allowing the light to fall at the junction. Figure shows symbolic representation of a photodiode.



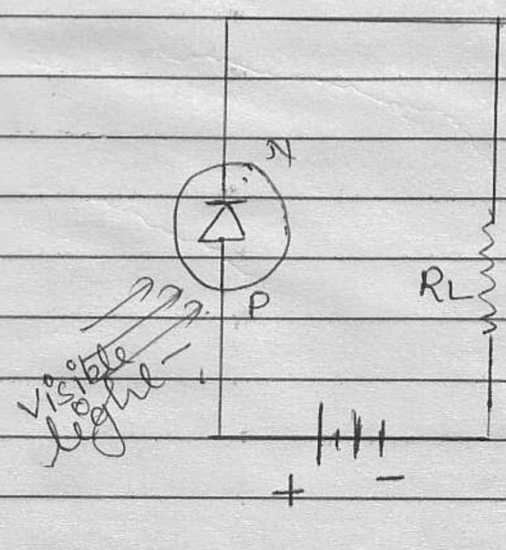
(photodiode) (Reverse-biasing of photodiode)

fig 4.26

In a semiconductor electrons jump from valence band to conduction band by absorbing energy from some external source of energy. If the incident visible light is the external source of energy, then the semiconductor is said to be photosensitive. When visible light is incident on photosensitive. When visible light is incident on photosensitive semiconductor, more electrons become available to participate in conduction. Thus the conductivity of photosensitive semiconductor increases when light is incident on it.

Figure shows the experimental arrangement in which photodiode has been reversed biased. The applied voltage is less than the breakdown voltage, when visible light of suitable energy ($h\nu >$ forbidden gap) is made incident on photodiode, current begins to flow due to shifting of electrons from valence band to conduction band. This current increases with the increase in the intensity of incident light. When the intensity of light increases to a value, say E_0, the current become maximum. This maximum current is called saturation current.

If photodiode is forward biased then certain current exist in circuit even when no visible light is made incident. This current is called <u>dark current</u>. It is represented by OA in graph. When light of suitable intensity is made incident on the photodiode, more electrons move from valence band to conduction band. Consequently current increase. When intensity becomes equal to E_0, the current attains it's maximum value. It is called saturation current. It is represented by BC



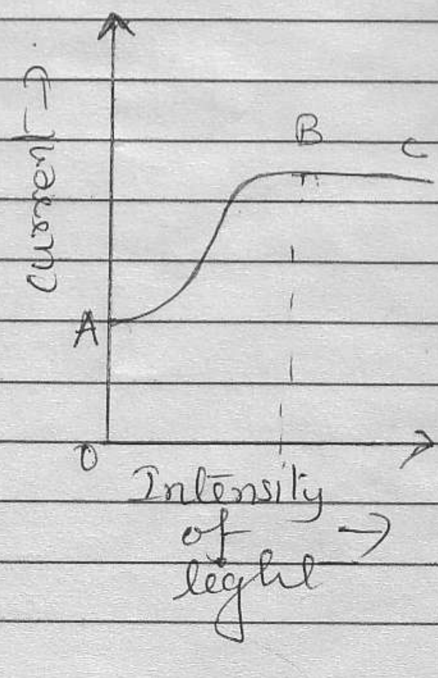


fig 4.27

Q. cal. following for simple cubic, FCC (i) No. of atoms / unit cell. (ii) Co-ordination No. (iii) packing fraction (iv) % of void.

Q.2. Define fermi level. Show that fermi level of intrinsic semiconductor lies at the centre of forbidden gap.

Q.3. What do you understand by extrinsic semiconductor. With the help of band dig. explain n & p type semiconductor at T = 0 K & T = 300 K.

Q.4 (a) The density of Cu is 8980 $kg \cdot m^{3}$ and unit cell dim is 3.61 A°. Given (At. wt. of Cu = 63.54)

(i) Crystal structure
(ii) Cal. at. radius.
(3) cal. spacing of (110) planes.
(4) Draw (110) plane in unit cell.

(b)