2012 – 80M
45M
———
125M

2013 – 54M
85M
———
139M

Syllabus:

- ✓ → Electrons & Holes in SemiConductors
- ✓ → Carrier Statistics
- ✓ → Mechanism of Current flow in a SemiConductor
- ✓ → Hall Effect

$\left.\right\}$ Semiconductor Physics

- ✓ → p-n junction theory
- → Different types of diodes and their characteristics
- ✓ → Bipolar Junction Transistor (BJT)
- → Field Effect Transistor (FET)
- → Power Switching Devices SCR, GTOs, Power MOSFET (only for IES)
- → Basics of IC:
  Bipolar, MOS & CMOS
- → Basics of OptoElectronic Devices (only for IES)

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## Electronic Device:

It is a device in which conduction takes place by the movement of electrons through a semiconductor.

→ Electronic Devices are capable of performing various functions like amplification (magnifying the signals), rectification (converting AC to DC), generation (Converting dc power to ac power) and control (switching).

→ Oscillator - Low power, High frequency
Inverter - High Power, Low frequency

## Matter:

It is anything which has certain weight and occupies some space.

→ Matter is divided into molecules without changing its identity.

→ Molecules are again subdivided into smallest minute particles called atoms.

## Electric Field Intensity / Electric field ($\mathcal{E}$ & E):

It is defined as force per unit positive charge that would be experienced by a stationary point charge at a given location in the field.

$$\mathcal{E} = F/q, \quad \text{volts}/\text{cm} \ \& \ \text{volts}/\text{m}$$

$PE = QV = F \cdot d$, J or eV

$1 \text{ eV} = 1.6 \times 10^{-19} J$

## Nature/Structure of Atom:

### 1. Rutherford Atomic Model: (1911)

→ Atom consists of central core called nucleus which is positively charged.

→ Negatively charged electrons orbit around the nucleus.

→ The charge of the proton is positive and electron is negative. Therefore, atom is electrically neutral.

→ According to Coulomb's law, the attractive force exists between electrons and protons and is given by

$$F = \frac{-e^2}{4\pi\varepsilon r^2} \quad \text{—①}$$

e is the charge

ε is the permittivity.

→ This attractive force is compensated by centripetal force i.e,

$$F = -\frac{mv^2}{r} \quad \text{—②}$$

m is the mass of $e^-$

r is the radius force

v is the velocity of $e^-$

$$\frac{mv^2}{r} = \frac{e^2}{4\pi\varepsilon r^2}$$

$$\Rightarrow \boxed{mv^2 = \frac{e^2}{4\pi\varepsilon r}} \quad \text{—③}$$

→ The energy of $e^-$ is the sum of PE and KE.

$$W = KE + PE$$

As the $e^-$ approaches nucleus, energy of

As the $e^-$ moves away from nucleus, energy of $e^-$ increases.

**Drawback:**

It could not explain the stability of the atom.

2. **Bohr Atomic Model:** (1913)

→ When $e^-$ orbiting in the stationary energy levels, atom will not radiate any energy.

→ When $e^-$ moves from one energy level to the another energy level, then atom will radiate or absorb energy.

→ Radiated/Absorbed energy $W_2 - W_1 = hf$

$$\Rightarrow W_n - W_{n-1} = hf \quad ; \quad h = 6.625 \times 10^{-34} \text{ J-sec}$$

where $h$ is Planck's constant

$f$ is the frequency of radiation

→ The energy of the stationary streets/energy levels can be calculated by equating angular momentum of $e^-$ to integral multiples of $h/2\pi$

$$\Rightarrow mvr = \frac{nh}{2\pi} \quad \text{where } n = 1, 2, 3 \ldots$$

$$V = \frac{nh}{2\pi mr} \quad \text{— (5)}$$

Substitute (5) in (3)

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$$\boxed{W = \frac{-e^4 m}{8\varepsilon^2 h^2 n^2}}$$

i.e, Energy levels are not equidistant.

$$\boxed{W = \frac{-me^4}{8\varepsilon^2 h^2} \cdot \frac{1}{n^2}}$$

$$\boxed{W_n = \frac{-me^4}{8\varepsilon^2 h^2} \cdot \left(\frac{1}{n^2}\right)}$$

$\rightarrow \omega_2 - \omega_1 = hf$

$\Rightarrow$ frequency of radiation $f = \frac{\omega_2 - \omega_1}{h}$

$$\omega_2 - \omega_1 = \frac{me^4}{8\varepsilon^2 h^2}\left[\frac{1}{n_1^2} - \frac{1}{n_2^2}\right]$$

$$f = \frac{me^4}{8\varepsilon^2 h^3}\left[\frac{1}{n_1^2} - \frac{1}{n_2^2}\right]$$

$$\lambda = c/f \Rightarrow \lambda = \frac{c}{\frac{me^4}{8\varepsilon^2 h^3}\left[\frac{1}{n_1^2} - \frac{1}{n_2^2}\right]}$$

$$\lambda = \frac{c}{\frac{\omega_2 - \omega_1}{h}} = \frac{ch}{\omega_2 - \omega_1} = \frac{ch}{\Delta\omega}$$

Units of $\lambda = \frac{cm/sec \cdot \cancel{J} \cdot sec}{\cancel{J}}$ (or) $\frac{m/s \cdot J \cdot s}{J}$

$\lambda = cm$ $\qquad$ $\lambda = m$

$1\ eV = 1.6 \times 10^{-19}\ J$

$1\ J = \frac{1 eV}{1.6 \times 10^{-19}}$

$$\Rightarrow \lambda = \frac{ch/1.6\times10^{-19}}{E_2 - E_1} = \frac{ch/1.6\times10^{-19}}{\Delta E}$$

$$= \frac{cm/\cancel{s} \times \cancel{eV} - \cancel{sec}}{\cancel{eV}} = cm\ \&\ m$$

$$\lambda = \frac{12400 \times 10^{-10}}{E_2 - E_1} m = \frac{12400}{E_2 - E_1} A^\circ$$

$A^\circ = 10^{-10} m$

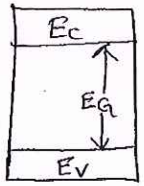
$$\boxed{\lambda = \frac{12400}{E_2 - E_1} A^\circ \ \& \ \frac{12400}{\Delta E} A^\circ}$$ (2012 IES)

E in eV

For Semiconductors,

$$E_G = E_C - E_V = hf$$

$$\lambda = \frac{12400}{E_C - E_V} A^\circ \ \& \ \lambda = \frac{12400}{E_G} A^\circ$$




→ The wavelength of the light radiated from GaAs LASER is $8670 \times 10^{-10} m$. Calculate Energy gap of GaAs at room temperature

$$\lambda = \frac{12400}{\Delta E} A^\circ$$

$$8670 A^\circ = \frac{12400}{\Delta E} A^\circ$$

$$\Rightarrow \Delta E = \frac{12400}{8670} = \underline{\underline{1.43 eV}}$$

* $E_G$ for GaAs at room temperature is 1.43eV.

→ A photon of wavelength 1400 A° absorbed by mercury and it radiated two photons out of which one is having a wavelength of 1850 A°. Calculate the wavelength of the second photon.

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$$E_{G_2} = 8.857 - 6.7$$
$$= 2.15\, eV$$

$$\lambda_{E_{G_2}} = \frac{12400}{2.15} = 5756\, A^0$$

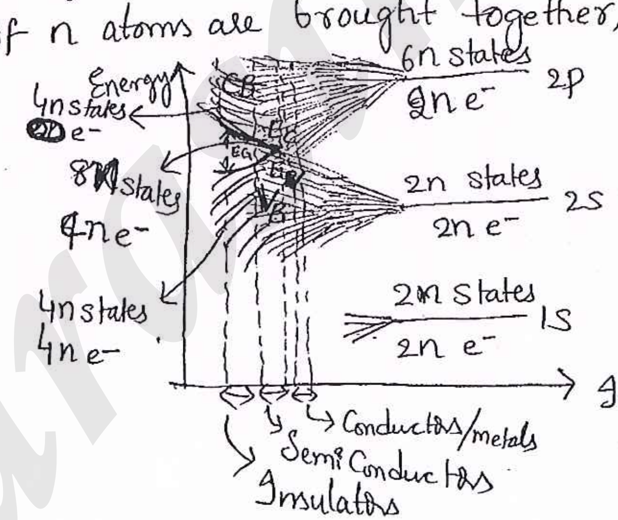
## * Energy Band Theory:

1S $\xrightarrow[\text{2 states}]{2e^-}$

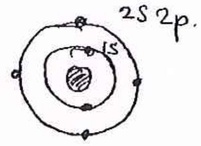
2S $\xrightarrow[\text{2 states}]{2e^-}$

2P $\xrightarrow[\text{6 states}]{6e^-}$

If n atoms are brought together,



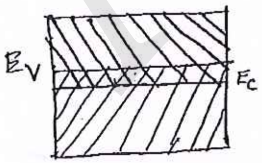

for carbon atom.
$1S^2 2S^2 2p^2$




$$E_G = E_C - E_V$$

→ Metals/Conductors

$E_G = 0$

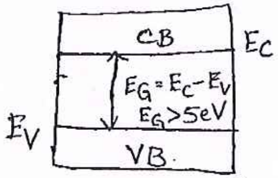



→ No holes are present.

→ Ex: Gold, Silver, Cu, Al

Insulator

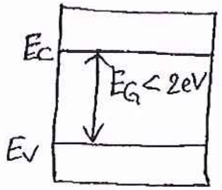
$E_G > 5eV$




→ Ex: Diamond ($E_G = 6eV$)
Porcelain, Glass,
Quartz, Rubber,
Bakelite

SemiConductor

$E_G \simeq 1eV$ (or) $E_G < 2eV$




→ Ex: Si, Ge

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mho/cm (or) mho/m

S/cm (or) S/m.

$\boxed{E_G = 1.21 - 3.6\times10^{-4}T \text{ eV at } T K}$

where T is temperature in K.

Conductor

Conductivity: $10^{3}$ to $10^{7}$ S/m

Insulator

Conductivity: $10^{-20}$ to $10^{-12}$ S/m

Semi Conductor

Conductivity: $10^{-7}$ to $10^{4}$ S/m

Germanium:

$E_{G_0} = 0.785$ eV at 0K

$E_G = 0.72$ eV at 300K

$\Rightarrow$ $E_G$ depends on temperature

As T↑, E↓ by $2.23\times10^{-4}$ eV/k

$\boxed{E_G = 0.785 - 2.23\times10^{-4}T \text{ eV}}$

Ge: $E_G(T) = 0.785 - 2.23\times10^{-4}T$ eV

Si $E_G(T) = 1.21 - 3.6\times10^{-4}T$ eV

$E_G^{(T)} = E_{G_0} - \beta T$

Si:

$E_{G_0} = 1.21$ eV

$\beta = 3.6\times10^{-4}$

Ge:

$E_{G_0} = 0.785$ eV

$\beta = 2.23\times10^{-4}$

785 eV

| II | III | IV | V | VI |
|---|---|---|---|---|
| | B | C | N | |
| | Al | Si | P | S |
| Zn | Ga | Ge | As | Se |
| Cd | In | | Sb | Te |
| | | | Bi | |

10/7/13

## Classification of semiconductors based on no: of Elements:

1. Elementary SC ex: Si, Ge

2. Compound SC:

i) Two element (Binary) Compound SC.

Ex: GaAs, GaP, ~~GaAs~~ InP (Compounds formed with III-V groups)

CdS, CdSe, ZnS, ZnSe (II-VI Compounds)

SiC, SiGe (IV-IV Compounds)

ii) Three element (Ternary) Compound SC.

Ex: GaAsP, AlGaAs

iii) Four element (Quartenary) Compound SC

Ex: GaAlAsP, InGaAsP

## Atomic Concentration:

It represents no: of atoms per cubic value.

$$A.C = \frac{A_o d}{A} \text{ atoms}/cm^3$$

where $A_o$ is Constant Avogadro's number $= 6.023 \times 10^{23} \frac{\text{molecule}}{\text{mole}}$

$d$ is the density

$A$ is the atomic weight

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Electron Concentration (n)

= A·C × no: of free $e^-$/atom.

Ex: If Si AC = 1000 atoms/$cm^3$ and each atom has 1 free $e^-$.

then $n = 1000 \text{ atoms}/cm^3 \times 1 e^-/\text{atom}$

$= 1000 e^-/cm^3$.

Density = 5.32 g/$cm^3$.

$$A\cdot C = \frac{6.023\times10^{23}\times5.32}{72.6} \text{ atoms}/cm^3$$

$$AC = 4.4\times10^{22} \text{ atoms}/cm^3.$$

→ The specific gravity of Tungsten is 18.8 gm/$cm^3$ and its atomic weight is 184. If each atom is having 2 free $e^-$ Calculate n ($e^-$ concentration).

$$AC = \frac{A_0 d}{A} = \frac{6.023\times10^{23}\times18.8}{184}$$

$$= 6.154\times10^{22} \text{ atoms}/cm^3$$

$n$ = AC × no: of free $e^-$

$= 6.154\times10^{22}\times2$

$= 1.23\times10^{23}\ e^-/cm^3$.

$n = 1.23\times10^{23}/cm^3$

Electron Gas theory:

According to $e^-$ gas theory of a metal, $e^-$ are in continuous motion. Their direction of flight being changed when they collide with the heavy ions.

obtained by the electron under the influence of the applied electric field is called drift velocity or drift speed.

→ The drift velocity is proportional to applied electric field.

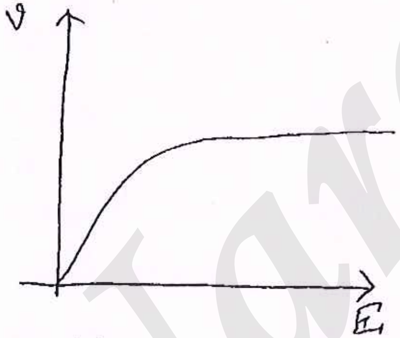
$$v \propto E$$

$$v = \mu E$$

where $\mu$ is the mobility of electrons.

⇒ Mobility $\mu = \dfrac{v}{E}$  $\dfrac{m/sec}{V/m} = m^2/V\text{-}sec$

$\dfrac{cm/sec}{V/cm} = cm^2/V\text{-}Sec$




$v$ is not propotional to all the values of $E$, it is propotional to only a set of values of $E$

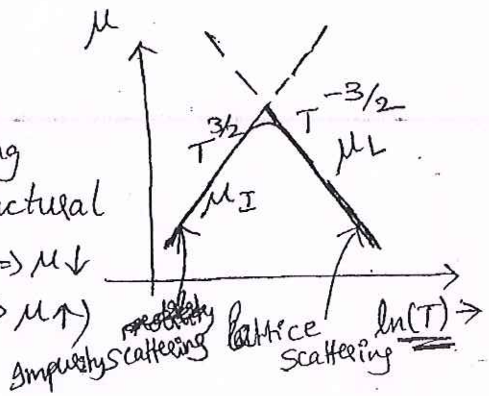
→ Mobility depends on temperature and electric field.

Mobility wrt temperature:

As temperature increases, mobility decreases. (due to scattering)

Scattering
- Lattice scattering (As temp↑ vibration↑ mobility↓)
  $\mu_L \propto T^{-3/2}$
- Impurity Scattering ( because of structural defects, as T↓ ⇒ μ↓ T↑ ⇒ μ↑)
  $\mu_I \propto T^{3/2}$

$$\frac{1}{\mu} = \frac{1}{\mu_L} + \frac{1}{\mu_I}$$

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Mobility wrt $E$ :

$\mu$: constant for $E < 10^3 V/cm$

$\mu \propto E^{-1/2}$ for $10^3 V/cm < E < 10^4 V/cm$

$\mu \propto E^{-1}$ for $E > 10^4 V/cm$

$v = \mu E$

$v$ = Drift Velocity

$\mu$ = Mobility of an $e^-$

$v_n = \mu_n E$ (for $e^-$)

$v_p = \mu_p E$ (for holes)

$v_n = \mu_n E \Rightarrow \mu_n = \frac{v_n}{E} = \frac{e\tau_{cn}}{m_n} = \frac{e\tau_{sc}}{m_n}$

where $e$ is charge of $e^-$

$\tau_{cn}$ is mean time between collisions for electrons

$m_n$ is effective mass of the electron.

$\tau_{sc}$ is scattering time

* Because of interaction b/n atoms, there is a deviation in the mass of $e^-$ and it is called effective mass of electron.

$m_n$ = Effective mass of $e^-$

| | Ge | Si | GaAs |
|---|---|---|---|
| $m_n$ = | 0.55m | 1.08m | 0.067m |
| $m_p$ = | 0.37m | 0.56m | 0.48m |

$v_p = \mu_p E \Rightarrow \mu_p = \frac{v_p}{E} = \frac{e\tau_{cp}}{m_p} = \frac{e\tau_{sc}}{m_p}$

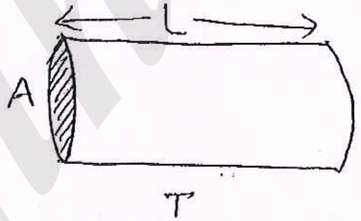
$\tau_{cp}$ = mean time b/n collisions for holes

$\tau_{sc}$ = Scattering time

$m_p$ = Effective mass of hole

## Conductivity and Current Density of a Metal: $\mu_n = 8500\ cm^2/V\text{-}sec$

$n = e^-$ concentration, $e^-/m^3$ & $e^-/cm^3$




$N$ = Total no: of $e^-$ & no: of $e^-$, $e^-$

$N = n \times \text{volume} = e^-/\cancel{m^3} \times \cancel{m^3}$, $e^-$

$= e^-/\cancel{cm^3} \times \cancel{cm^3}$, $e^-$

$n = \dfrac{N}{\text{Volume}}$, $e^-/m^3$ & $e^-/cm^3$

$T$ = Time taken by carriers to move from one end to other end

Drift Velocity $(v) = \dfrac{L}{T}$

$\Rightarrow v = \dfrac{L}{T}$ — ①

Current $(I) = \dfrac{Q}{T} = \dfrac{Nq}{T} = \dfrac{Ne}{T}$; where $q$ is the charge of $e^-$

$I = \dfrac{Ne}{T} = \dfrac{Nq}{T}$ — ②

Current Density $J = \dfrac{I}{A} = \dfrac{Ne}{TA} = \dfrac{Nq}{TA}$ — ③

From ①, $T = \dfrac{L}{v}$

① in ③ $\Rightarrow J = \dfrac{Ne}{\frac{L}{v}A} = \dfrac{Nev}{LA} = \underbrace{\dfrac{N}{LA}}_{n} \cdot ev$

$J = nev = nqv$

$J = ne\mu E = nq\mu E$

$J = n\mu eE = n\mu qE$

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Resistivity of a metal ($\rho$):

$$\rho = \frac{1}{\sigma} = \frac{1}{n\mu e} = \frac{1}{n\mu q}, \quad \Omega\text{-cm} \ \& \ \Omega\text{-m}$$

Current Density of a metal (J):

$$J = n\mu e E = n\mu q E = nev = nqv, \quad A/cm^2 \ \& \ A/m^2$$

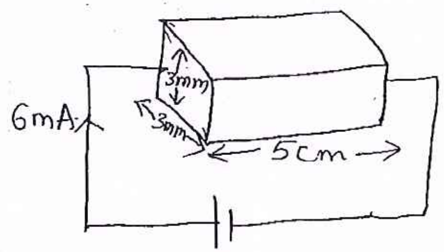
Current (I):

$$I = J \cdot A = ne\mu EA = nq\mu EA$$
$$= nevA = nqvA, \quad \text{Amp}$$

All these are Drift equations.

→ A specimen of a metal having square cross section area of 3mm x 3mm and its length 5cm. When a PD of 1V applied across its length gives a current of 6mA. Calculate concentration of $e^-$, drift velocity of $e^-$ and no: of $e^-$. (Assume $\mu = 1300\ cm^2/V\text{-sec}$)

$$A = 9\ mm^2 = 9\times10^{-2}\ cm^2$$
$$L = 5\ cm$$
$$V\ \cancel{E} = 1V \Rightarrow E = 1/5\ V/cm$$
$$I = 6mA$$




$$J = \frac{I}{A} = \frac{6\times10^{-3}}{9\times10^{-2}} = \frac{2}{3}\times10^{-1}$$

$$v = \mu E = 1300 \times \frac{1}{5} = 260\ cm/sec$$

$$I = n\mu e E A = n\mu e E A$$
$$n = \frac{I}{vqA}$$
$$n = \frac{6\times10^{-3}}{260\times1.6\times10^{-19}\times9\times10^{-2}} = 1.6\times10^{15}\ e^-/cm^3$$

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$dn = \rho_E \, dE$

$dn$ = no: of free $e^-$

$\rho_E$ = Density of $e^-$

$\rho_E = f(E) \cdot N(E)$

where $f(E)$ = density of states

$N(E)$ = no: of states per cubic volume

$N(E) = \gamma E^{1/2}$

where $\gamma$ = constant = $\frac{4\pi}{h^3} \times (2m)^{3/2} \times (1.6 \times 10^{-19})^{3/2}$

$$\gamma = \frac{4\pi}{h^3} (2m)^{3/2} (1.6 \times 10^{-19})^{3/2}$$

$$= 6.82 \times 10^{27}$$

E is the energy of states

$f(E)$: Fermi-Dirac probability function

Fermi-Dirac Probability function $f(E)$:

$$f(E) = \frac{1}{1 + e^{(E-E_F)/kT}}$$

$f(E)$ represents probability of occupancy of energy states by the electrons.

E is the energy of states

$E_F$ is the fermi level. It represents probability of finding $e^-$.

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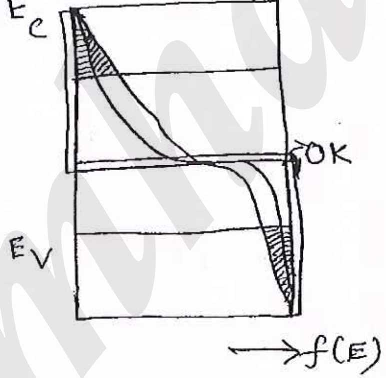
If $E > E_F$

$$f(E) = \frac{1}{1+e^{\infty}} = 0$$




Probability of filled states $= f(E)$

Probability of empty states $= 1 - f(E)$

$$f_n(E) + f_p(E) = 1$$

$$\Rightarrow f_p(E) = 1 - f_n(E)$$

→ Fermi-Dirac probability function symmetrical about the fermi level.

## Semi Conductor:

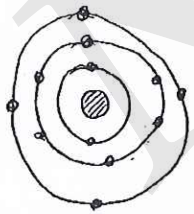
Si : 14

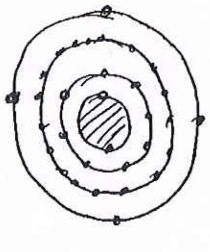
$1s^2 2s^2 2p^6 3s^2 3p^2$

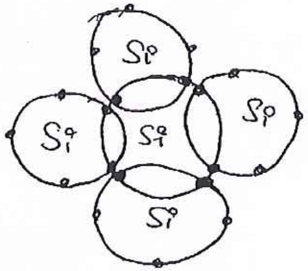
Ge : 32.

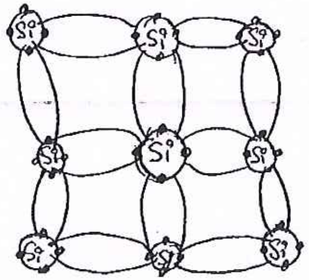
$ns^2 np^6$

No: of $e^-$ in $n^{th}$ energy level $= 2n^2$

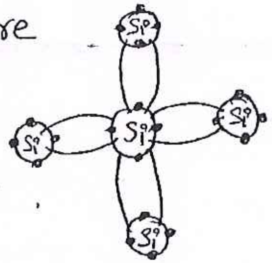







Crystalline Structure and Tetrahedral shape

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## Conductivity of a SemiConductor:

$$\sigma = \sigma_p + \sigma_n$$
$$= (n\mu_n)q + (p\mu_p)q$$
$$\sigma = (n\mu_n + p\mu_p)q$$

## Resistivity of a SemiConductor

$$\rho = \frac{1}{\sigma} = \frac{1}{(n\mu_n + p\mu_p)q}$$

## Current Density of a SemiConductor

$$J = (n\mu_n + p\mu_p)qE$$

Current I $= J \times A$
$$= (n\mu_n + p\mu_p)qEA.$$

| | Ge | Si | GaAs |
|---|---|---|---|
| $m_n =$ | 0.55m | 1.08 | 0.068 |
| $m_p =$ | 0.37 | 0.56 | 0.48 |

- SC
  - Intrinsic
  - Extrinsic
    - n-type
    - p-type.

## Intrinsic Semiconductor:

Pure and non defective semiconductors are called intrinsic semiconductors.

Ex: Pure Si, Pure Ge.

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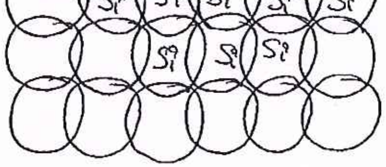
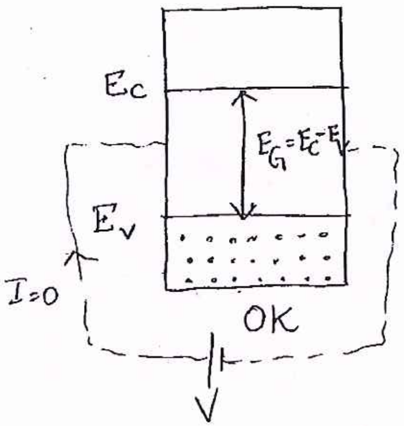
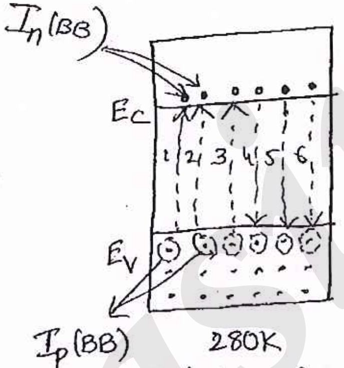


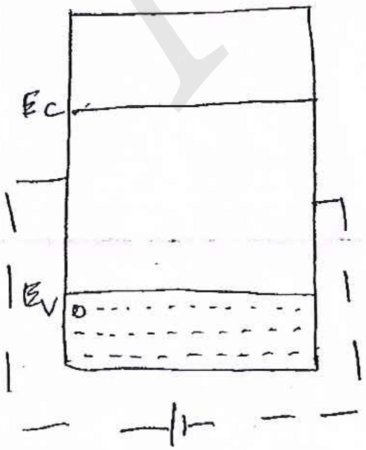

e⁻ hole pair generation rate is equal to e⁻ hole pair recombination at a given temperature

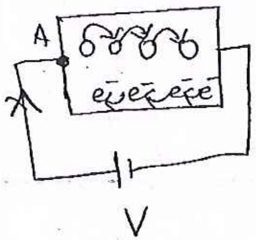
e⁻ hole pair generation } ①,②,③

e⁻ hole pair recombination } ④⑤⑥

e⁻ concentration = hole concentration in Intrinsic SC.

$\Rightarrow n = p = n_i$ (Intrinsic concentration)




$I = I_p + I_n$

KCL at A

$\Rightarrow I = I_p - I_n$

$= I_p - (-I_n) = I_p + I_n$

BB: Band to Band Transition

$$I = \underbrace{I_p(BB)}_{I_p} + \underbrace{I_n(BB)}_{I_n}$$

$I_n > I_p$

$(\because \mu_n > \mu_p)$

$$I = \frac{q}{T} = \frac{-1.6 \times 10^{-19}}{T}$$

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$$n = \int_{E_c}^{\infty} f(E)\, N(E)\, dE$$

$$dn = \rho_E\, dE$$

$$\Rightarrow n = \int_{E_c}^{\infty} dn = \int_{E_c}^{\infty} \rho_E\, dE$$

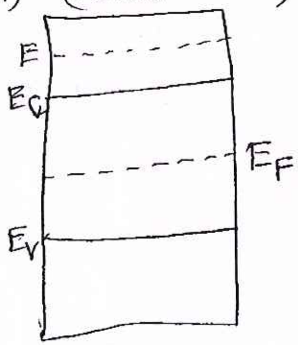
$$= \int_{E_c}^{\infty} f(E) \cdot N(E)\, dE$$

$$N(E) = \gamma E^{1/2}$$

Consider $E$ level in CB, then

$$N(E) = \gamma (E - E_c)^{1/2} \qquad \left(\because \gamma = \frac{4\pi}{h^3}(2m)^{3/2}(1.6\times10^{-19})^{3/2}\right)$$

$$= \frac{4\pi}{h^3}(2m)^{3/2}(1.6\times10^{-19})^{3/2}(E-E_c)^{1/2}$$




$$f(E) = \frac{1}{1 + e^{(E-E_F)/KT}}$$

K : Boltzman's Constant $= 8.62 \times 10^{-5}\ eV/K$

$$K\ \&\ (\bar{K}) = 1.38 \times 10^{-23}\ J/K$$

$$\bar{K} = K \cdot q = 8.82 \times 10^{-5} \times 1.6 \times 10^{-19}$$

$$\Rightarrow K = \frac{\bar{K}}{q}$$

$V_T$ : Thermal voltage & Voltage equivalent of temperature

$$V_T = \frac{\bar{K}T}{q} = KT = T/_{1/K} = \frac{T}{11600}$$

$$\Rightarrow V_T = \frac{T}{11600}$$

At room temperature,

$$V_T = \frac{300}{11600} = 0.02586 \simeq 26\,mV$$

$$f(E) = \frac{1}{1 + e^{(E-E_F)/KT}} \qquad (\because e^{(E-E_F)/KT} >> 1)$$

$$\Rightarrow \gamma \frac{(\ldots)}{\frac{1}{2}+1} \cdot e$$

$$= \gamma \int_{E_c}^{\infty} (E-E_c)^{1/2} e^{-(E-E_F)/KT} dE \qquad \approx \int_{E_c}^{\infty} (x-K_1)^{1/2} e^{-(x-K_2)/K_3} dx$$

Let $E-E_c = KTx \Rightarrow E = E_c + KTx$

If $E = E_c \Rightarrow E_c - E_c = KTx \Rightarrow 0 = KTx \Rightarrow x = 0$

$E = \infty \Rightarrow \infty - E_c = KTx \Rightarrow \infty = KTx \Rightarrow x = \infty$

$$n = \gamma \int_0^{\infty} (KTx)^{1/2} \cdot e^{-(E_c-E_F)/KT} \cdot e^{-\cancel{KT}x/\cancel{KT}} KT dx$$

$$= \gamma \int_0^{\infty} (KTx)^{1/2} e^{-(E_c-E_F)/KT} \cdot e^{-x} KT dx$$

$E - E_c = KTx$

$dE = KTdx$

$$\Rightarrow n = \gamma \int_0^{\infty} (KTx)^{1/2} e^{-(E_c + KTx - E_F)/KT} KT dx$$

$$\Rightarrow n = \gamma (KT)^{3/2} \int_0^{\infty} x^{1/2} e^{-(E_c-E_F)/KT} \cdot e^{-x} dx$$

$$\Rightarrow n = \gamma (KT)^{3/2} \int_0^{\infty} x^{1/2} e^{-(E_c-E_F)/KT} e^{-x} dx$$

$$\Rightarrow n = \gamma (KT)^{3/2} e^{-(E_c-E_F)/KT} \int_0^{\infty} x^{1/2} \cdot e^{-x} dx$$

$$\Rightarrow n = \frac{4\pi}{h^3} (2m)^{3/2} (1.6\times10^{-19})^{3/2} (KT)^{3/2} e^{-(E_c-E_F)/KT} \underbrace{\int_0^{\infty} \sqrt{x}\, e^{-x} dx}$$

$$= \frac{4}{\sqrt{\pi}} (2m_n)^{3/2} (1.6\times10^{-19})^{3/2} (KT)^{3/2} e^{-(E_c-E_F)/KT} \quad \sqrt{\pi}/2 \quad \frac{\sqrt{\pi}}{2}$$

$\because$ It is for entire semiconductor mass could be effective mass $m_n$.

$N_c$ = Effective density of ...

$$N_c = 2\left[\frac{2\pi m_n \bar{k} T}{h^2}\right]^{3/2} \quad \text{where } \bar{k} = k \cdot q$$

$$N_c = 2\left[\frac{2\pi \times \bar{k} \times 9.107 \times 10^{-31}}{h^2}\right]^{3/2} \left(\frac{m_n}{m}\right)^{3/2} \cdot T^{3/2}$$

® $$N_c = 4.82 \times 10^{21} \times \left(\frac{m_n}{m}\right)^{3/2} T^{3/2} / m^3 \quad (\text{~~mass of $e^-$ in kg~~})$$

$$= 4.82 \times 10^{15} \left(\frac{m_n}{m}\right)^{3/2} T^{3/2} / cm^3 \quad (\text{~~mass of $e^-$ in gms~~})$$

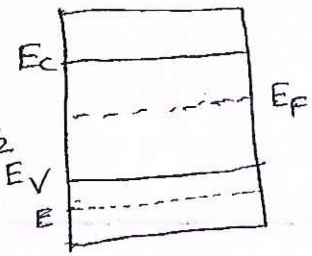
$$n = N_c \, e^{-(E_c - E_F)/kT}$$

$$N_c = 4.82 \times 10^{21} \left(\frac{m_n}{m}\right)^{3/2} \cdot T^{3/2} \; / m^3$$

$$N_c = 4.82 \times 10^{15} \left(\frac{m_n}{m}\right)^{3/2} \cdot T^{3/2} \; / cm^3$$

## Hole Concentration in VB:

$$P = \int_{-\infty}^{E_V} (1 - f(E))\, N(E)\, dE$$




$$N(E) = \gamma \, (E_V - E)^{1/2}, \quad \gamma = \frac{4\pi}{h^3} (2m)^{3/2} (1.6 \times 10^{-19})^{3/2}$$

$$1 - f(E) = 1 - \frac{1}{1 + e^{(E - E_F)/kT}}$$

$$= \frac{e^{(E - E_F)/kT}}{1 + e^{(E - E_F)/kT}}$$

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$$= \gamma \int_{-\infty}^{E_V} (E_V - E)^{1/2} e^{-(E_F - E)/KT} dE \qquad E_V - E = KTx$$

$$-dE = KTdx$$

$$= \gamma \int_{-\infty}^{E_V} (E_V - E)^{1/2} e^{-(E_F - E)/KT} dE$$

$$= \gamma \int_{-\infty}^{E_V} (KTx)^{1/2} e^{-(E_F - E_V + KTx)/KT} (-KTdx)$$

$$= +\gamma (KT)^{3/2} \int_{\infty}^{\infty} x^{1/2} e^{-(E_F - E_V)/KT} e^{-x} dx$$

$$= + \frac{4\pi}{h^3} (2m)^{3/2} (1.6\times10^{-19})^{3/2} (KT)^{3/2} e^{-(E_F - E_V)/KT} \int_0^{\infty} x^{1/2} e^{-x} dx$$

$$= \frac{4}{\sqrt{\pi}} 2 (2m_p)^{3/2} (1.6\times10^{-19})^{3/2} (KT)^{3/2} e^{-(E_F - E_V)/KT} \frac{\sqrt{\pi}}{2}$$

$$p = 2\left[\frac{2\pi m_p KT}{h^2}\right]^{3/2} (1.6\times10^{-19})^{3/2} e^{-(E_F - E_V)/KT}$$

$$\Rightarrow \boxed{P = N_V \cdot e^{-(E_F - E_V)/KT}}$$

$N_V$ is the effective density of states function

$$N_V = 2\left[\frac{2\pi m_p KT}{h^2}\right]^{3/2} (1.6\times10^{-19})^{3/2}$$

$$= 2\left[\frac{2\pi K \times 9.1\times10^{-3}}{h^2}\right]^{3/2} \left(\frac{m_p}{m}\right)^{3/2} \cdot T^{3/2}$$

$$N_c\, e^{-(E_C-E_F)/KT} = N_V\, e^{-(E_F-E_V)/KT}$$

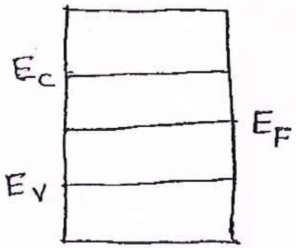
$$\frac{N_c}{N_V} = \frac{e^{-(E_F-E_V)/KT}}{e^{-(E_C-E_F)/KT}}$$

$$\cancel{\frac{N_c}{N_V} = e^{-(E_F-E_V+E_C-E_F)/KT}}$$

$$\cancel{\Rightarrow \frac{N_c}{N_V} = e^{-(E_C-E_V)/KT}}$$

$$\frac{N_c}{N_V} = e^{-(E_F-E_V)/KT} \cdot e^{(E_C-E_F)/KT}$$

$$\frac{N_c}{N_V} = e^{(E_C+E_V-2E_F)/KT}$$




$$\Rightarrow \ln\left(\frac{N_c}{N_V}\right) = (E_C+E_V-2E_F)/KT$$

$$E_C+E_V-2E_F = KT\ln\left(\frac{N_c}{N_V}\right)$$

$$\Rightarrow 2E_F = E_C+E_V-KT\ln\left(\frac{N_c}{N_V}\right)$$

$$\Rightarrow \boxed{E_F = \frac{E_C+E_V}{2} - \frac{KT}{2}\ln\left(\frac{N_c}{N_V}\right)}$$

$$E_{Fi} = \frac{E_C+E_V}{2} - \frac{KT}{2}\ln\left(\frac{N_c}{N_V}\right)$$

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If $\frac{KT}{2}\ln\left(\frac{N_c}{N_V}\right)$ is $-ve \Rightarrow E_F$ lies above the ...

→ In a semiconductor, if $m_n$ is 2 times that of hole, find the position of fermi level in an intrinsic semi conductor with reference to the centre of the energy gap at room temperature.

$$m_n = 2m_p$$

$$\Rightarrow \frac{m_n}{m_p} = 2$$

$$\frac{KT}{2}\ln\left(\frac{N_c}{N_V}\right) = \frac{0.02586}{2}\ln\left\{(2)^{3/2}\right\}$$

$$= 0.0134 > 0$$

⇒ Fermi level is below the centre at a distance of 0.0134 eV

## Mass Action Law:

According to Mass-Action law, the product of electrons and holes remains constant at fixed temperature. This will be applicable for intrinsic as well as extrinsic semiconductors.

$$\boxed{n \cdot p = n_i^2}$$

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$$\Rightarrow \boxed{n_i^2 = N_c N_v e^{-E_G/KT}}$$

Ge:

$$N_c = 4.82\times10^{15}\times\left(\frac{0.55\,m}{m}\right)^{3/2}\times(300)^{3/2}$$

$$= 1.02\times10^{19}$$

Si

$$N_c = 4.82\times10^{15}\times\left(\frac{1.08\,m}{m}\right)^{3/2}\times 300^{3/2}$$

$$= 2.81\times10^{19}$$

$$n_i^2 = 4.82\times10^{21}\left(\frac{m_n}{m}\right)^{3/2}\cdot T^{3/2}\cdot 4.82\times10^{21}\left(\frac{m_p}{m}\right)^{3/2}\cdot T^{3/2}\, e^{-E_G/KT}$$

$$n_i^2 = \underbrace{2.33\times10^{43}\left(\frac{m_n m_p}{m^2}\right)^{3/2}}_{N} T^3\cdot e^{-E_G/KT} \;/m^3$$

$$n_i^2 = NT^3 e^{-E_G/KT}$$

$$N = 2.33\times10^{43}\left(\frac{m_n m_p}{m^2}\right)^{3/2} \Big/ (m^3)^2 \;\&\; m^3$$ (∵ we are calculating for $n_i^2$)

$$N = 2.33\times10^{31}\left(\frac{m_n m_p}{m^2}\right)^{3/2} \Big/ (cm^3)^2 \;\&\; cm^3$$

$$n_i^2 = 2.33\times10^{31}\left(\frac{m_n m_p}{m^2}\right)^{3/2} T^3\cdot e^{-E_G/KT} \;/ cm^3$$

$$\because E_G = E_{G_0} - \beta T$$

$$e^{-E_G/KT} = e^{-(E_{G_0}-\beta T)/KT} = e^{-E_{G_0}/KT}\cdot e^{+\beta/K}$$

$n_i = 2.5 \times 10$ /cm$^3$

$$n_i^2 = A_0 T^3 e^{-E_{G0}/KT} \ /cm^3$$

Si:
$n_i = 1.5 \times 10^{10}$ /cm$^3$

$$A_0 = 2.33 \times 10^{31} \left(\frac{m_n m_p}{m^2}\right)^{3/2} e^{\beta/K}$$

IES→ Calculate intrinsic concentration of Ge at 400K

$n_i$ at 400K

$$\Rightarrow n_i^2 = 2.33 \times 10^{31} \left(\frac{m_n m_p}{m^2}\right)^{3/2} T^3 e^{-E_G/KT}$$

$$= 2.33 \times 10^{31} \left(\frac{0.55 \times 0.37\ m^2}{m^2}\right)^{3/2} 400^3 \times e^{\frac{-0.696}{0.0345}}$$

$$E_G = E_{G0} - \beta T$$

$$= 0.785 - 2.23 \times 10^{-4} \times 400$$

$$= 0.696\ eV$$

$$KT = \frac{T}{11600} = \frac{400}{11600} = 0.0345$$

$$= 2.87 \times 10^{29}$$

$$n_i = 4.88 \times 10^{14}\ /cm^3$$

## Conductivity of a SemiConductor (Intrinsic) : ($\sigma_i$)

$$\sigma_i = n_i(\mu_n + \mu_p) q \quad (\because n = p = n_i) \quad S/m \ \& \ S/cm$$

## Resistivity of an Intrinsic SemiConductor ($\rho_i$):

$$\rho_i = \frac{1}{\sigma_i} = \frac{1}{n_i(\mu_n + \mu_p) q} \quad \text{omh-m \& ohm-cm}$$

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Ge at room temperature.

$$\mu_p = 0.18\ m^2/V\text{-sec} = 1800\ cm^2/V\text{-sec}$$
$$\mu_n = 0.38\ m^2/V\text{-sec} = 3800\ cm^2/V\text{-sec}$$
$$T = 300K$$
$$n_i = 2.5\times10^{13}/cm^3;\ q = 1.6\times10^{-19}\ c$$
$$\rho_i = \frac{1}{n_i(\mu_n+\mu_p)q} = 44.64\ \text{ohm-cm}$$

Conductivity $\sigma_i = 0.0224$ S/cm.

Ⓡ Intrinsic resistivity = 44.64 $\Omega$-cm $\simeq$ 45
Intrinsic Conductivity = 0.0224 S/cm
for Ge

→ Calculate intrinsic resistivity and conductivity of Si at room temperature

$$\mu_p = 500\ cm^2/V\text{-sec}$$
$$\mu_n = 1300\ cm^2/V\text{-sec}$$
$$T = 300K$$
$$n_i = 1.5\times10^{10}/cm^3$$
$$\sigma_i = n_i(\mu_n+\mu_p)q = 4.32\times10^{-6}\ S/cm$$
$$\rho_i = 231.481\ K\Omega\text{-cm}$$

Ⓡ Intrinsic resistivity = 231.481 K$\Omega$-cm $\simeq$ 230 k$\Omega$-cm
Intrinsic Conductivity = $4.32\times10^{-6}$ S/cm
for Si

→ In the case of intrinsic semiconductors, as temperature increases, conductivity increases and also resistivity decreases. Therefore resistance decreases.

→ Intrinsic semiconductors are having negative temperature coefficient. Therefore these can be used as thermistors except Silicon and Germanium. Because Silicon and Germanium are too sensitive to impurities.

→ The conductivity of Germanium increases by 6% per °c rise in temperature.

→ The conductivity of Silicon increases by 8% per °c rise in temperature.

Metal & Conductor wrt Temperature:

$$\underbrace{T\uparrow \rightarrow \mu\downarrow \rightarrow \sigma\downarrow \rightarrow \rho\uparrow \rightarrow R\uparrow}_{PTC}$$

In the case of metals as temperature ↑, mobility ↓, conductivity ↓. Therefore resistivity increases and also resistance increases.

Metals are having positive temperature coefficient

The resistance of metals increases by 0.4% per degree rise in temperature.

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→ This impurity ...

Extrinsic semi conductor.

ESC — n-type
ESC — p-type

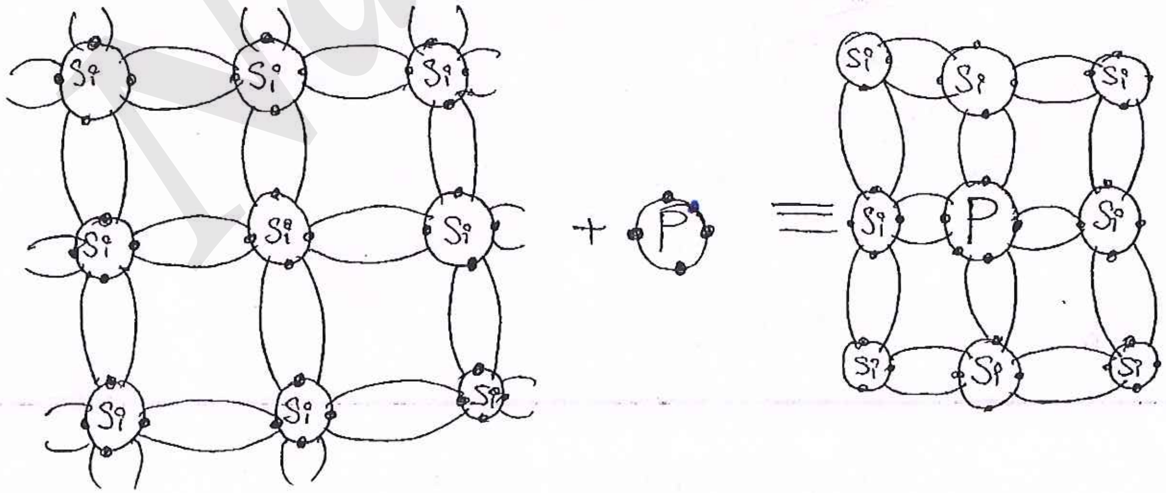
## n-type Semi Conductor:

→ When $\underline{V}$ group or pentavalent impurities are added to an intrinsic semiconductor, then it is called n-type semiconductor.

→ $\underline{V}$ group & pentavalent impurities are Arsenic (As), Antimony (Sb), Phosphorous (P) and Bismuth (Bi).

→ $\underline{V}$ group impurities have 5 valence electrons

→ $\underline{V}$ group elements are also called Donors. $\oplus \rightarrow \cdot \Rightarrow \oplus$




→ Concentration of Donor atoms is $N_D$

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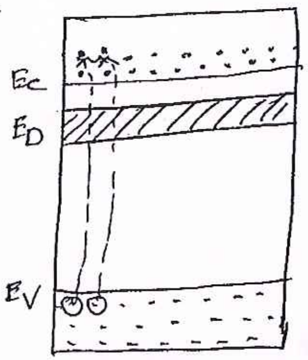
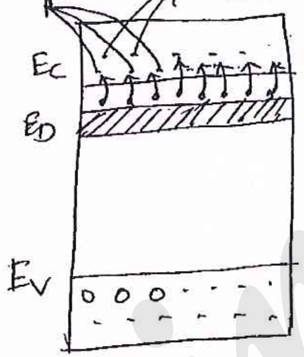



280K



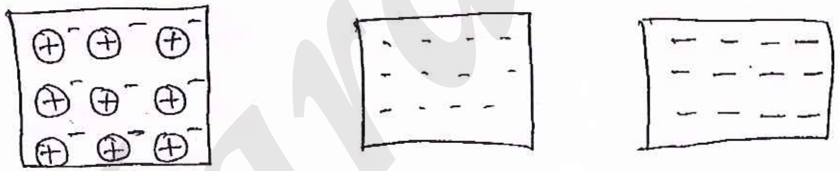

$I_n(II) \Rightarrow$ Current due to Impurity Ionization

$I_n(BB) \Rightarrow$ Current due to Band to Band transition

$$I = \underbrace{I_n(II) + I_n(BB)}_{I_n} + \underbrace{I_p(BB)}_{I_p}$$

$$\Rightarrow I_n >> I_p$$

n-Type



| n : majority<br>p : minority |
|---|

$n >> p$

| $n_n$ : $e^-$ conc in n-type<br>$P_n$ : hole conc in n-type |
|---|

$n_n >> P_n$

Mass - Action Law:

$$n_n P_n = n_i^2$$

$$P_n = \frac{n_i^2}{n_n}$$

$$\Rightarrow P_n \simeq \frac{n_i^2}{N_D} \quad (\because n_n \simeq N_D)$$

Conductivity of n-type SC($\sigma_n$):

$$\sigma_n = (n_n \mu_n + P_n \mu_p) e$$

$$\simeq n_n \mu_n e \quad (\because n_n >> P_n)$$

$$\simeq N_D \mu_n e \quad (\because n_n \simeq N_D)$$

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$$J_n = \sigma_n E = (n_n \mu_n + P_n \mu_p) e E$$
$$\simeq n_n \mu_n e E = n_n e v_n \quad (\because v_n = \mu_n E)$$
$$= N_D \mu_n e E = N_D e v_n$$

**Current $(I_n)$:**

$$I_n = (n_n \mu_n + P_n \mu_p) e E A$$
$$\simeq n_n \mu_n e E A = n_n e v_n A$$
$$= N_D \mu_n e E A = N_D e v_n A.$$

**P-Type SemiConductor:**

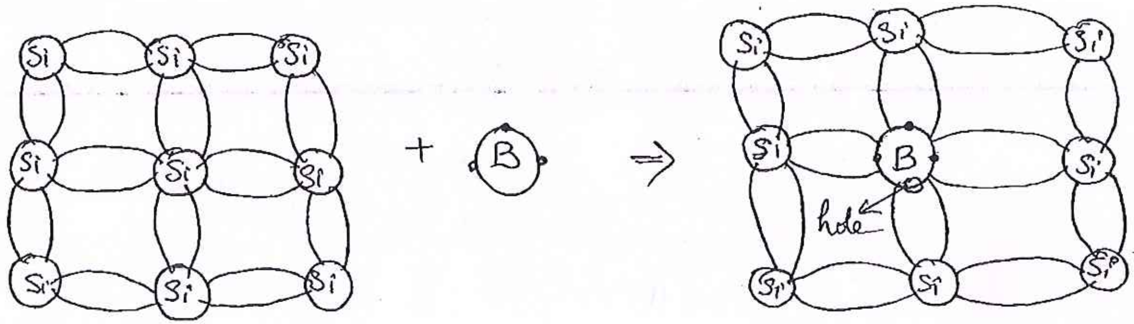
→ When III group or trivalent impurities are added to an intrinsic semiconductor, then it is called P-type semi-conductor

→ III group impurities are B, Ga, In

→ III group impurities have three valence electrons

→ III group impurities are also called acceptors

→ Concentration of acceptors atoms is $N_A$ $\quad \ominus^{o} + \cdot \Rightarrow \ominus$

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P: Majority $\qquad$ $P_p$ : majority

$P >> n$ $\qquad$ $P_p >> n_p$ $\qquad$ $n_p = \frac{n_i^2}{P_p} \simeq \frac{n_i^2}{N_A} \quad (\because P_p \simeq N_A)$

$$I = \underbrace{I_p(II) + I_p(BB)}_{I_p} + \underbrace{I_n(BB)}_{I_n}$$

$$I = I_p + I_n$$

$\rightarrow I_p >> I_n$

$\rightarrow P = N_A$ for doping concentration >> intrinsic concentration

$N_A >> n_i$

$$* \quad P = \frac{N_A}{2} + \sqrt{\left(\frac{N_A}{2}\right)^2 + n_i^2}$$

## Conductivity of P-type sc ($\sigma_p$):

$$\sigma_p = (n_p\mu_n + P_p\mu_p)e \simeq P_p\mu_p e \quad (\because P_p >> n_p)$$
$$= N_A\mu_p e \quad (\because P_p \simeq N_A)$$

## Resistivity of p-type sc ($\rho_p$):

$$\rho_p = \frac{1}{\sigma_p} = \frac{1}{((n_p\mu_n) + (P_p\mu_p))e} \simeq \frac{1}{P_p\mu_p e} \quad (\because P_p >> n_p)$$
$$= \frac{1}{N_A\mu_p e} \quad (\because P_p \simeq N_A$$

## Current Density of P-type sc ($J_p$):

$$J_p = \sigma_p E = (n_p\mu_n + P_p\mu_p)eE \simeq P_p\mu_p eE = N_A\mu_p eE$$
$$\simeq P_p v_p e = N_A v_p e$$


$$\frac{N_C}{N_D} = e^{(E_C - E_F)/KT}$$

$$\ln\left(\frac{N_C}{N_D}\right) = (E_C - E_F)/KT$$

$$\Rightarrow \quad E_F = E_C - KT\ln\left(\frac{N_C}{N_D}\right) \Rightarrow \boxed{E_C - E_F = KT\ln\left(\frac{N_C}{N_D}\right)}$$

$$\boxed{\therefore E_{F_n} = E_C - KT\ln\left(\frac{N_C}{N_D}\right)}$$

* Position of the fermi level with reference to edge of the conduction band

$$E_C - E_F = KT\ln\left(\frac{N_C}{N_D}\right)$$

$$N_C = 4.8 \times 10^{21}\left(\frac{m_n}{m}\right)^{3/2} T^{3/2} / m^3$$

$$N_C = 4.8 \times 10^{15}\left(\frac{m_n}{m}\right)^{3/2} T^{3/2} / cm^3$$

$N_D$ : Donor Concentration

1:10 $\Rightarrow$ Donor atoms correspond to 1 in 10 Si atoms

$\Rightarrow$ 1 donor impurity / 10 Si atoms

$N_D$ = Atomic Concentration × no of donor impurity atoms / (Si/Ge) atoms

Calculate $KT\ln\left(\frac{N_C}{N_D}\right)$ value,

if $KT\ln\left(\frac{N_C}{N_D}\right) = 0 \Rightarrow E_F = E_C \Rightarrow$ Fermi level coincides with edge of conduction band

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$n_i$

$$\cancel{KT}\frac{(E_F - E_{F_i})}{KT} = \ln\left(\frac{n}{n_i}\right)$$

$$E_F - E_{F_i} = KT\ln\left(\frac{n}{n_i}\right)$$

$$\boxed{\Rightarrow E_F - E_{F_i} = KT\ln\left(\frac{N_D}{n_i}\right)}$$

## Position of Fermi level in p-type Semiconductor:

$$P = N_V e^{-(E_F - E_V)/KT}$$

$$P = P_p \approx N_A = N_V e^{-(E_F - E_V)/KT}$$

$$\Rightarrow \frac{N_A}{N_V} = e^{-(E_F - E_V)/KT}$$

$$\Rightarrow e^{(E_F - E_V)/KT} = \frac{N_V}{N_A}$$

$$\Rightarrow E_F - E_V = KT\ln\left(\frac{N_V}{N_A}\right)$$

$$\Rightarrow \boxed{E_{F_p} - E_V = KT\ln\left(\frac{N_V}{N_A}\right)}$$

$$\boxed{E_{F_p} = E_V + KT\ln\left(\frac{N_V}{N_A}\right)}$$

Position of fermilevel with reference to edge of the valence band

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$$N_V = 4.82\times 10^{21}\left(\frac{m_p}{m}\right)^{3/2} T^{3/2} /m^3 = 4.82\times 10^{15}\left(\frac{m_p}{m}\right)^{3/2} T^{3/2} /cm^3$$

* Position of the fermilevel with reference to centre of the energy gap & with reference to intrinsic fermilevel:

$$P = n_i\, e^{(E_{F_i}-E_F)/KT}$$

$$\frac{P}{n_i} = e^{(E_{F_i}-E_F)/KT}$$

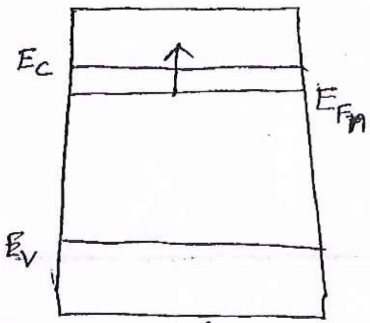
$$\Rightarrow \frac{(E_{F_i}-E_F)}{KT} = \ln\left(\frac{P}{n_i}\right)$$

$$\Rightarrow E_{F_i} - E_F = KT\ln\left(\frac{P}{n_i}\right)$$

$$\boxed{E_{F_i} - E_F = KT\ln\left(\frac{N_A}{n_i}\right)}$$

<u>Fermilevel with respect to Doping in n-type Semiconductor at fixed temperature.</u>

$$E_C - E_F = KT\ln\left(\frac{N_C}{N_D}\right)$$




$$N_C = 4.8\times 10^{21}\left(\frac{m_n}{m}\right)^{3/2} T^{3/2}$$

As T is const $\Rightarrow$ $N_C$ is const

$E_C$ is also constant

As $N_D \uparrow \Rightarrow \frac{N_C}{N_D}\downarrow \Rightarrow E_C - E_F \downarrow \Rightarrow$ $E_F$ moves upwards

In n-type semiconductor, as doping concentration increases, fermilevel moves upwards.

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intrinsic semiconductors.

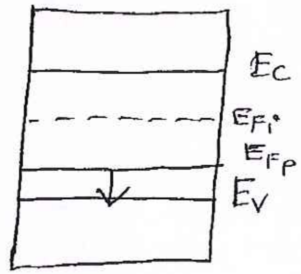
i.e, As temp ↑ ⇒ $E_{Fn}$ moves downwards. at fixed doping concentration

$$E_C - E_F = KT \ln\left(\frac{N_C}{N_D^*}\right)$$

## Fermi level wrt doping in p-Type Semiconductor at fixed temperature:

$$E_F - E_V = KT \ln\left(\frac{N_V}{N_A}\right)$$

$$N_V = 4.82 \times 10^{21}\left(\frac{m_p}{m_p}\right)^{3/2} T^{3/2} /m^3$$




As doping ↑ ⇒ $N_A$ ↑ ⇒ $(E_F - E_V)$ ↓

$E_V$ is fixed ⇒ $E_F$ decreases

⇒ $E_{F_p}$ moves downwards.

$\downarrow x - y^* = K \downarrow$

$y$ ↓ fixed

In p-type semiconductor, as doping concentration increases, fermilevel moves downwards at fixed temperature.

## Fermilevel wrt temperature in p-type semiconductor at fixed doping:

$$E_F \uparrow - E_V^* = \left[KT\uparrow \ln\left(\frac{N_V}{N_A}\right)\right] \uparrow$$

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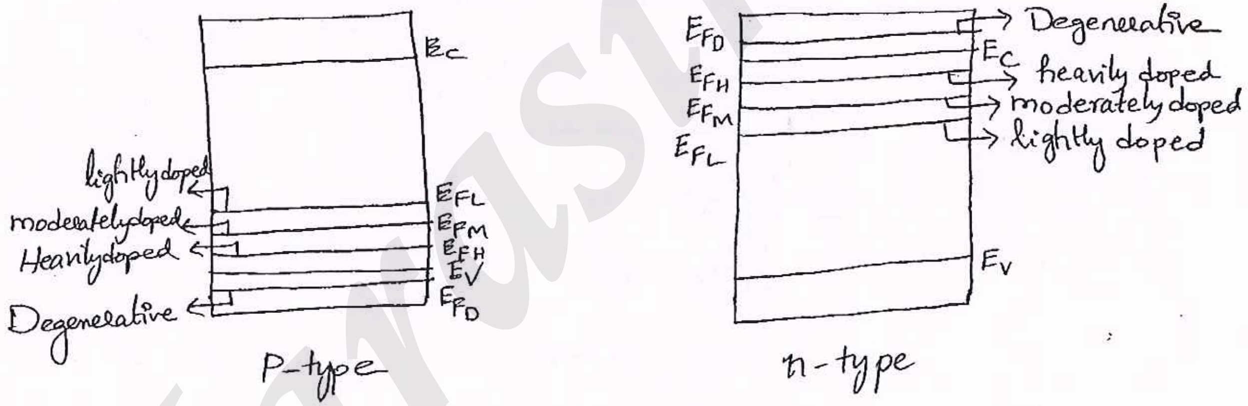
1. Lightly doped Semiconductors ⇒ [illegible] /cm$^3$

2. Moderately doped Semi Conductors ⇒ $10^{15}$ to $10^{16}$ imp atoms /cm$^3$

3. Heavily doped Semi Conductors ⇒ $10^{17}$ to $10^{18}$ imp atoms /cm$^3$

***4. Degenerative Semi Conductors ⇒ $>10^{18}$ imp atoms/cm$^3$

↳ ($E_F$ lies inside $E_C$ (or) $E_D$ coincides with $E_C$)




## Intrinsic Semiconductor doped with III and V group:

If acceptor concentration i.e, $N_A$ is greater than Donor Concentration i.e, $N_D$

⇒ $N_A > N_D$ ⇒ It forms p-type Semiconductor

Hole concentration = $N_A - N_D$ (If $N_A >> N_D$) · if $N_A - N_D >> n_i$

Otherwise $\frac{N_A - N_D}{2} + \sqrt{\left(\frac{N_A - N_D}{2}\right)^2 + n_i^2}$

If Donor concentration ($N_D$) is greater than Acceptor concentration ($N_A$)

⇒ $N_D > N_A$ ⇒ It forms n-type semiconductor

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as well as extrinsic semiconductor.

Total positive charge = $p + N_D$

Total Negative charge = $n + N_A$

According to charge neutrality principle,

total positive charge = total negative charge.

$$\boxed{p + N_D = n + N_A}$$

n-Type Semiconductor:

$$N_A = 0$$

$$\Rightarrow p + N_D = n + 0$$

$$\Rightarrow n = p + N_D$$

$$(\because n >> p) \Rightarrow n \simeq N_D.$$

$$\Rightarrow n_n \simeq N_D.$$

$$n_n p_n = n_i^2$$

$$\boxed{p_n = \frac{n_i^2}{n_n} = \frac{n_i^2}{N_D}}$$

P-type Semiconductor:

$$N_D = 0$$

$$\Rightarrow 0 + p = n + N_A$$

$$\Rightarrow p = n + N_A$$

to $e^-$ and $1/4$th of the current ... drift velocity of the $e^-$ is 3 times that of holes, find the ratio of $e^-$ to holes.

$3/4$th of current due to $e^-$ $\Rightarrow$ n-type

$$v_n = 3v_p \qquad I = \text{hole current} + e^- \text{ current}$$

$$\mu_n E = 3\mu_p E \qquad I_n = 3/4\, I$$

$$\Rightarrow \frac{\mu_n}{\mu_p} = 3. \qquad I_p = 1/4\, I$$

$$I_n = n\mu_n eEA = nv_n eA$$

$$I_p = p\mu_p eEA = pv_p eA$$

$$\frac{I_n}{I_p} = \frac{n}{p} \cdot \frac{v_n}{v_p}$$

$$\Rightarrow \frac{n}{p} = \frac{I_n v_p}{I_p v_n} = \frac{3/4\, I}{1/4\, I} \cdot \frac{1}{3}$$

$$\Rightarrow \frac{n}{p} = 1$$

$$\Rightarrow \boxed{n = p}$$

Q) Find the density of the impurity atoms that must be added to an intrinsic germanium to convert it into 10 Ω-cm n-type germanium at room temperature.

$$\rho_n = 10\,\Omega\text{-cm}$$

$$\frac{1}{n_n \mu_n e} = 10\,\Omega\text{-cm}$$

$$\Rightarrow N_D = \frac{1}{\rho_n \mu_n e} = 1.6 \times 10^{14} /\text{cm}^3$$

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$$N_D = \frac{1}{\rho_n \mu_n e} = 3.69\times10^{14}/cm^3$$

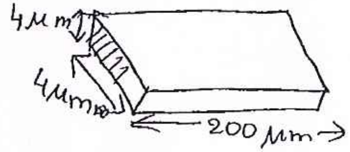
From above two problems, $\rho_n = 10\,\Omega\text{-cm} \Rightarrow N_D = 1.6\times10^{14}/cm^3$

$\rho_n = 4.46\,\Omega\text{-cm} \Rightarrow N_D = 3.7\times10^{14}/cm^3$

$\Rightarrow$ To $\downarrow \rho \Rightarrow N_D \uparrow$

Q) A $1k\Omega$ resistor is to be fabricated as a narrow strip of p type Si with $4\,\mu m$ thick, $40\mu m$ width and $200\,\mu m$ length. Calculate density of the impurity atoms needed.

$$\text{Area} = 40\times10^{-4}\,cm \times 200\times10^{-4}\,cm$$
$$= 8\times10^{3}\times10^{-8}\,cm^2$$
$$= 8\times10^{-5}\,cm^2$$




$$R_p = \frac{\rho_p l}{A}$$

$$\rho_p = \frac{1K\times 8\times10^{-5}}{200\,\mu m} = \frac{10^3\times8\times10^{-5}}{200\times10^{-4}} = \frac{8\times10^{-2}}{2\times10^{-2}} = 4\,\Omega\text{-cm}$$

$$N_D = \frac{1}{1500\times4\times1.6\times10^{-19}}$$

$$N_D = 1.04\times10^{15}/cm^3$$

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$$2 \times 10^{-2}$$

$$= \frac{8}{10^{+2}} \Omega\text{-cm} = 0.08\ \Omega\text{-cm}$$

$$N_D = \frac{1}{500 \times 8 \times 1.6\times10^{-19} \times 10^{-2}}$$

$$= 1.56 \times 10^{17}/cm^3$$

Q) (a) In n-type Ge, donor concentration corresponds to 1 in $10^8$ Ge atoms. If the effective mass of the $e^-$ is half of its true mass, at room temperature, how far from the edge of the conduction band is the fermi level. Is $E_F$ below or above $E_C$.

$$m_n = \frac{1}{2}m \Rightarrow \frac{m_n}{m} = 0.5$$

$$N_C = 4.82\times10^{21} \cdot \left(\frac{m_n}{m}\right)^{3/2} \cdot T^{3/2} /m^3$$

$$= 8.85 \times 10^{24} = 8.85 \times 10^{18}/cm^3$$

$$E_C - E_F = KT \ln\left(\frac{N_C}{N_D}\right)$$ ; $N_D$ = atomic conc $\times$ no: of donor imp/Ge atoms
$= 4.4\times10^{22} \times 1/10^8 = 4.4\times10^{14}/cm^3$

$$E_C - E_F = 26m \ln\left(\frac{8.85\times10^{18}}{4.4\times10^{14}}\right)$$

$$= 0.02586 \times 9.909$$

$$E_C - E_F = 0.256\ eV$$

→ Fermi level is at a distance of 0.256eV from the edge of the conduction band.

→ $E_F$ is below $E_C$

$\Rightarrow E_C - E_F = -0.0414\ eV$

→ Fermi level is at a distance of 0.0414 eV from the edge of Conduction band.

→ $E_F$ is above $E_C$.

(c) Under what circumstances, will $E_F$ coincides with $E_C$

$\Rightarrow E_F = E_C$

If $N_C = N_D$ then fermilevel coincides with edge of Conduction band

$\Rightarrow 8.85\times10^{18} = $ Atomic concentration × no: of Donor atoms/Geatom

$\Rightarrow$ no: of donor impurity atoms/Geatoms $= \dfrac{8.85\times10^{18}}{4.4\times10^{22}}$

$= 2.01\times10^{-4}$

$\simeq \dfrac{2}{10^4}$

i.e. if doping concentration is 2 in $10^4$ Ge atoms, then fermi level coincides with the edge of the conduction band.

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$$E_F - E_V = KT \ln\left(\frac{N_V}{N_A}\right)$$

$$= 0.02586 \ln\left(\frac{8.818\times10^{18}}{4.22\times10^{19}}\right)$$

$$= -0.0404 \text{ eV}$$

→ Fermi level is at a distance of 0.0404 eV from the edge of the VB.

→ $E_F$ is below $E_V$

(c) Under what circumstances, will $E_F$ coincides with $E_V$.

$$\Rightarrow E_F = E_V$$

If $N_V = N_A$, fermi level coincides with $E_V$

$8.85\times10^{18} = AC \times$ no: of accepter impurity atoms/$cm^3$

$$\text{No: of accepter impurity atoms / Ge atom} = \frac{8.85\times10^{18}}{4.4\times10^{22}}$$

$$= 2.01\times10^{-4}$$

$$= \frac{2}{10^4}$$

i.e. if doping concentration is 2 in $10^4$ Ge atoms, then fermi level coincides with the edge of valence band.

Q) a) In p-type Si, accepter concentration corresponds to 1 in $10^8$ Si atoms, If the effective mass of the hole is half of its true mass at room temperature, how far from the edge of the valence band is the fermi level. Is $E_F$ above & below $E_V$?

$$N_V = 4.82\times10^{15}\left(\frac{m_p}{m}\right)^{3/2} T^{3/2} / cm^3$$

$$= 5 \times 10^{14} /cm^3$$

$$E_F - E_V = KT \ln\left(\frac{N_V}{N_A}\right)$$

$$= 0.02586 \ln\left(\frac{8.818 \times 10^{14}}{5 \times 10^{14}}\right)$$

$$= 0.2528 \text{ eV}$$

(b) Repeat part (a) for doping concentration of 1 in $10^3$ Si atoms.

$$N_V = 4.82 \times 10^{15} \times \left(\frac{m_p}{m}\right)^{3/2} T^{3/2}$$

$$= 4.82 \times 10^{15} \times (0.5)^{3/2} T^{3/2} = 8.818 \times 10^{18} /cm^3$$

$$N_A = 5 \times 10^{22} \times 1/10^3 /cm^3$$

$$= 5 \times 10^{19} /cm^3$$

$$E_F - E_V = KT \ln\left(\frac{N_V}{N_A}\right)$$

$$= 0.02586 \ln\left(\frac{8.818 \times 10^{18}}{5 \times 10^{19}}\right)$$

$$= -0.0448 \text{ eV}$$

→ Fermilevel is at a distance of 0.0448 eV from the edge of Valence Band.

→ $E_F$ is below $E_V$

(c) Under what circumstances will $E_F$ coincides with $E_V$.

⇒ $E_F = E_V$

If $N_V = N_A$, Fermilevel coincides with $E_V$.

$8.85 \times 10^{18} =$ AC × No. of Acceptor impurity atoms / Si atom

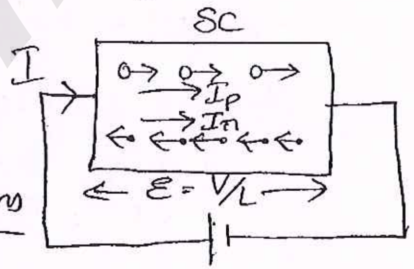
$I(drift)$: $I_{n(drift)}$, $I_{p(drift)}$

$I(diffusion)$: $I_{n(diff)}$, $I_{p(diff)}$

## Drift Current:

The current which is due to drifting of the carriers by the applied external electric field is called drift current.

$$I = I_{n(diff)} + I_{p(diff)}$$




## Drift Current Density due to electrons $J_{n(drift)}$:

$$J_{n(drift)} = ne\mu_n E$$

## Drift Current Density due to holes $J_p$ (drift:

$$J_p(drift) = pe\mu_p E$$

Total drift current density $J_{(drift)}$ :

$$J_{(drift)} = ne\mu_n E + pe\mu_p E$$

$$= (n\mu_n + p\mu_p)eE$$

Total drift current $I_{(drift)}$ :

$$I_{(drift)} = J_{(drift)} \times \text{Area}$$

$$I_{(drift)} = (n\mu_n + p\mu_p)eEA.$$

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$dx$ ... $x_1$ $x_2$

$D_p$ is diffusion constant for holes

$$D_p = 47\ cm^2/s \text{ for Ge}$$

$$D_p = 13\ cm^2/s \text{ for Si}$$

$$\frac{dP}{dx} = \frac{P_2 - P_1}{x_2 - x_1}$$

$100 - 80 \Rightarrow I_1$

$100 - 50 \Rightarrow I_2$

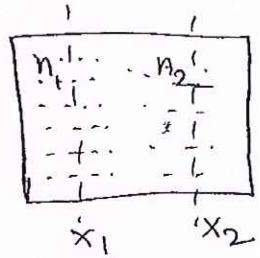
$I_2 > I_1$

Diffusion current density due to electrons

$$J_{n(diff)} = +eD_n \frac{dn}{dx}$$

($\because$ charge of $e^-$ is negative)

$$\left(\frac{dn}{dx}\right) = \frac{n_1 - n_2}{x_2 - x_1}$$




$$\frac{dn}{dx} = \frac{n_2 - n_1}{x_2 - x_1}.$$

Total diffusion current density

$$J_{diff} = J_{n(diff)} + J_{p(diff)}$$

$$J_{diff} = eD_n \frac{dn}{dx} - eD_p \frac{dP}{dx}$$

$D_n = 99\ cm^2/s$ for Ge

$D_n = 34\ cm^2/s$ for Si

Total Diffusion Current $\quad I_{diff} = J_{diff} \cdot A$

$$I_{diff} = \left(eD_n \frac{dn}{dx} - eD_p \frac{dp}{dx}\right) A$$

Total Current Density $\quad J = J_{drift} + J_{diff}$

$$J = \underbrace{(n\mu_n + p\mu_p)eE}_{\text{drift}} + \underbrace{\left[eD_n \frac{dn}{dx} - eD_p \frac{dP}{dx}\right]}_{\text{diffusion}}$$

Total Current $\quad I = \underbrace{(n\mu_n + p\mu_p)eEA}_{\text{drift}} + \underbrace{\left(eD_n \frac{dn}{dx} - eD_p \frac{dp}{dx}\right)}_{\text{diffusion}} A$

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$$\frac{D_n}{\mu_n} = \frac{D_p}{\mu_p} = V_T$$

n-Type: $\dfrac{D_n}{\mu_n} = V_T = 0.02586$

$$\Rightarrow \mu_n = \frac{D_n}{0.02586} \simeq 39 D_n$$

$$\Rightarrow \boxed{\mu_n = 39 D_n}$$

P-Type: $\dfrac{D_p}{\mu_p} = V_T = 0.02586$

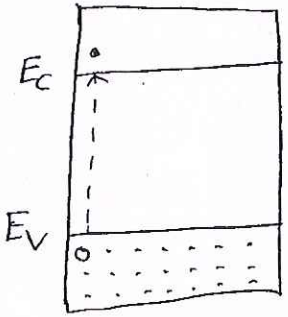
$$\Rightarrow \mu_p = \frac{D_p}{0.02586} \simeq 39 D_p$$

$$\Rightarrow \boxed{\mu_p = 39 D_p}$$

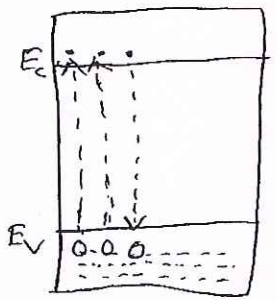
$$\Rightarrow \boxed{\mu = 39 D}$$

## Carrier Lifetime:

Thermal agitation continues to produce $e^-$-hole pairs, while $e^-$ and hole pairs disappears due to recombination. On an average, an $e^-$ or hole exists for $\tau_n$ & $\tau_p$ seconds before the recombination. This is called Carrier Life-time.




$e^-$-hole pair Generation




$e^-$-hole pair Recombination

→ Carrier Life time ranges from nanoseconds to microseconds.

$$\tau_n = \frac{L_n^2}{D_n} \Rightarrow L_n = \sqrt{\tau_n D_n}$$

where $L_n$ is diffusion length for an $e^-$ i.e, distance travelled by $e^-$ in its life time

$$\tau_p = \frac{L_p^2}{D_p} \Rightarrow L_p = \sqrt{\tau_p D_p}$$

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where $\Delta n$ is excess $e^-$ generation

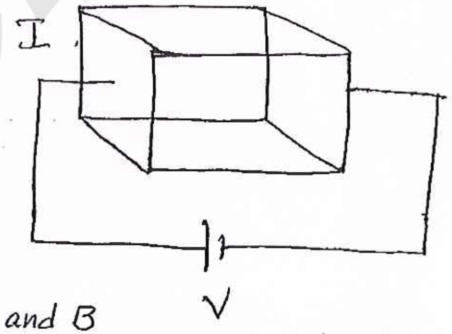
$\tau_p$ is minority carrier lifetime

If n & p is not given,

$$\tau = \frac{L^2}{D} \Rightarrow L = \sqrt{\tau D}.$$

## Hall Effect: (Faraday's law for Semiconductors)

When a specimen of a semiconductor carrying a current of I in the positive x-direction placed in a magnetic field B which is in positive z-direction, an electric field E induces perpendicular to both I and B in the negative y-direction.

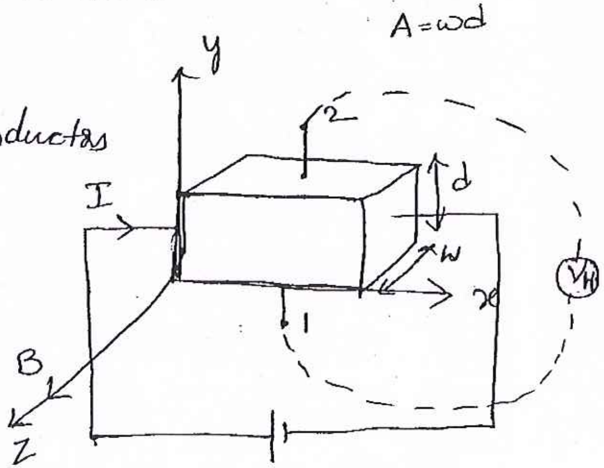



→ Hall effect is applicable to Semiconductors only.

→ It is used to find whether a semiconductor is n-type or p-type

→ To find carrier concentration.

→ Also used to calculate mobility by simultaneously measuring the conductivity.




$$E = \frac{V_H}{d} \quad \text{—①}$$

$$V_H = Ed = \text{Hall Voltage} \quad \text{—②}$$

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$$\rho v = J = \frac{I}{A}$$

$$\Rightarrow \rho v = \frac{I}{wd} \quad \text{—(4)}$$

$$\boxed{V_H = Ed = Bvd = \frac{BJd}{\rho} = \frac{BI}{\rho w}}$$

n-type:

$J_n = ne\mu_n E = nev_n = \rho v_n$

P-type:

$J_p = pe\mu_p E = pev_p = \rho v_p$ $\Big\} \rightarrow \rho v$

$J = \rho v \Rightarrow v = \frac{J}{\rho}$

$J = \frac{I}{wd} \Rightarrow Jd = \frac{I}{w}$

## Hall Coefficient (or) Hall Constant ($R_H$):

$R_H = \frac{1}{\rho}$ ($\rho$ is chargedensity but not resistivity)

$\Rightarrow R_H = \frac{V_H w}{BI} = \frac{1}{\rho}$ ; $cm^3/C$ & $m^3/C$ $\left(\because V_H = \frac{BI}{\rho w} \Rightarrow \frac{1}{\rho} = \frac{wV_H}{BI}\right)$

$R_H = \frac{1}{\rho} = \frac{1}{ne}$ $\frac{ele}{cm^3} \cdot C \Rightarrow \frac{cm^3}{elec \cdot C}$

$= \frac{1}{pe}$ ; $\frac{cm^3}{hole \cdot C}$

n-Type:

$\sigma_n = ne\mu_n = \rho\mu_n$

P-type

$\sigma_p = pe\mu_p = \rho\mu_p$ $\Big\} \dashrightarrow \sigma = \rho\mu$

$\sigma = \rho\mu \Rightarrow \mu = \sigma \cdot \frac{1}{\rho} \Rightarrow \boxed{\mu = \sigma R_H}$

$R_H = \frac{1}{\rho} = \frac{1}{ne} \Rightarrow n = \frac{1}{R_H q} /cm^3$

$p = \frac{1}{R_H q} /cm^3$

Induced Electric force $F_n = -q(v_n \times B)$ (for n-type)

$$E = \frac{F_n}{q} = -(v_n \times B)$$

$F_p = q(v_p \times B)$

$\Rightarrow E = F_p/q = (v_p \times B)$ (for p-type)

$$\mu = \sigma R_H$$

$$\sigma = \frac{1}{300\,K\text{-}\Omega\text{-cm}} = 3.33\times10^{-6}\ \mho/cm = 3.33\times10^{-4}\ \mho/m$$

$$R_H = \frac{V_H W}{BI} = \frac{60m \times 6\times10^{-3}}{0.1\times 10\times10^{-6}} = 360\ m^3/C$$

$$\mu_p = \sigma R_H = 0.11988 = 0.12\ m^2/V\text{-sec}$$

$$= 1200\ cm^2/V\text{-sec}$$

* Continuity Equation & Heiny-Shockley Experiment for IES.

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| | | |
|---|---|---|
| $(E_G)_{0K}$, eV | | 1.1 |
| Energy gap $(E_G)_{300K, eV}$ | — 0.72 | |
| Intrinsic Concentration $(n_i)/cm^3$ | — $2.5\times10^{13}$ | $1.5\times10^{10}$ |
| Intrinsic resistivity $\Omega$-cm | — 45 | 230K |
| Mobility of $e^-$ $(\mu_n)$ $cm^2/V\text{-}s$ | 3800 | 1300 |
| Mobility of holes $(\mu_p)$ $cm^2/V\text{-}s$ | — 1800 | 500 |
| $D_n$; $cm^2/s$ | — 99 | 34 |
| $D_p$; $cm^2/s$ | — 47 | 13 |

→ In n-type silicon, donor concentration is 1 atom / $2\times10^8$ Si atom. Assuming that the effective mass of the $e^-$ equals to its true mass. At what temperature will the fermilevel coincides with the edge of conduction band.

$$N_D = \frac{1}{2\times10^8} \text{ atoms}/cm^3 \times \text{atomic concentration of Si atoms}$$

$$\Rightarrow N_D = 2.5\times10^{14}/cm^3$$

$$m_n = m$$

$E_F = E_C \Rightarrow$ fermilevel coincides with conduction band

$$\boxed{N_C = N_D}$$

$$E_C - E_F = KT \ln\left(\frac{N_C}{N_D}\right)$$

$$N_C = 4.82\times10^{15} \times \left(\frac{m_n}{m}\right)^{3/2} \times T^{3/2}$$

$$N_C = 4.82\times10^{15} \times T^{3/2}$$

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→ In an n-type semiconductor fermi level lies 0.3eV below the conduction band at 300K. If the temperature is increased to 330K, find the new position of the fermi level.

$$E_C - E_F = 0.3\,eV \; ; \; T = 300K$$

$$E_C - E_F = KT \ln\left(\frac{N_C}{N_D}\right)$$

$$0.3 = 0.02586 \ln\left(\frac{N_C}{N_D}\right)$$

$$\ln\left(\frac{N_C}{N_D}\right) = 11.6$$

$$E_C - E_F = KT \ln\left(\frac{N_C}{N_D}\right)$$

$$= 8.85 \times 10^{-5} \times 330 \times 11.6$$

$$= 0.338\,eV$$

(or)

$$E_C - E_F \propto T$$

$$\Rightarrow \frac{(E_C - E_F)_{300}}{(E_C - E_F)_{330}} = \frac{T_1}{T_2}$$

$$\Rightarrow E_C - E_F = 0.33\,eV$$

→ If the effective mass of an $e^-$ is equal to thrice the effective mass of a hole, find the distance of the fermi level in an intrinsic semiconductor from the centre of the forbidden band at room temperature.

$$m_n = 3m_p$$

$$\frac{m_n}{m_p} = 3$$

$$KT \ln\left(\frac{N_C}{N_V}\right) = \frac{0.02586}{2} \ln\left(3^{3/2}\right)$$

$$= 0.021\,eV$$

$$E_{F_i} = E_F = \frac{E_C + E_V}{2} - \frac{KT}{2} \ln\left(\frac{N_C}{N_V}\right)$$

i.e, Fermi level lies ~~above~~ below the centre at a distance of 0.021eV

$= 10^{20}$ e-h pair/cm$^3$/sec

→ A Si sample is uniformly doped with $10^{16}$ phosphorous atoms/cm$^3$ and $2\times10^{16}$ Boron atoms/cm$^3$. If all the dopants are fully ionised, the material is ....

a) n-type with a carrier concentration of $10^{16}$/cm$^3$

✓b) p-type " " $10^{16}$/cm$^3$

c) n-type " " $2\times10^{16}$/cm$^3$

d) p-type " " $2\times10^{16}$/cm$^3$

$N_A > N_D \Rightarrow$ p-type

$p = N_A - N_D$ if doping concentration $(N_A - N_D) >> n_i$

$\therefore p = (2\times10^{16} - 10^{16})$ atoms/cm$^3$

$\Rightarrow p = 10^{16}$ atoms/cm$^3$ (or) use $\left(\frac{N_A - N_D}{2}\right) + \sqrt{\left(\frac{N_A - N_D}{2}\right)^2 + n_i^2}$

→ A small concentration of minority carriers are injected into a semiconductor crystal at one point. An electric field of 10V/cm is applied across the crystal and this moves the minority carriers a distance of 1 cm in 20 μs. The mobility of the carriers is.

$E = 10V/cm$

$V_d = \mu E \Rightarrow \mu = \frac{1cm/20\times10^{-6}}{10} = 5000$ cm$^2$/V-sec

$= 0.1\,cm$

→ $e^-$ mobility and life time in a semiconductor at room temperature are $0.36\,m^2/V\text{-}s$ and $340\,\mu s$. Diffusion length is

$* \mu = 39D *$

$$D = \frac{0.36}{39} = 9.23 \times 10^{-3}$$

$$L = \sqrt{9.23 \times 10^{-3} \times 340 \times 10^{-6}}$$

$$= 1.77 \times 10^{-3}\,m$$

$$L = 1.77\,mm$$

→ The Hall constant in a p-type Si ball is given by $5 \times 10^3\,cm^3/C$. The hole concentration in ball is

$$R_H = \frac{1}{\rho} = \frac{1}{pe} \Rightarrow p = \frac{1}{R_H e} = 1.25 \times 10^{15}/cm^3$$

→ Two pure specimens of a semiconductor materials are taken one is doped with $10^{18}/cm^3$ no: of donors and the other is doped with $10^{16}/cm^3$ no: of acceptors. The minority carrier density in first specimen is $10^7/cm^3$. What is the minority carrier density in the other specimen.

$n_1 = 10^{18}/cm^3$ $\quad\quad$ $P_2 = 10^{16}/cm^3$

$P_1 = 10^7/cm^3$ $\quad\quad$ $n_2 = ?$

According to mass action law, $np = n_i^2$

$$n_1 P_1 = n_2 P_2 \Rightarrow n_2 = \frac{n_1 P_1}{P_2} = 10^9/cm^3$$

$= -0.416\ mA/cm^2$

→ A heavily doped n-type semiconductor has the following data: Hole – $e^-$ mobility ratio $= \frac{\mu_p}{\mu_n} = 0.4$

Doping Concentration $= 4.2\times10^8/m^3$

Intrinsic Concentration $= 1.5\times10^4/m^3$

The ratio of conductivity of the n-type semiconductor to that of the intrinsic semiconductor of same material under the same temperature is given by

$$\sigma = \rho\mu$$

$$\frac{\mu_p}{\mu_n} = 0.4 ;\quad N_D = 4.2\times10^8/m^3 \simeq n$$

$$n_i = 1.5\times10^4/m^3$$

$$\frac{\sigma_n}{\sigma_{ni}} = \frac{n\cancel{e}\mu_n}{n_i(\mu_n+\mu_p)\cancel{e}} = \frac{n\mu_n}{(\mu_n+0.4\mu_n)n_i} = 20{,}000$$

$$= \frac{4.2\times10^8}{1.4\times1.5\times10^4}$$

→ $e^-$ concentration in a sample of uniformly doped n-type Si at 300K varies linearly from $10^{17}/cm^3$ at $x=0$ to $6\times10^{16}/cm^3$ at $x = 2\ \mu m$. If $e^-$ charge is $1.6\times10^{-19}$ C and Diffusion constant $D_n = 35\ cm^2/sec$, the $J_n$ in Si if no electric field is present is

$$J_n = e D_n \frac{dn}{dx}$$

$$= 1.6\times10^{-19}\times35\times\frac{10^{17}-6\times10^{16}}{2\times10^{-4}-0}$$

$$= 1120\ A/cm^2$$

$$= 25\times10^{-3}\times \ln\left(\frac{4\times10^{17}}{1.5\times10^{10}}\right)$$

$$= 0.427\,eV$$

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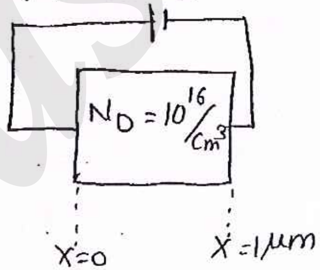
→ A Si sample with unit cross sectional area shown below is in thermal equilibrium. The following information is given $T = 300K$; electric charge $= 1.6\times10^{-19}C$, Thermal voltage $V_T = 26mV$ and $e^-$ mobility $1350\ cm^2/V\text{-}sec$.




$V = 1V,\ L = 1\mu m$

$E = V/L = 10^6$

$J = neμE$

$v = μE$

1) The magnitude of electricfield at $x = 0.5\ \mu m$ is:

a) 1kV/m b) 5kV/m c) 10kV/m d)

$$E = V/L = 1/1\mu m = 10^6\,V/m$$

$$= 10^4\,V/cm$$

$$= 10\,KV/cm$$

* Electric field remains same at any point. It is independent of Length.

2) The magnitude of the $e^-$ drift current density at $x = 0.5\mu m$ is

$$J_n = N_D e \mu E$$

$$= 10^{16}\times1.6\times10^{-19}\times 1350\times 10\times10^{3}$$

$$= 21600\ A/cm^2$$

$$= B \times \vartheta$$

→ A Si sample A is doped with $10^{18}$ atoms/cm³ of Boron. Another sample B of identical dimensions is doped with $10^{18}$ atoms/cm³ of Phosphorous. The ratio of $e^-$ to hole mobility is 3. The ratio of conductivity of the sample A to B is

$N_A = P = 10^{18}$ atoms/cm³

$N_B = n = 10^{18}$ atoms/cm³

$\vartheta = \cancel{ne}\, \mu E$

$\sigma = ne\mu$

$$\frac{\sigma_A}{\sigma_B} = \frac{\mu_p n_A}{\mu_n n_B} = \frac{1}{3} \times \frac{10^{18}}{10^{18}} = \frac{1}{3} \,//$$

→ The resistivity of a uniformly doped n-type silicon sample is 0.5 Ω-cm. If the $e^-$ mobility is 1250 cm²/V-sec, and the charge of an $e^-$ is $1.6 \times 10^{-19}$ C, the donor impurity concentration in the sample is

$\rho_n = 0.5\ \Omega\text{-cm}$

$$\rho_n = \frac{1}{N_D e \mu_n}$$

$$\Rightarrow N_D = \frac{1}{0.5 \times 1.6 \times 10^{-19} \times 1250} = 1 \times 10^{16} / cm^3$$

→ The intrinsic carrier concentration in Si is to be no greater than $n_i = 1 \times 10^{12}$ /cm³. The maximum temperature allowed for Si is

a) 300K b) 360K c) 399K d) 381K ✓

Given $E_G = 1.12$ eV

$\Rightarrow T = 250K$ But

$$(1\times 10^{12})^2 = 2.33\times 10^{31}\left[\frac{m_n m_p}{m^2}\right]^{3/2} \cdot T^{3} \cdot e^{-E_G/KT}$$

$$10^{24} = 2.33\times 10^{31}\left[\frac{1.08\times 0.56 \cdot m^2}{m^2}\right]^{3/2} \cdot T^{3} \cdot e^{-1.12/KT}$$

$$\boxed{K = 8.6\times 10^{-5}}$$

$$\cancel{e^{1.12/KT} \cdot T^{3} = 10958067.32}$$

$$\Rightarrow e^{-1.12/KT} \cdot T^{3} = 9.125\times 10^{-8}$$

$$-\frac{1.12}{KT} + 3\ln T = -16.21$$

$$3\ln T = -16.21 + \frac{13023}{T}$$

$T = 300K \Rightarrow 17.11 \neq 27.2$

$T = 360K \Rightarrow 5.88 \neq 19.96$

$T = 399K \Rightarrow 17.96 \neq 16.42$

✓ $T = 381 \Rightarrow 17.82 = 17.97$

$$\Rightarrow T = 381K$$

→ Two semiconductor materials have exactly the same properties except that material A has a band gap of 1eV. and material B has a band gap energy of 1.2eV. The ratio of Intrinsic concentration of material A to that of material B is

$$\frac{n_1}{n_2} = \frac{e^{-E_{G_1}/2KT}}{e^{-E_{G_2}/2KT}}$$

$$= \frac{\cancel{5.798\times 10^{-10}}}{8.386\times 10^{-11}} = \cancel{6.91}$$

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$n_{iB}$

→ In Si, at $T = 300K$ if the fermi energy level is 0.22eV above the valence band energy, calculate hole concentration

$$\cancel{E_F - E_V = KT \ln\left(\frac{N_V}{N_A}\right)} \Rightarrow \quad p = N_V e^{-(E_F - E_V)/KT}$$

$$N_V = 4.82 \times 10^{15} \left(\frac{m_p}{m}\right)^{3/2} T^{3/2}$$

$$= 4.82 \times 10^{15} \left(\frac{0.56m}{m}\right)^{3/2} 300^{3/2}$$

$$= 1.0496 \times 10^{19}$$

$$0.22 = 0.02586 \ln\left(\frac{1.0496 \times 10^{19}}{N_A}\right)$$

$$p = N_V e^{-(E_F - E_V)/KT}$$

$$= 2.12 \times 10^{+15} / cm^3$$

→ In Ge semiconductor, at $T = 300K$, the $N_A$ is $10^{13}/cm^3$ and donor concentration $N_D = 0$. Calculate thermal equilibrium concentration of $e^-$ and holes.

$N_A = 10^{13}/cm^3$

$N_D = 0$

$T = 300K$

$n_i$ in Ge $= 2.5 \times 10^{13}/cm^3$

$$np = n_i^2$$

$$p = \frac{N_A - N_D}{2} + \sqrt{\left(\frac{N_A - N_D}{2}\right)^2 + n_i^2}$$

$$\cancel{p = \frac{N_A - N_D}{2} + \frac{N_A - N_D}{2} = N_A - N_D}$$

$$\Rightarrow p = 3 \times 10^{13} / cm^3$$

is to be $10^{-6}$ cm$^2$. and also the doping efficiency is known to be 90%. Calculate doping needed. Assume $\mu_n = 8000$ cm$^2$/V-sec

$R = 2k\Omega$, $L = 20\mu m$, $A = 10^{-6}$ cm$^2$

$$R = \frac{\rho L}{A} \Rightarrow \rho = \frac{RA}{L} = \frac{2\times10^3 \times 10^{-6}}{20\times10^{-4}} = 1$$

$$\rho = \frac{1}{ne\mu}$$ doping efficiency = 90%.

$\Rightarrow n = 0.9 N_D$

$$\Rightarrow 1 = \frac{1}{0.9 N_D \times 1.6\times10^{-19} \times 8000}$$

$$\Rightarrow N_D = 8.68\times10^{14} /cm^3$$

→ A Si sample doped n-type at $10^{18}/cm^3$ have a resistance of $10\Omega$. The sample has an area of $10^{-6}$ cm$^2$ and a length of 10 μm. The doping efficiency of the sample is Assume $\mu_n = 800$ cm$^2$/V-sec

$R = 10\Omega$, $L = 10^{-3}$cm, $A = 10^{-6}$ cm$^2$, $N_D = 10^{18}$

$$R = \frac{\rho L}{A} \Rightarrow \rho = \frac{RA}{L} = \frac{1}{100}\ \Omega\text{-cm}$$

$\rho = \frac{1}{ne\mu}$ =

A

$\rho = \frac{1}{ne\mu} \Rightarrow n = \frac{1}{\rho e \mu} = 7.8125 \times 10^{17} /cm^3$

Doping Efficiency $= \frac{n}{N_D} \times 100 = \frac{7.8 \times 10^{17}}{1 \times 10^{18}} \times 100$

$= 78\ \%$

→ Three scattering mechanisms exist in a semiconductor if only the first mechanism was present, the mobility would be $500\ cm^2/V\text{-}sec$, if only second mechanism was present, $\mu_2$ would be $750\ cm^2/V\text{-}se$, if only third mechanism was present, $1500\ cm^2/V\text{-}sec$. Then the net mobility is

$$\frac{1}{\mu} = \frac{1}{\mu_1} + \frac{1}{\mu_2} + \frac{1}{\mu_3}$$

$$= \frac{1}{500} + \frac{1}{750} + \frac{1}{1500}$$

$$\Rightarrow \frac{1}{\mu} = \frac{1}{250} \Rightarrow \mu = 250\ cm^2/V\text{-}sec$$

→ 6V is applied across a 2 cm long semiconductor bar the average drift velocity is $10^4$ cm/sec. Then the $e^-$ mobility is

$E = \frac{6}{2} = 3\ V/cm$

$v = \mu E$

$$\mu = \frac{v}{E} = \frac{10^4}{6/2} = \frac{10^4}{3} = 3.333 \times 10^3\ cm^2/V\text{-}sec$$

→ In a GaAs sample, the $e^-$ are moving under an electric field of 5 kV/cm and the carrier concentration is uniform at $10^{16}/cm^3$. The $e^-$ velocity is the saturated velocity of

→ For a sample of [illegible], scattering time $\tau_{sc}$ = 10 sec and $e^-$ effective mass $m_n = 0.067\,m$. If an electric field of 1 KV/cm is applied, the drift velocity produced is

$$\mu = \frac{e\tau_{sc}}{m_n}$$

$$v = \mu E$$

$$= \frac{e\tau_{sc}}{m_n} \times E$$

$$= \frac{1.6\times10^{-19} \times 10^{-13} \times 1000}{0.067 \times 9.1\times10^{-28}}$$

$$= 262.42 \times 10^{-3}\ \text{cm/sec}$$

$$= 0.2624\ \text{cm/sec}.$$

→ An n-type Ge sample is 2mm wide and 0.2 mm thick. A current of 10mA is passed through the sample (x-direction) and a magnetic field of $0.1\ wb/m^2$ is directed perpendicular to the current flow (z-direction). The developed Hall voltage is 1mV. Calculate Hall coefficient and $e^-$ concentration.

$$R_H = \frac{V_H W}{BI} = \frac{1\times\cancel{10^{-3}} \times 2\times10^{-3}}{0.1 \times \cancel{10^{-3}}\times10} = 2\times10^{-3}\ m^3/C$$

$$R_H = \frac{1}{ne} \Rightarrow n = \frac{1}{2\times10^{-3}\times1.6\times10^{-19}}$$

$$\Rightarrow n = 3.125\times10^{21}\ /m^3$$

$$= 3.125\times10^{15}\ /cm^3$$

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$$\sigma = ne\mu$$

$$= n_i e(\mu_n + \mu_p)$$

$$= 1.6 \times 10^{16} \times 1.6 \times 10^{-19} \times (1250 + 480)$$

$$= 4.4288 \times 10^{-4}\ (\Omega\text{-}m)^{-1}$$

$N_D = 10^{23}\ \text{atoms}/m^3 \simeq n$

$$E_F - E_{F_i} = KT \ln\left(\frac{N_D}{n_i}\right) = +0.404\,eV$$

$np = n_i^2$

$$\Rightarrow p = \frac{n_i^2}{N_D} = 2.56 \times 10^{9}/m^3$$

Conductivity $\sigma_n = (n_n \mu_n + P_n \mu_p) q$ & $\sigma_n = n_n \mu_n q$

$$= (10^{23} \times 0.125 + 2.56 \times 10^{9} \times 0.048)\, 1.6 \times 10^{-19}$$

$$= 2000\ (\Omega\text{-}m)^{-1}$$

→ A Si body is doped with $10^{17}$ As atoms/$cm^3$. What is the equilibrium hole concentration at 300K. Where is the fermi level of the sample located relative to intrinsic fermi level; it is known that $n_i = 1.5 \times 10^{10}/cm^3$

$np = n_i^2$

$N_D >> n_i$

$$\Rightarrow p = \frac{n_i^2}{N_D} = 2250$$

$$E_F - E_{F_i} = KT \ln\left(\frac{N_D}{n_i}\right) = 0.406\,eV$$

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$R = 100\,\Omega$

$L = 10\,cm$

$A = 1\times(10^{-3})^2$

$= 1\times10^{-6}\times10^{-4}\ m^2$

$= 1\times10^{-2}\ cm^2$

$\mu_n = 1350$

$\rho = \frac{RA}{L}$

$\rho = 100\times10^{-2}$

$= 1\ (\Omega\text{-cm})$

$\rho = \frac{1}{ne\mu} \Rightarrow n = \frac{1}{\rho e\mu}$

$n = 4.62\times10^{15}/cm^3$

→ In an n-type semiconductor at $T = 300K$, the $e^-$ concentration varies linearly from $2\times10^{18}$ to $5\times10^{17}/cm^3$ over a distance of 1.5 mm and diffusion current density is $360\ A/cm^2$. Find the mobility of $e^-$

$J_n = eD_n\frac{dn}{dx}$

$\Rightarrow D_n = \frac{360}{\frac{(2\times10^{18}-5\times10^{17})}{1.5\times10^{-1}cm}\times1.6\times10^{-19}} = \frac{360}{\frac{15\times10^{17}}{0.15}\times1.6\times10^{-19}}$

$= 225\ cm^2/sec$

$\mu = 39\,D_n$

$= \cancel{58500}\ cm^2/V\text{-sec}$

$= 8775$

→ In intrinsic GaAs, the $e^-$ and hole mobilities are $0.85\ m^2/V\text{-sec}$ and $0.04\ m^2/V\text{-sec}$ and corresponding effective masses are $0.068\,m_0$ and $0.5\,m_0$ respectively where $m_0$ is the rest

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$$= 4.44 \times 10^{17} /m^3$$

$$N_V = 4.82 \times 10^{15} \left(\frac{m_p}{m}\right)^{3/2} T^{3/2}$$

$$= 8.85 \times 10^{18} /m^3$$

$$n_i^2 = 2.33 \times 10^{31} \times \left(\frac{m_n m_p}{m^2}\right)^{3/2} T^3 e^{-E_G/KT} /cm^3$$

$$= 3.806 \times 10^{12} /cm^3$$

$$n_i = 1.9 \times 10^6 /cm^3$$

Conductivity $\sigma_i = n_i e (\mu_n + \mu_p)$

$$= 1.9 \times 10^6 \times 1.6 \times 10^{-19} \times (8500 + 400)$$

$$= 2.7 \times 10^{-9} (\Omega - cm)^{-1}$$

→ The intrinsic resistivity of Ge at room temperature is (44.6 Ω-cm; 0.47 (Ω-m). The $e^-$ and hole mobilities at room temperature are $0.39 \, m^2/V\text{-sec}$ and $0.9 \, m^2/V\text{-sec}$. Calculate the density of $e^-$ in the intrinsic semiconductor and also calculate drift velocities of charge carriers for a field of 10 KV/m

$\rho = 0.47 \Rightarrow \sigma = \frac{1}{\rho} = n_i e \mu$

$$n_i e (\mu_n + \mu_p) = \frac{1}{0.47}$$

$$n = p = n_i = \frac{1}{0.47 \times 1.6 \times 10^{-19} \times (0.39 + 0.9)}$$

$$= 2.29 \times 10^{19} /m^3 = 2.29 \times 10^{13} /cm^3$$

$$v_n = \mu_n E$$

$$= 0.39 \times 10 \times 10^3$$

$$= 3.9 \times 10^3 \, m/sec$$

$$v_p = \mu_p E$$

$$= 0.9 \times 10 \times 10^3$$

$$= 9 \times 10^3 \, m/sec$$

$$\Rightarrow 4\mu_p = \frac{1}{\rho n_i e} \Rightarrow \frac{1}{4\times 3000 \times 1.6\times 10^{-19} \times 1.1\times 10^{6}}$$

$$= 4734.8485 \times 10^{5}\ m^2/V\text{-sec}$$

$$\mu_n = 3\mu_p = 1420.4545 \times 10^{6}\ m^2/V\text{-sec}$$

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→ A semiconductor has the following data

$$\mu_n = 7500\ cm^2/V\text{-}s$$

$$\mu_p = 300\ cm^2/V\text{-}s$$

$$n_i = 3.2\times 10^{9}\ cm^2/V\text{-sec}$$

i) When conductivity is minimum, calculate hole concentration

$$\sigma = (n\mu_n + p\mu_p)q$$

$$np = n_i^2 \Rightarrow n = n_i^2/p$$

$$\sigma = \left(\frac{n_i^2}{p}\mu_n + p\mu_p\right)q$$

$$\frac{d\sigma}{dp} = -\frac{n_i^2}{p^2}\mu_n q + \mu_p q$$

$$\frac{d\sigma}{dp} = 0 \Rightarrow -\frac{n_i^2}{p^2}\mu_n q + \mu_p q = 0$$

$$\Rightarrow \frac{n_i^2}{p^2}\mu_n = \mu_p$$

$$\Rightarrow p^2 = n_i^2 \frac{\mu_n}{\mu_p}$$

$$\Rightarrow \boxed{p = n_i\sqrt{\frac{\mu_n}{\mu_p}}}$$

$$P_{min} = n_i\sqrt{\frac{\mu_n}{\mu_p}}$$

$$P_{min} = 3.2\times 10^{9}\sqrt{\frac{7500}{300}} = 1.6\times 10^{10}/cm^3.$$

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$$\sigma_{min} = 2 \times 3.2 \times 10^9 \times \sqrt{7500 \times 300} \times 1.6 \times 10^{-19}$$

$$= 1.5 \times 10^{-6} (\Omega\text{-cm})^{-1}$$

iii) Calculate intrinsic conductivity.

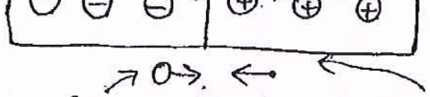
$$\sigma_i = n_i(\mu_n + \mu_p) q$$

$$= 3.2 \times 10^9 \, (7500 + 300) \, 1.6 \times 10^{-19}$$

$$= 3.99 \times 10^{-6}$$

$$\frac{P}{n_i} = \frac{1.6 \times 10^{10}}{3.2 \times 10^9} = 5$$

$$\frac{\sigma_{min}}{\sigma_i} = \frac{1.5 \times 10^{-6}}{3.99 \times 10^{-6}} = 0.37$$



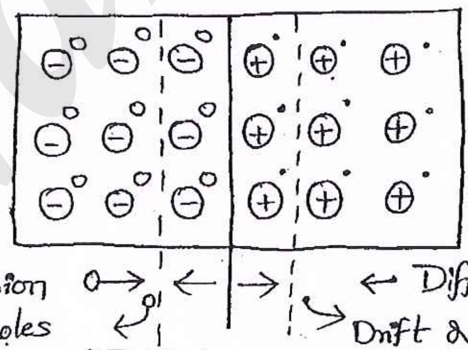
Diffusion force on holes $\oplus^{\cdot} \rightarrow \cdot \Rightarrow \oplus$ Diffusion force on electrons

$\ominus^{\circ} \rightarrow \circ \Rightarrow \ominus$

→ Donor ions represented with +ve sign, because after donating $e^-$, donor atoms become +ve ions.

→ Acceptor ions are represented with -ve sign because after accepting $e^-$, acceptor atoms becomes -ve ions.

| Direction of Charge carriers | Type of Carriers | Direction of Current |
|---|---|---|
| → | Hole - diffusion | → $J_p$ (diff) |
| ← | $e^-$ diffusion | → $J_n$ (diff) |




| | | |
|---|---|---|
| ← - - | hole drift | ← - - $J_p$ (drift) |
| - - → | electron drift | ← - - $J_n$ (drift) |

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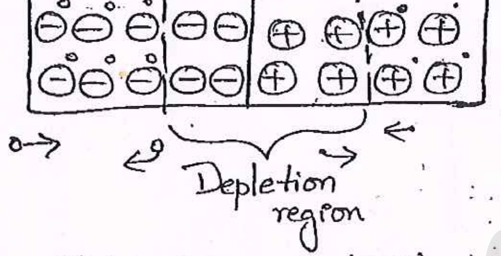


Here $J_p(\text{drift}) = J_p(\text{diff})$

$J_n(\text{drift}) = J_n(\text{diff})$

→ Depletion region is also called space charge region (or) Transition region.

→ In normal p-n junction diodes, the width of the depletion region is in the order of $\mu m$.

→ The width of the depletion region is inversely proportional to the square root of doping concentration.

$$W \propto \sqrt{\left(\frac{1}{N_A} + \frac{1}{N_D}\right)}$$

→ In normal p-n junction diodes, the doping concentration is 1 impurity atom per $10^8$ Si & Ge atoms.

→ In Zener diode, the doping concentration is 1 impurity atom per $10^5$ Si & Ge atoms.

→ In Tunnel diode, the doping concentration is 1 impurity atom per $10^3$ Si & Ge atoms.

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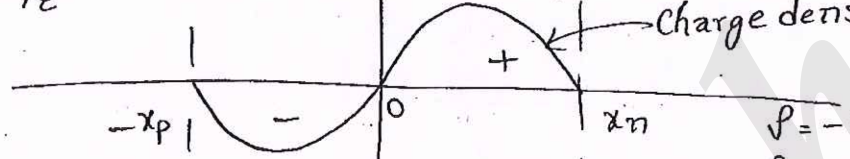
$\frac{d^2V}{dx^2} = -\rho/\varepsilon$



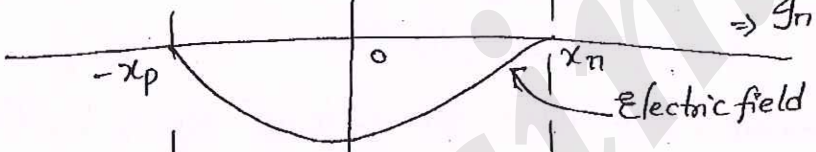

$\rho = -N_A e \; ; \; -x_p < x < 0$

$\rho = N_D e \; ; \; 0 < x < x_n$

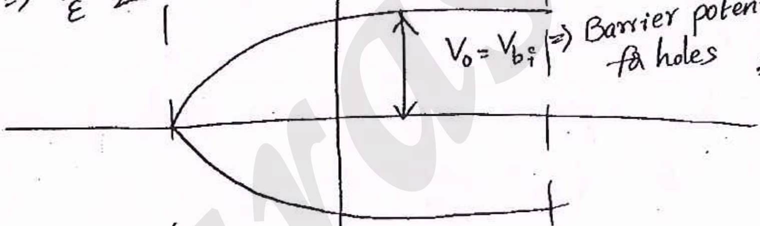
$E = \int \rho/\varepsilon \, dx$

$= \rho/\varepsilon \, x$

⇒ Integrating above $\rho$




$V = -\int \frac{\rho}{\varepsilon} x \Rightarrow -\frac{\rho}{\varepsilon}\frac{x^2}{2}$




⇒ Barrier potential fr holes

⇒ Integrating again above 'E'

Poisson's Equation:

$\nabla^2 V = -\rho/\varepsilon$

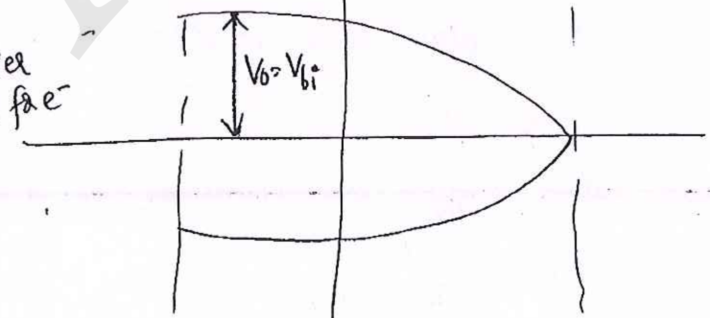
(or) $\nabla^2 \phi = -\rho/\varepsilon$

Laplace Equation

$\nabla^2 V = 0$

(or) $\nabla^2 \phi = 0$

Barrier potential fr $e^-$

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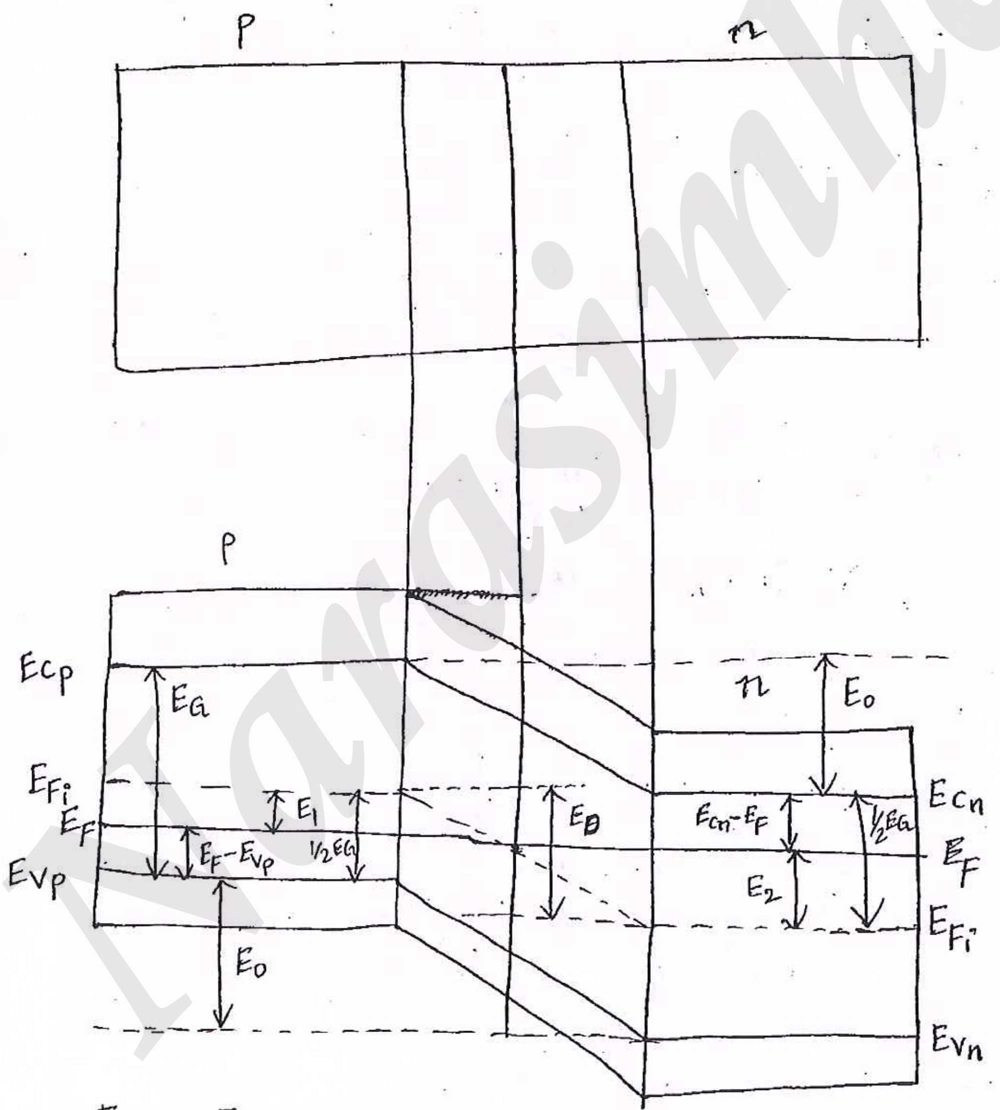


$$E_0 = E_{Cp} - E_{Cn} = E_{Vp} - E_{Vn} = E_1 + E_2$$

$$E_F - E_{Vp} = \frac{1}{2}E_G - E_1 \Rightarrow E_1 = \frac{1}{2}E_G - (E_F - E_{Vp}) \quad \text{— ①}$$

$$E_{Cn} - E_F = \frac{1}{2}E_G - E_2 \Rightarrow E_2 = \frac{1}{2}E_G - (E_{Cn} - E_F) \quad \text{— ②}$$

$$E_0 = E_1 + E_2 = E_G - (E_{Cn} - E_{Vp})$$

$$E_0 = KT \ln\left(\frac{\quad}{n_i^2}\right) \ldots \left(\ldots N_A\right) \ldots N_D)$$

$$= KT\left[\ln\left(\frac{N_C N_V}{n_i^2}\right) - \ln\left(\frac{N_V}{N_A}\right) - \ln\left(\frac{N_C}{N_D}\right)\right]$$

$$= KT \ln\left(\frac{\cancel{N_C}\cancel{N_V}}{n_i^2} \cdot \frac{N_A}{\cancel{N_V}} \cdot \frac{N_D}{\cancel{N_C}}\right)$$

$$\Rightarrow \boxed{E_0 = KT \ln\left(\frac{N_A N_D}{n_i^2}\right) eV}$$

$$eV_0 = E_0$$

$$\cancel{e}V_0 = KT \ln\left(\frac{N_A N_D}{n_i^2}\right) \cancel{e}V$$

$$\boxed{V_0 = KT \ln\left(\frac{N_A N_D}{n_i^2}\right) \text{ volts}}$$

$\boxed{M2}$

$$E_0 = E_1 + E_2$$

$$E_1 = E_{F_i} - E_F = KT \ln\left(\frac{N_A}{n_i}\right)$$

$$E_2 = E_F - E_{F_i} = KT \ln\left(\frac{N_D}{n_i}\right)$$

$$E_0 = KT \ln\left(\frac{N_A}{n_i}\right) + KT \ln\left(\frac{N_D}{n_i}\right)$$

$$\boxed{E_0 = KT \ln\left(\frac{N_A N_D}{n_i^2}\right) eV}$$

$V_0 = 0.6\,V$ & $0.7\,V$ for Si

$V_0 = 0.2\,V$ & $0.3\,V$ for Ge

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$$\frac{dV_0}{dT} = \frac{V_{02} - V_{01}}{T_2 - T_1} = -2.5\ mV/^\circ C$$

$$\Rightarrow V_{02} - V_{01} = -(T_2 - T_1)\ 2.5\ mV/^\circ C$$

$$\Rightarrow \boxed{V_{02} = V_{01} - (T_2 - T_1)\ 2.5\ mV/^\circ C}$$

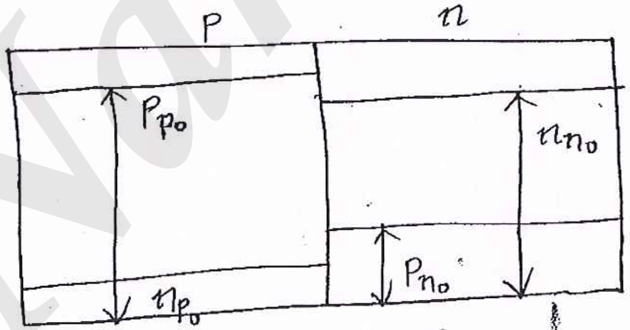
a) 700 mV at 20°C, then at 40°C ?

$$V_{02} = V_{01} - (T_2 - T_1)\ 2.5\ mV/^\circ C$$

$$= 700 - (40 - 20)\ 2.5\ mV/^\circ C$$

$$= 700 - (20)(2.5)\ mV/^\circ C$$

$$= 650\ mV$$




($\because$ As mobility of $\mu_p$ is less than $\mu_n$)
The doping concentration for p-type should be more than n-type and so minority carriers are less in p-type (doping more)

$P_{p_0}$
$n_{p_0}$

$n_{n_0}$
$P_{n_0}$

$$n_{p_0} \cdot P_{p_0} = n_i^2 \qquad n_{n_0} \cdot P_{n_0} = n_i^2$$

$$n_{p_0} = \frac{n_i^2}{P_{p_0}} = \frac{n_i^2}{N_A} \qquad P_{n_0} = \frac{n_i^2}{n_{n_0}} = \frac{n_i^2}{N_D}$$

$(\because P_{p_0} \simeq N_A)$ $\qquad$ $(\because n_{n_0} \simeq N_D)$

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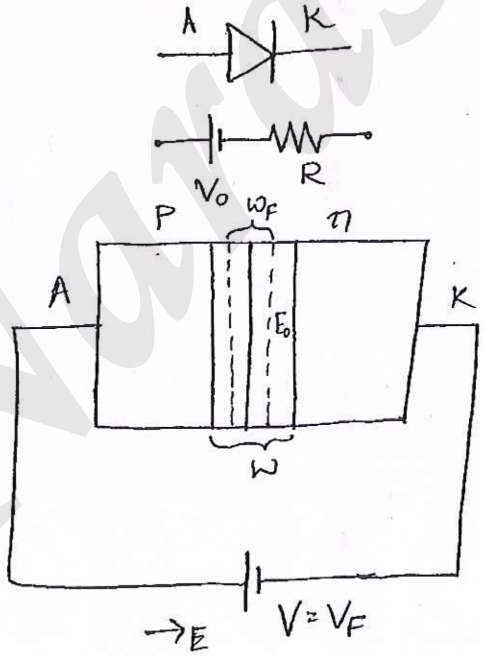
$$= KT \ln \left( \frac{N_D}{(n_i^2/N_A)} \right)$$

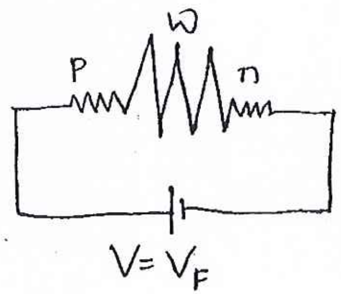
$$\boxed{V_0 = KT \ln \left( \frac{n_{n0}}{n_{p0}} \right)}$$

$$\boxed{\therefore V_0 = V_{bi} = KT \ln \left( \frac{N_A N_D}{n_i^2} \right) = KT \ln \left( \frac{P_{p0}}{P_{n0}} \right) = KT \ln \left( \frac{n_{n0}}{n_{p0}} \right)}$$

Forward Bias:

Schematic Diagram




$$E = \frac{V}{W}$$

$$\boxed{W_F < W}$$

$$E_j = E_0 - E$$

$$\boxed{V_j = V_0 - V = V_0 - V_F}$$

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$-\quad +$

$V=V_R$

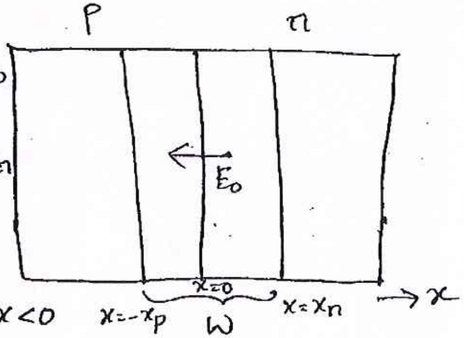
$V_j$ = Junction Voltage

$E_j = E_0 + E$

$$\boxed{V_j = V_0 + V = V_0 + V_R}$$

## p-n junction Depletion Region Width:

### Forward Bias:




Charge density in p-side : $\rho = -N_A e; \ -x_p < x < 0$

Charge density in n-side: $\rho = N_D e; \ 0 < x < x_n$

Electric field in P-side $(E) = \int \frac{\rho}{\varepsilon} dx; \quad -x_p < x < 0$

$$= \int (-)\frac{eN_A}{\varepsilon} dx; \quad -x_p < x < 0$$

$$E = -\frac{eN_A}{\varepsilon}(x) + C_1; \quad -x_p < x < 0$$

At $x = -x_p \Rightarrow E = 0$

$$0 = -\frac{eN_A}{\varepsilon}(-x_p) + C_1$$

$$\Rightarrow C_1 = -\frac{eN_A}{\varepsilon} x_p$$

$$\boxed{E_p = -\frac{eN_A}{\varepsilon}(x_p + x); \quad -x_p < x < 0} \quad \text{—} (1)$$

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$$0 = \frac{eN_D}{\varepsilon} x + C_2$$

$$\Rightarrow \quad C_2 = -\frac{eN_D}{\varepsilon} x_n$$

$$E = \frac{eN_D}{\varepsilon} x - \frac{eN_D}{\varepsilon} x_n$$

$$= \frac{eN_D}{\varepsilon} (x - x_n)$$

$$\boxed{E_n = -\frac{eN_D}{\varepsilon} (x_n - x) \; ; 0 < x < x_n} \quad — (2)$$

At $x = 0$; $E_p = E_n$

$$-\frac{eN_A}{\varepsilon}(x_p + 0) = -\frac{eN_D}{\varepsilon}(x_n - 0) \Rightarrow \boxed{N_A x_p = N_D x_n}$$

## Potential on p-side:

$$\phi = +\int -E\,dx \; ; \; -x_p < x < 0$$

$$E = \frac{-eN_A}{\varepsilon} (x_p + x) \; ; \; -x_p < x < 0$$

$$\phi = \int \frac{eN_A}{\varepsilon} (x_p + x)\, dx \; ; \; -x_p < x < 0$$

$$\phi = \frac{eN_A}{\varepsilon} \left[ x_p x + \frac{x^2}{2} \right] + C_1' \; ; \; -x_p < x < 0$$

At $x = -x_p \Rightarrow \phi = 0$

$$0 = \frac{eN_A}{\varepsilon} \left( x_p(-x_p) + \frac{(-x_p)^2}{2} \right) + C_1' \; ; \; -x_p < x < 0$$

$$0 = \frac{eN_A}{\varepsilon} \left( -x_p^2 + x_p^2/2 \right) + C_1' \; ; \; -x_p < x < 0$$

$$\frac{x_p^2}{2} \frac{eN_A}{\varepsilon} = C_1' \; ; \; -x_p < x < 0$$

$$\phi = \frac{eN_A}{\varepsilon} \left( x_p x + \frac{x^2}{2} \right) + \frac{eN_A}{2\varepsilon} x_p^2 \; ; \; -x_p < x < 0$$

$$\phi = \int \frac{eN_D}{\varepsilon}(x_n - x)\,dx,$$

$$\phi = \frac{eN_D}{\varepsilon}\left(x_n x - \frac{x^2}{2}\right) + C_2' \quad \text{—⑤}$$

At $x=0$, potential on p-side = potential on n-side

$$\frac{eN_A}{2\varepsilon}(x_p+0)^2 = \frac{eN_D}{\varepsilon}\left(x_n(0) - 0^2/2\right) + C_2'$$

$$\frac{eN_A}{2\varepsilon}x_p^2 = \frac{eN_D}{\varepsilon}(0-0) + C_2'$$

$$\therefore\ C_2' = \frac{eN_A}{2\varepsilon}x_p^2$$

$$\phi = \frac{eN_D}{\varepsilon}\left(x_n x - x^2/2\right) + \frac{eN_A}{2\varepsilon}x_p^2 \ ; \quad 0 < x < x_n$$

At $x = x_n$ ; $V_0 = V_{bi}$ ?

$$V_0 = V_{bi} = \frac{eN_D}{\varepsilon}\left(x_n x_n - x_n^2/2\right) + \frac{eN_A}{2\varepsilon}x_p^2$$

$$= \frac{eN_D}{2\varepsilon}x_n^2 + \frac{eN_A}{2\varepsilon}x_p^2$$

$$\boxed{V_0 = V_{bi} = \frac{e}{2\varepsilon}\left[N_D x_n^2 + N_A x_p^2\right]} \quad \text{—⑥}$$

From eqn ③; $N_A x_p = N_D x_n$

$$x_p = \frac{N_D}{N_A}x_n$$

$$V_{bi} = \frac{e}{2\varepsilon}\left[N_D x_n^2 + N_A\left(\frac{N_D}{N_A}x_n\right)^2\right]$$

$$V_{bi} = \frac{e}{2\varepsilon}\left[N_D x_n^2 + \frac{N_D^2}{N_A}x_n^2\right]$$

$$V_{bi} = \frac{e}{2\varepsilon}\left[N_D\left[x_p\frac{N_A}{N_D}\right]^2 + N_A x_p^2\right]$$

$$= \frac{e}{2\varepsilon}\left[N_D x_p^2 \frac{N_A^2}{N_D^2} + N_A x_p^2\right]$$

$$= \frac{e}{2\varepsilon}\left[\frac{N_A^2}{N_D} x_p^2 + N_A x_p^2\right]$$

$$= \frac{e}{2\varepsilon}\left[\frac{N_A}{N_D}\right]\left[N_A + N_D\right] x_p^2$$

$$x_p^2 = \frac{2\varepsilon}{e} V_{bi}\left[\frac{N_D}{N_A}\right]\frac{1}{(N_A+N_D)}$$

$$x_p = \sqrt{\left(\frac{2\varepsilon}{e}\right)(V_{bi})\left(\frac{N_D}{N_A}\right)\left[\frac{1}{N_A+N_D}\right]}$$

**Width of the Depletion Region ($\omega$):**

$$\omega = x_n + x_p$$

$$= \left[\sqrt{\left(\frac{2\varepsilon}{e}\right)(V_{bi})\left(\frac{1}{N_A+N_D}\right)}\right]\left[\sqrt{\frac{N_D}{N_A}} + \sqrt{\frac{N_A}{N_D}}\right]$$

$$= \sqrt{\left(\frac{2\varepsilon}{e}\right)(V_{bi})\left(\frac{1}{N_A+N_D}\right)}\left[\frac{N_D+N_A}{\sqrt{N_A}\sqrt{N_D}}\right]$$

$$= \sqrt{\left(\frac{2\varepsilon}{e}\right)(V_{bi})\left(\frac{1}{N_A+N_D}\right)}\sqrt{\left[\frac{N_D+N_A}{\sqrt{N_A N_D}}\right]^2}$$

(c) Under what circumstances will $E_F$ coincide with $E_C$.

(d) Try this for p-type also.

(a) $m_n = \frac{1}{2}m \Rightarrow \frac{m_n}{m} = 0.5$

$$N_C = 4.8\times10^{21}\cdot\left(\frac{m_n}{m}\right)^{3/2} T^{3/2} /m^3$$

$$= 4.8\times10^{15}\left(\frac{m_n}{m}\right)^{3/2} T^{3/2} /cm^3$$

$$= 8.818\times10^{18}/cm^3$$

$E_C - E_F = KT\ln\left(\frac{N_C}{N_D}\right)$ ; $N_D = AC \times$ no: of Donor atoms / Si atom
$= 5\times10^{22}\times10^{-8}$ / Si atoms
$= 5\times10^{14}$

$$E_C - E_F = 0.02586\ln\left(\frac{8.818\times10^{18}}{5\times10^{14}}\right)$$

$$= 0.2528\ eV$$

→ Fermi level is at a distance of 0.2528 eV from the edge of CB

→ $E_F$ lies below $E_C$

(b) $N_C = 8.818\times10^{18}/cm^3$

$$N_D = \frac{5\times10^{22}}{10^3} = 5\times10^{19}$$

$$E_C - E_F = KT\ln\left(\frac{N_C}{N_D}\right) = 0.02586\ln\left(\frac{8.818\times10^{18}}{5\times10^{19}}\right)$$

$$= -0.0448\ eV$$

→ Fermi level is at a distance of 0.0448 eV from the edge of conduction band

→ $E_F$ is above $E_C$.



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$$5 \times 10^{22}$$

$$= \frac{1.77}{10^4}$$

i.e, if doping concentration is 1.77 in $10^4$ Si atoms, then fermi level coincides with the edge of conduction band.

Q) a) In p-type Ge, acceptor concentration corresponds to 1 in $10^8$ Ge atoms, If the effective mass of the hole is half of its true mass at room temperature, how far from the edge of the valence band is the fermi level. Is $E_F$ above or below $E_V$?

$$N_V = 4.82 \times 10^{15} \left(\frac{m_p}{m_0}\right)^{3/2} \cdot T^{3/2} \ /cm^3$$

$$E_F - E_V = KT \ln\left(\frac{N_V}{N_A}\right)$$

$$N_V = 4.82 \times 10^{15} (0.5)^{3/2} \ 300^{3/2} \ /cm^3$$

$$N_V = 8.818 \times 10^{18} \ /cm^3$$

$$N_A = AC \times \text{No: of acceptor impurity atoms}/cm^3$$

$$= 4.4 \times 10^{22} \times 1/10^8 \ /cm^3$$

$$N_A = 4.4 \times 10^{14} \ /cm^3$$

$$E_F - E_V = KT \ln\left(\frac{N_V}{N_A}\right)$$

$$= 0.02586 \ \ln\left(\frac{8.818 \times 10^{18}}{4.4 \times 10^{14}}\right)$$

$$= 0.256 \ eV$$

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$$FB: \quad V_j = V_{bi} - V = V_{bi} - V_F = V_0 - V = V_0 - V_F$$

$$RB: \quad V_j = V_{bi} + V = V_{bi} + V_R = V_0 + V = V_0 + V_R$$

$$\underline{\underline{FB}} \downarrow \quad W = \sqrt{\left(\frac{2\varepsilon}{e}\right)\left(V_{bi} - V\right)\left(\frac{1}{N_A} + \frac{1}{N_D}\right)}$$

$$\underline{\underline{RB}} \uparrow \quad W = \sqrt{\left(\frac{2\varepsilon}{e}\right)\left(V_{bi} + V\right)\left(\frac{1}{N_A} + \frac{1}{N_D}\right)}$$

$$\therefore \quad W \propto \sqrt{\frac{1}{N_A} + \frac{1}{N_D}}$$

Here $x_p$ & $W_p$ = Depletion region width on p-side

$x_n$ & $W_n$ = Depletion region width on n-side

$W$ = Total depletion region width

$N_A$ = Acceptor concentration on p-side

$N_D$ = Donor Concentration on n-side

$$N_A x_p = N_D x_n$$

$$W_p N_A = W_n N_D$$

**Depletion width on p-side:**

$$x_p = \frac{N_D}{N_A} x_n$$

$$W_p = \frac{N_D}{N_A} x_n$$

$$W_p = x_p = \frac{N_D}{N_A + N_D} W$$

$$W = W_n + W_p = x_n + x_p$$

$$W_p = \frac{N_D}{N_A + N_D}\left(W_p + W_n\right)$$

$$W_p\left(N_A + N_D\right) = N_D\left(W_p + W_n\right)$$

$$W_p N_A + \cancel{W_p N_D} = \cancel{N_D W_p} + N_D W_n$$

$$W_p N_A = N_D W_n$$

$$\Rightarrow \quad W_p = \frac{N_D}{N_A} W_n$$

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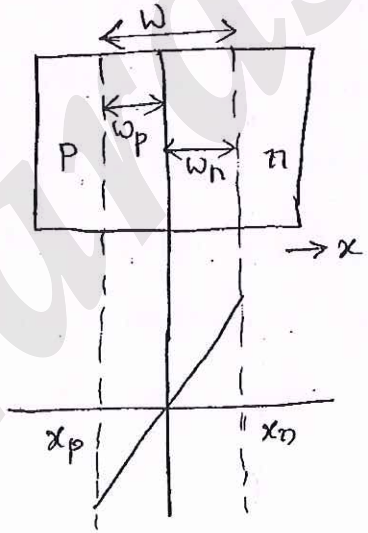
p-n junction

- Linear junction
- Non-linear junction

## Linear Junction:

If the doping concentrations are same on both the sides of the junction (i.e, p-side and n-side), it is called Linear junction.

→ Linear junction is also called grown junction (or) graded junction.




⇒ If $N_A = N_D \Rightarrow W_p = W_n$ & $x_p = x_n$

⇒ $W = W_p + W_n = x_p + x_n$

## Non-linear Junction:

If the doping concentrations are not same on both the sides of the junction (i.e, p-side and n-side) are called non-linear junction.

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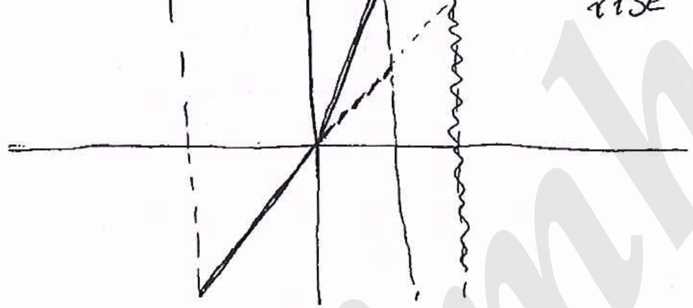
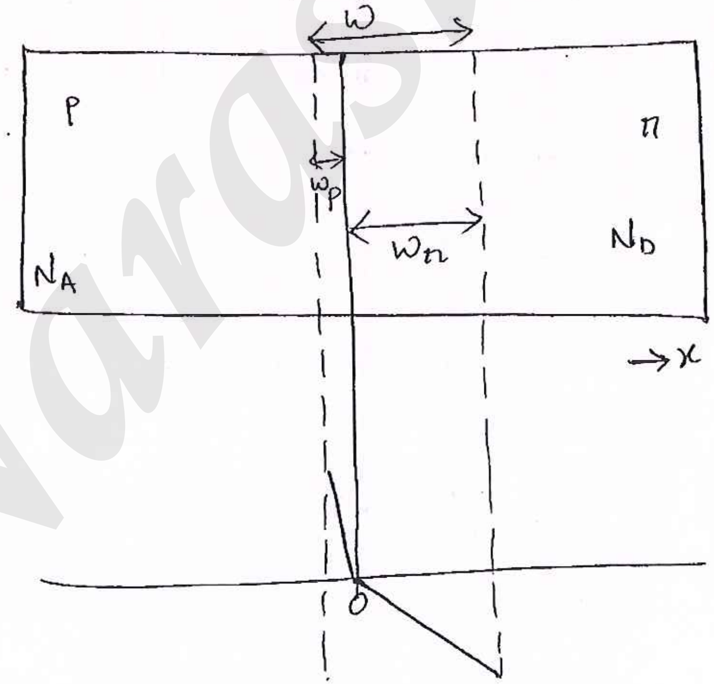


If $N_A << N_D \Rightarrow W_p >> W_n$

$\rightarrow W = W_p + W_n \simeq W_p$




If $N_A >> N_D \Rightarrow W_p << W_n$

$\rightarrow W = W_p + W_n \simeq W_n$

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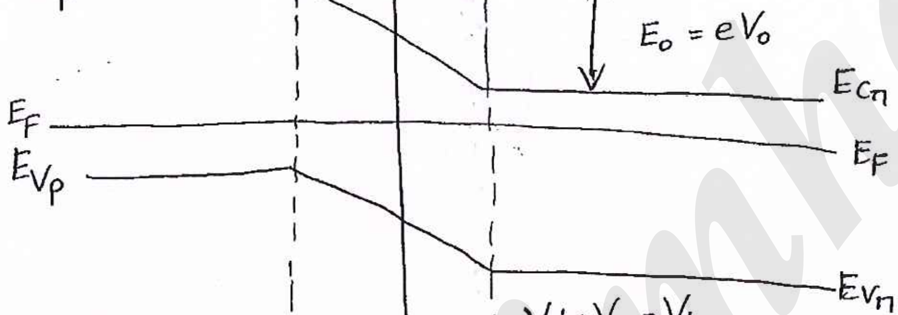
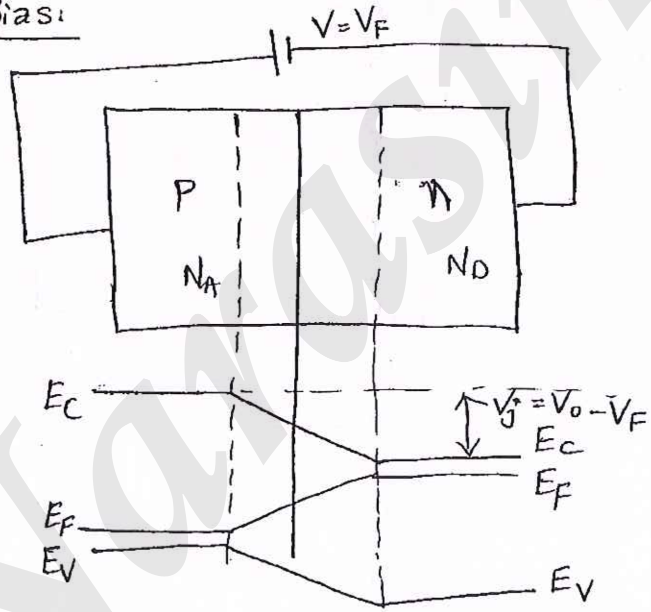


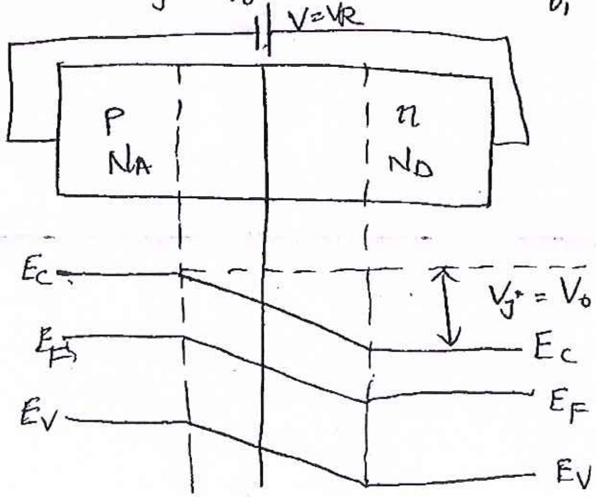

$V_j = V_o = V_{bi}$

## Forward Bias:



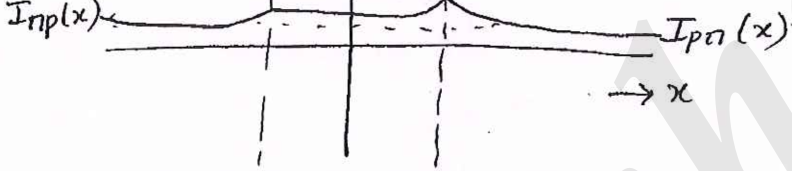

$V_j = V_o - V = V_o - V_F = V_{bi} - V_F$

## Reverse Bias:




$V_j = V_o + V = V_{bi} + V_R$

$= V_o + V_R$




$$I = I_{pp}(x) + I_{np}(x) \quad \text{on p-side}$$
$$I = I_{nn}(x) + I_{pn}(x) \quad \text{on n-side}$$

→ In a p-n junction, diffusion length of the carrier should be greater than the depletion width

$$\therefore I = I_{pp}(x) + I_{np}(x) = I_{nn}(x) + I_{pn}(x)$$

At $x=0 \Rightarrow I = I_{pn}(0) + I_{np}(0)$

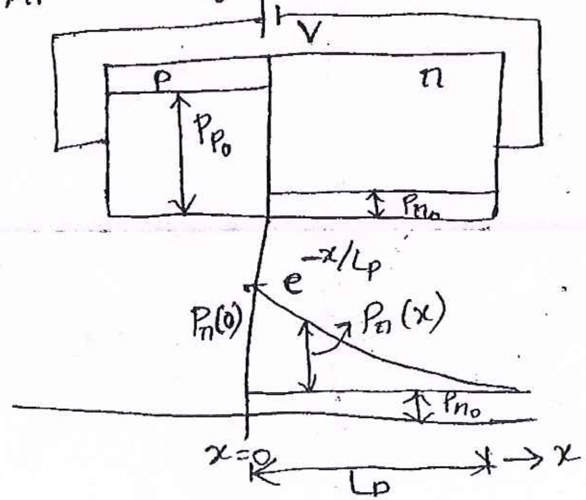
$$\boxed{I = I_{pp}(x) + I_{np}(x) = I_{nn}(x) + I_{pn}(x) = I_{pn}(0) + I_{np}(0)}$$

The concentration of holes on n-side

$$P_n(x) = P_{n_0} + P_n(0)\, e^{-x/L_p}$$

Hole concentration on n-side at $x=0$

$$P_n(0) = P_{n_0} + P_n(0) \quad \text{— (1)}$$

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$P_n(x)$ : Concentration of holes on n-side at any point 'x' (or) at any distance $x$.

## Diffusion Current due to holes on n-side:

$$I_{P_n}(x) = -\underset{?}{A}e D_p \frac{dP_n(x)}{dx}$$

$$\because I_p(diff) = J_p(diff) \cdot A$$

$$J_p(diff) = -eD_p \frac{dP}{dx}$$

$$I_p(diff) = -AeD_p \frac{dP}{dx}$$

$$I_{P_n}(x) = -AeD_p \cancel{\frac{dP}{dx}}\, P_n(0) \cdot e^{-x/L_p}\left(-1/L_p\right)$$

$$I_{P_n}(x) = -AeD_p P_n(0) e^{-x/L_p}\left(-1/L_p\right)$$

$$= AeD_p P_n(0) e^{-x/L_p}\left(1/L_p\right)$$

At $x=0$

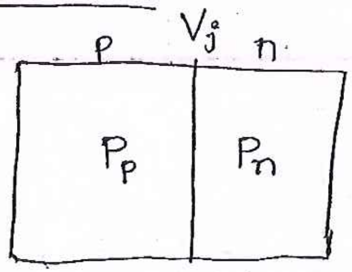
$$I_{P_n}(0) = \frac{AeD_p}{L_p} P_n(0)$$

From eqn (1)

$$P_n(0) = P_{n_0} + P_n(0)$$

$$I_{P_n}(0) = \frac{AeD_p}{L_p}\left[P_n(0) - P_{n_0}\right] \quad \text{—} (2)$$

## Law of Junctions:




$$P_p = P_n \cdot e^{V_j/V_T}$$

$$P_n = P_p e^{-V_j/V_T}$$

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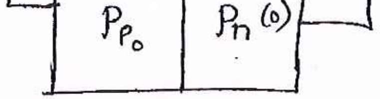


$$P_n(0) = P_{p_0}\, e^{-(V_0 - V)/V_T}$$

Eq ③ = ④ $\Rightarrow$ $P_{n_0} e^{V_0/V_T} = P_n(0) e^{+(V_0 - V)/V_T}$

$$P_{n_0} e^{V_0/V_T} = P_n(0) e^{+(V_0 - V)/V_T}$$

$$P_{n_0} \cancel{e^{V_0/V_T}} = P_n(0) \cancel{e^{+V_0/V_T}} \cdot e^{-V/V_T}$$

$$P_{n_0} = P_n(0)\, e^{-V/V_T}$$

$$\Rightarrow \quad P_n(0) = P_{n_0} e^{V/V_T} \quad \text{—⑤}$$

$$I_{P_n}(0) = \frac{AeD_P}{L_P}\left[P_{n_0} e^{V/V_T} - P_{n_0}\right]$$

$$\boxed{I_{P_n}(0) = \frac{AeD_P}{L_P}\left[e^{V/V_T} - 1\right](P_{n_0})} \quad \text{—⑥}$$

Similarly

$$I_{n_p}(0) = \frac{AeD_n}{L_n}(n_{p_0})\left[e^{V/V_T} - 1\right]$$

$$I = I_{P_n}(0) + I_{n_p}(0)$$

$$= \frac{AeD_P}{L_P}(P_{n_0})\left[e^{V/V_T} - 1\right] + \frac{AeD_n}{L_n}(n_{p_0})\left[e^{V/V_T} - 1\right]$$

$$= Ae\left[e^{V/V_T} - 1\right]\left[\frac{D_P}{L_P}(P_{n_0}) + \frac{D_n}{L_n}(n_{p_0})\right]$$

$$= \underbrace{\left[\frac{AeD_P}{L_P}(P_{n_0}) + \frac{AeD_n}{L_n}(n_{p_0})\right]}_{I_0}\left(e^{V/V_T} - 1\right)$$

$$\boxed{I = I_0\left(e^{V/V_T} - 1\right)}$$

$I_0 \Rightarrow$ Saturation Current (or) Leakage Current (or) Reverse Saturation current.

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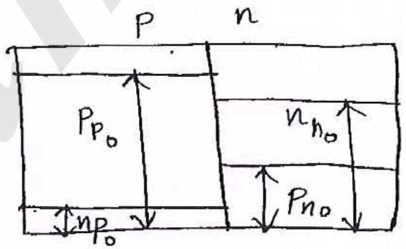
or

Si $\begin{cases} I = I_0\left[e^{V/2V_T} - 1\right] & \text{for small \& rated currents} \\ I = I_0\left[e^{V/V_T} - 1\right] & \text{for large currents.} \end{cases}$

Ge $\Rightarrow \eta = 1$ for both small and large currents.

**Saturation Current $I_0$:**




$P_{p_0} \cdot n_{p_0} = n_i^2 \qquad n_{n_0} \cdot P_{n_0} = n_i^2$

$n_{p_0} = \dfrac{n_i^2}{P_{p_0}} = \dfrac{n_i^2}{N_A} \qquad P_{n_0} = \dfrac{n_i^2}{n_{n_0}} = \dfrac{n_i^2}{N_D}$

$$I_0 = \frac{AeD_p}{L_p} P_{n_0} + \frac{AeD_n}{L_n} n_{p_0}$$

$$I_0 = \frac{AeD_p}{L_p}\left(\frac{n_i^2}{N_D}\right) + \frac{AeD_n}{L_n}\left(\frac{n_i^2}{N_A}\right)$$

$$\boxed{I_0 = Ae\left[\frac{D_p}{L_p N_D} + \frac{D_n}{L_n N_A}\right] n_i^2}$$

Ge: $I_0 = K_1 T^2 e^{-E_G/V_T}$

$I_0 \propto T^2$

In Ge p-n junction diodes, saturation current is directly proportional to square of the temperature. Therefore in Ge, p-n junction diode, $I_0 \uparrow$ by 11 % /°c rise in temperature.

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temperature.

$\Rightarrow I_0 = nA$

$\Rightarrow I = mA$

$\Rightarrow I/I_0 = \frac{1mA}{1nA} = 10^6.$

→ In all practical cases:

$I_0 \uparrow$ by 7% /°c rise in temperature.

$I_{01} \to T_1$ ; $I_{02} \to T_2$

$$I_{02} = I_{01} + 0.07 I_{01}$$
$$= (1+0.07) I_{01}$$
$$= (1.07) I_{01}$$
$$= (1.07)^{\Delta T} . I_{01}$$
$$= (2^{1/10})^{\Delta T} . I_{01}$$
$$= 2^{\Delta T/10} . I_{01}$$

$$\boxed{I_{02} = 2^{(T_2 - T_1)/10} . I_{01}}$$

$I_{01} \to T_1$ $\qquad I_{02} = 2^{10/10} . I_{01}$

$I_{02} \to T_2 = T_1 + 10°c$ $\qquad = 2 . I_{01}$

$$I_{02} = 2^{20/10} . I_{01}$$
$$= 4 I_{01}$$

$I_0$: doubles /10°c //

ii) $D_p = \mu_p V_T$ ; $D_n = \mu_n V_T$

$$I_0 = Ae\left[\frac{\mu_p V_T}{L_p N_D} + \frac{\mu_n V_T}{L_n N_A}\right] n_i^2$$

$$\boxed{I_0 = Ae V_T\left[\frac{\mu_p}{L_p N_D} + \frac{\mu_n}{L_n N_A}\right] n_i^2}$$

iii) Multiply and divide first term with $\mu_n e$ and second term with $\mu_p e$, then

$$I_0 = Ae V_T\left[\frac{\mu_p \mu_n e}{L_p \underbrace{N_D \mu_n e}_{\sigma_n}} + \frac{\mu_p \mu_n e}{L_n \underbrace{N_A \mu_p e}_{\sigma_p}}\right] n_i^2$$

$$= Ae V_T\left[\frac{\mu_n \mu_p e}{L_p \sigma_n} + \frac{\mu_n \mu_p e}{L_n \sigma_p}\right] n_i^2$$

$$\boxed{I_0 = Ae^2 V_T \mu_n \mu_p\left[\frac{1}{L_p \sigma_n} + \frac{1}{L_n \sigma_p}\right] n_i^2}$$

$$I_{P_n}(0) = \frac{Ae^2 V_T \mu_n \mu_p n_i^2}{L_p \sigma_n}\left[e^{V/V_T} - 1\right]$$

$$I_{n_p}(0) = \frac{Ae^2 V_T \mu_n \mu_p n_i^2}{L_n \sigma_p}\left[e^{V/V_T} - 1\right]$$

$$\boxed{\frac{I_{P_n}(0)}{I_{n_p}(0)} = \frac{L_n \sigma_p}{L_p \sigma_n}}$$

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v) Let $b = \frac{\mu_n}{\mu_p}$

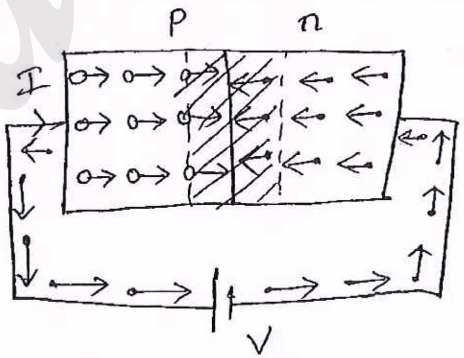
$$I_0 = \frac{A\mu_n\mu_p V_T \sigma_i^2}{\mu_p^2\left(1+\frac{\mu_n}{\mu_p}\right)^2}\left[\frac{1}{L_p\sigma_n}+\frac{1}{L_n\sigma_p}\right]$$

$$I_0 = \frac{A\mu_n V_T \sigma_i^2}{\mu_p(1+b)^2}\left[\frac{1}{L_n\sigma_p}+\frac{1}{L_p\sigma_n}\right]$$

$$\boxed{I_0 = \frac{AbV_T\sigma_i^2}{(1+b)^2}\left[\frac{1}{L_p\sigma_n}+\frac{1}{L_n\sigma_p}\right]}$$

## V-I Characteristics:

1) When p-n junction diode in Forward Bias:




When the applied net resultant voltage is positive at p-side wrt 'n' side, then p-n junction is in foward bias.

$$I = I_0\left[e^{V/\eta V_T}-1\right]$$

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which current flows through the diode exceeds 1% of the rated current.

1) If $V < V_\gamma$ : Zero Current

2) If $V_\gamma < V < V_{sat}$ : Current increases exponentially

i.e, $I \propto e^{V/\eta V_T}$

3) If $V > V_{sat}$ : very large current due to secondary effect.

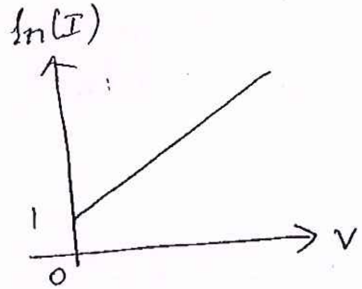
$\Rightarrow I \simeq I_o e^{V/\eta V_T} \quad (\because e^{V/\eta V_T} >> 1)$

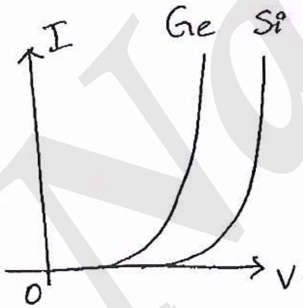
$$e^{V/\eta V_T} = \frac{I}{I_o}$$

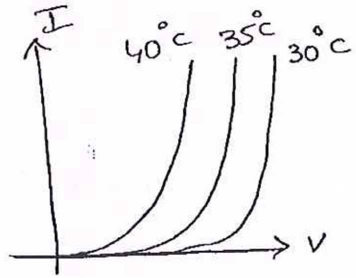
$$V/\eta V_T = \ln(I/I_o)$$

$$V = \eta V_T \ln(I/I_o)$$

$$V \propto \ln(I)$$

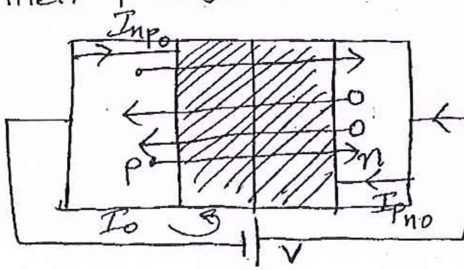



2) When p-n junction is in Reverse Bias:

When the applied net resultant voltage is -ve at p-side wrt 'n' side, then p-n junction is in reverse bias.

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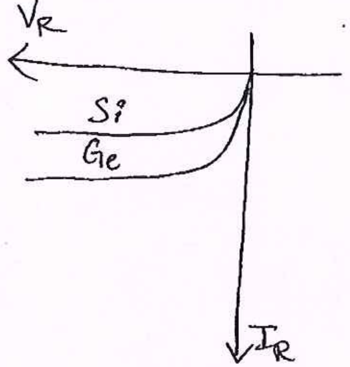
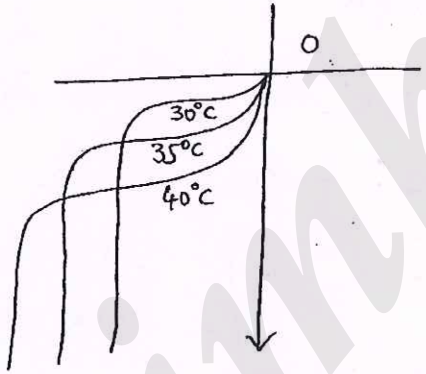


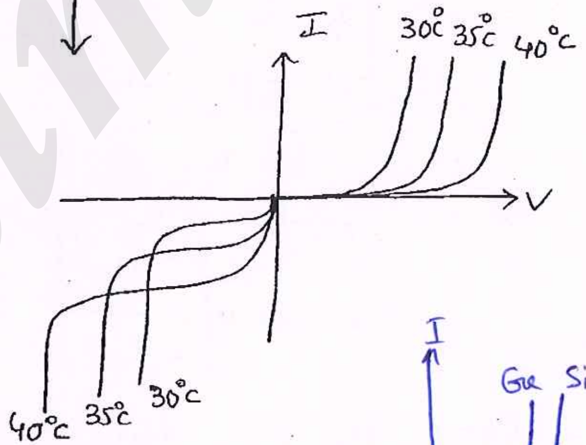



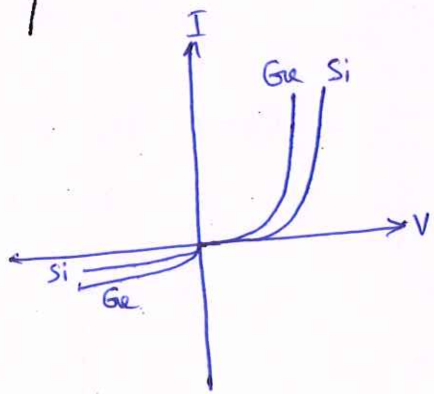


$I_o(Ge) : \mu A$

$I_o(Si) : nA$

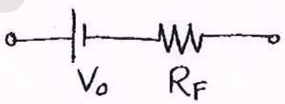
$\rightarrow I_o(Ge) \simeq 1000\, I_o(Si)$



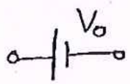




Diode equivalent Circuit (a) Forward Bias:

Piecewise linear equivalent Circuit:




Simplified linear equivalent Circuit:




Ideal equivalent Circuit: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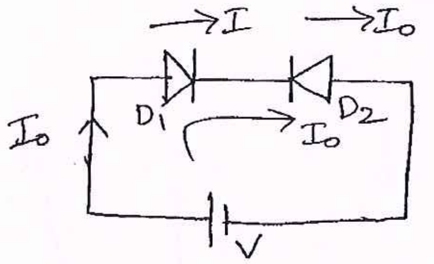
$I = I_0 e^{V/\eta V_T}$

$I_F = I \simeq I_0 e^{V/\eta V_T}$

$I \simeq -I_0$

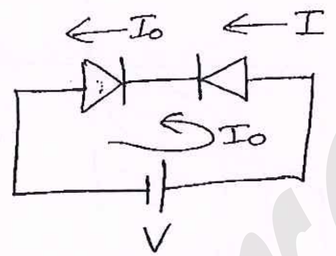
$I_R = I \simeq -I_0$

$\Rightarrow$




$D_1 : FB \rightarrow I$
$D_2 : RB \rightarrow I_0$ $\Big\}\ I_0$

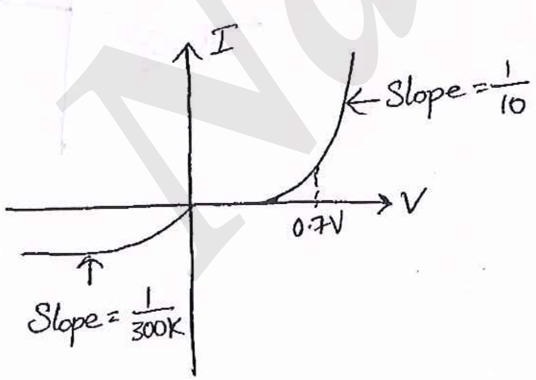
$\Rightarrow$

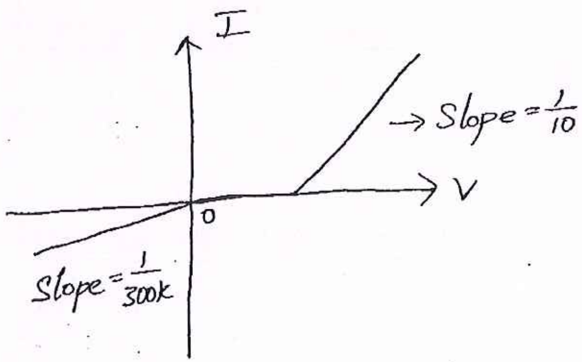



$D_1 : RB \rightarrow I_0$
$D_2 : FB \rightarrow I$ $\Big\}\ I_0$

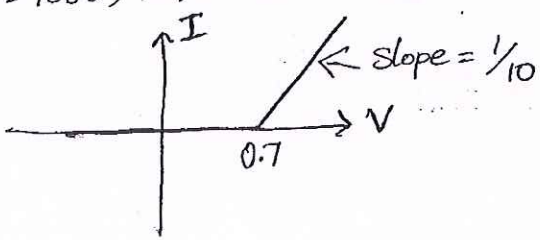
→ Draw the V-I characteristics for the following specifications.

i) $V_\gamma = 0.7V$, $R_F = 10\Omega$, $R_r = 300k\Omega$




ii) $V_\gamma = 0.7V$, $R_F = 10\Omega$, $R_r = \infty$




$\text{Slope} = \frac{1}{\infty} = 0$

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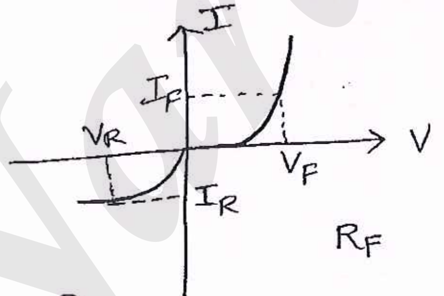
## Diode Resistance:

1. Static Resistance (R)
2. Dynamic Resistance (r)

### Static Resistance: (R)

It is the resistance offered by the p-n junction diode under dc condition. Therefore static resistance is also called dc resistance.

→ It is the ratio of voltage across the diode to the current through the diode



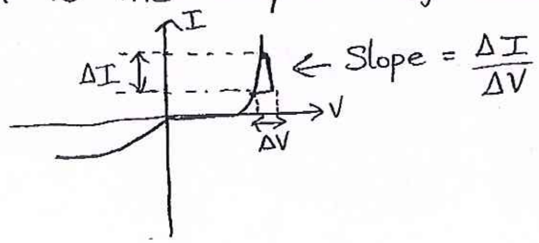

$$R_F = \frac{V_F}{I_F} = \text{`}\Omega\text{'}$$

$$R_r = \frac{V_R}{I_R} = \text{"}100\ k\Omega \text{ to } M\Omega\text{"}$$

### Dynamic Resistance: (r)

Dynamic Resistance is the resistance offered by the p-n junction diode under ac condition. Therefore, dynamic resistance is also called ac resistance.

→ It is the reciprocal of the slope of the V-I characteristics

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$$\frac{dI}{dV} = \frac{I+I_0}{\eta V_T} \simeq \frac{I}{\eta V_T}$$

$$r = r_f = \frac{\eta V_T}{I}$$

**Dynamic Resistance (r):**

$$r = \frac{dV}{dI} = \frac{\eta V_T}{I}$$

**Dynamic Conductance (g):**

$$g = \frac{dI}{dV} = \frac{1}{r} = \frac{I}{\eta V_T}$$

**Forward Dynamic Resistance ($r_F$):**

$$r_F = \frac{\eta V_T}{I_F} = \frac{\eta V_T}{I}$$

**Reverse Dynamic Resistance ($r_r$):**

$$r_r = \frac{\eta V_T}{I_R} = \frac{\eta V_T}{I_0}$$

Q) The resistivity of a Ge p-n junction diode is $2\Omega$-cm on p-side and $1\Omega$-cm on n-side. Calculate built in potential of the junction.

Sol: $\rho_p = 2\Omega$-cm

$\rho_n = 1\Omega$-cm

$$V_0 = V_{bi} = KT \ln\left(\frac{N_A N_D}{n_i^2}\right)$$

$$\rho_p = \frac{1}{N_A \mu_p q}$$

$$N_A = \frac{1}{\rho_p \mu_p q}$$

→ A Ge p-n junction diode is operating at a temperature of 125°C with a saturation current of 30 μA. Calculate its dynamic resistance when it is biased by a bias voltage of 0.2V in faward and reverse direction.

$$r_f = \frac{\eta V_T}{I_F}$$

$$V_T = \frac{T}{11600} = \frac{273+125}{11600} = 0.034$$

$$I_F = I = I_o\left[e^{V/\eta V_T} - 1\right] \; ; \; I_R = I_o\left[e^{-V/\eta V_T} - 1\right]$$

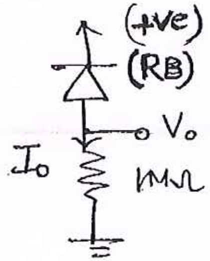
$$= 30\,\mu A\left[e^{0.2/1\times 0.034} - 1\right]$$

$$= 0.0107\,A$$

$$r_f = \frac{1\times 0.034}{0.0107} = 3.15\,\Omega$$

$$r_r = \frac{\eta V_T}{I_R} = \frac{\eta V_T}{I_o} = \frac{1\times 0.034}{30\times 10^{-6}} = 1.13\,k\Omega$$

→ For the circuit shown in the figure, $V_o = 1V$ at 20°c, Calculate $V_o$ at 40°c and 0°c




$$I_o = \frac{V_o}{1M\Omega} = \frac{1V}{1M\Omega} = 1\,\mu A \text{ at } 20°c$$

$I_o = ?$ at 40°C

$$I_o(40°c) = 2^{\left(\frac{40-20}{10}\right)} \cdot I_o(20°c)$$

$$= 2^2 \cdot 1\,\mu A = 4\,\mu A$$

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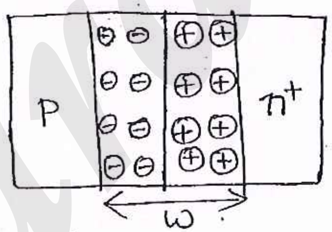
→ Transition Capacitor ($C_T$)
→ Diffusion Capacitance ($C_D$)

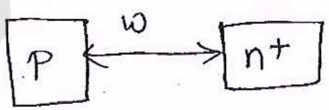
## Transition Capacitance:

Change in charge wrt change in voltage, which exists in a p-n junction diode, when it is in reverse bias is called transition capacitance.

→ Transition capacitance is the capacitance offered by the p-n junction diode when it is in reverse bias.

→ Therefore transition capacitance is also called junction capacitance

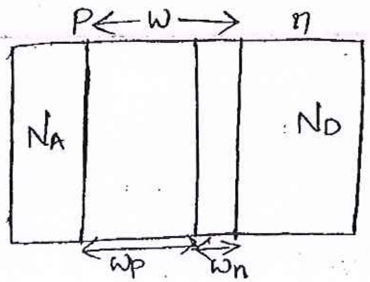



$$C_{T_0} = \frac{\varepsilon A}{\omega}$$

⇒ $C_T$ is of the order of pF.

1) $C_T$ for non-linear junction:

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$$E = \frac{dV}{dx} = -\frac{\rho}{\varepsilon} x$$

$$\boxed{\mathcal{E} = \frac{dV_j}{dw} = \frac{eN_D}{\varepsilon} \omega}$$

$$V = \int E\,dx = -\rho/\varepsilon \; x^2/2$$

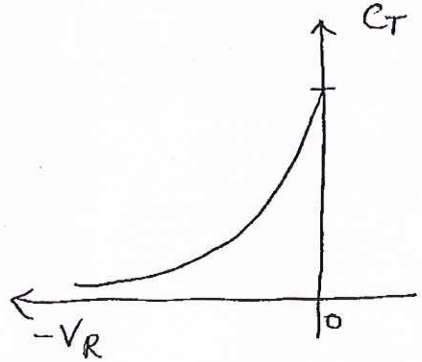
$$V = \frac{eN_A}{\varepsilon} \omega^2/2$$

$$\boxed{V_j = \frac{eN_A}{2\varepsilon} \omega^2} \quad \text{— (1)}$$

→ Transition capacitance ~~is~~ also called depletion capacitor (or) space charge capacitor.

<u>Total Charge on p-side:</u>

$$Q = A\omega N_A e \quad \text{— (2)}$$




$$\frac{dQ}{dV_j} = Ae\,N_A \frac{d\omega}{dV_j}$$

$$V_j = \frac{eN_A}{2\varepsilon} \omega^2$$

Diff wrt $V_j$, we have

$$1 = \frac{eN_A}{2\varepsilon} 2\omega \cdot \frac{d\omega}{dj} \Rightarrow \frac{d\omega}{dj} = \frac{\varepsilon}{eN_A \omega}$$

$$\frac{dQ}{dV_j} = A\cancel{e}\cancel{N_A} \frac{\varepsilon}{\cancel{eN_A}\omega}$$

$$\Rightarrow \boxed{V_R \uparrow \Rightarrow V_j \uparrow \Rightarrow \omega \uparrow \Rightarrow C_T \downarrow}$$

$$\Rightarrow \frac{dQ}{dV_j} = \frac{\varepsilon A}{\omega}$$

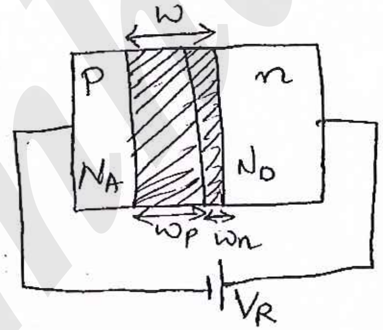
$$C_{T_0} = \frac{\varepsilon A}{\omega}$$

$$C_T \propto \frac{1}{\omega}$$

$$V_j \propto \omega^2 \Rightarrow \omega \propto V_j^{1/2} \Rightarrow C_T \propto \frac{1}{V_j^{1/2}} \Rightarrow C_T \propto V_j^{-1/2}$$

For Si:

$$V_j = V_o + V_R = V_{bi} + V_R$$




$$V_j = \frac{eN_A}{2\varepsilon} W^2 \quad -(1)$$

$$C_T = \frac{\varepsilon A}{W} \quad -(2)$$

From (1) ⇒ $W = \sqrt{\frac{2\varepsilon V_j}{eN_A}}$ —(3)

(3) in (2) ⇒ $C_T = \frac{\varepsilon A}{\sqrt{\frac{2\varepsilon V_j}{eN_A}}}$

$$C_T/A = \frac{\varepsilon}{\sqrt{\frac{2\varepsilon V_j}{eN_A}}} = \sqrt{\frac{e\varepsilon N_A}{2V_j}}\ F/cm^2$$

$$= \sqrt{\frac{\varepsilon e}{2}}\left(\frac{N_A}{V_j}\right)^{1/2} F/cm^2$$

$$= \sqrt{\frac{\varepsilon_0\varepsilon_r e}{2}}\left(\frac{N_A}{V_j}\right)^{1/2} F/cm^2$$

$$= \sqrt{\frac{1.6\times10^{-19}\times 11.7\times 8.85\times10^{-14}}{2}}\left(\frac{N_A}{V_j}\right)^{1/2} F/cm^2$$

$$= 2.878\times10^{-16}\left(\frac{N_A}{V_j}\right)^{1/2} F/cm^2$$

$$C_T/A = 2.9\times10^{-4}\left(\frac{N_A}{V_j}\right)^{1/2} pF/cm^2$$

$$\boxed{\text{For area} = 1 \Rightarrow C_T = 2.9\times10^{-4}\left(\frac{N_A}{V_j}\right)^{1/2} pF/cm^2}$$

$$= 3.36 \times 10^{-4} \left( \frac{N_A}{V_j} \right)^{1/2} \ pF/cm^2$$

→ The transition capacitance of a step graded Si p-n junction diode is 20pF at a reverse bias voltage of 5V. If reverse bias voltage is increased by 1V, find the change in the capacitance.

$$C_T \propto \frac{1}{\sqrt{V_j}}$$

$$\frac{C_{T_1}}{C_{T_2}} = \sqrt{\frac{V_{j_2}}{V_{j_1}}}$$

$$C_{T_2} = C_{T_1} \sqrt{\frac{V_{j_1}}{V_{j_2}}} = C_{T_1} \sqrt{\frac{V_0 + V_{R_1}}{V_0 + V_{R_2}}} = C_{T_1} \sqrt{\frac{0.7+5}{0.7+6}}$$

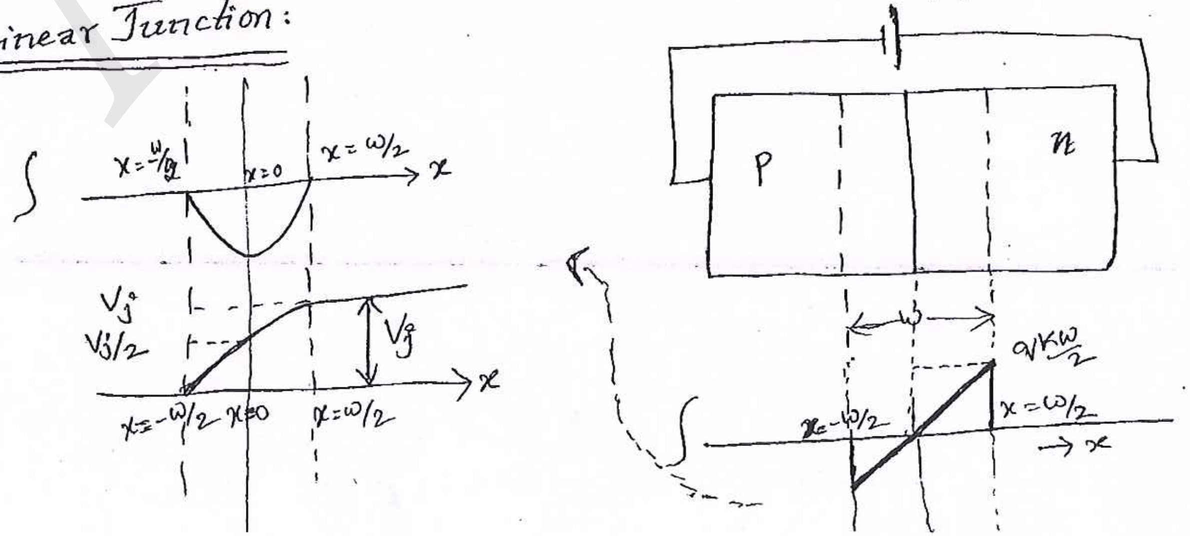
$$= C_{T_1} \sqrt{\frac{5.7}{6.7}}$$

$$C_{T_2} = 18.26 \ pF$$

$$\text{Change in Capacitance} = C_{T_1} - C_{T_2} = -18.26 + 20$$

$$= 1.74 \ pF$$

## Linear Junction:

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$$\frac{dV}{dx} = E = -\frac{qK}{\varepsilon}\frac{x^2}{2}+K_1 \quad — ①$$

At $x = \pm w/2 \Rightarrow E = 0$

The $K_1 - \frac{qK}{\varepsilon}\left(\frac{(w/2)^2}{2}\right) = 0$

$$\Rightarrow K_1 = \frac{qK}{\varepsilon}\frac{w^2}{8}$$

$$\Rightarrow \boxed{K_1 = \frac{qK}{8\varepsilon}.w^2} \quad — ②$$

For linear junction

$V_j \propto w^3 \Rightarrow w \propto V_j^{1/3}$

For non-linear junction

$V_j \propto w^2 \Rightarrow w \propto V_j^{1/2}$

Substitute ② in ①

$$\Rightarrow \frac{dV}{dx} = -\frac{qK}{2\varepsilon}x^2 + \frac{qK}{8\varepsilon}w^2$$

$$\frac{dV}{dx} = \frac{qK}{8\varepsilon}\left[-4x^2 + w^2\right] \quad — ③$$

$$\int\frac{dV}{dx} = V = \frac{qK}{8\varepsilon}\left[-\frac{4}{3}x^3 + w^2 x\right] + K_2 \quad — ④$$

$$\left.\begin{aligned} V|_{x=-w/2} &= 0 \\ V|_{x=0} &= \frac{V_j}{2} \\ V|_{x=w/2} &= V_j \end{aligned}\right\} \text{from graph.}$$

$$V_j^\circ = \frac{qK}{8\varepsilon}\left[-\frac{4}{3}\,\frac{\omega^3}{8} + \omega^2(\omega/2)\right] + \frac{V_j^\circ}{2}$$

$$\frac{V_j^\circ}{2} = \frac{qK}{8\varepsilon}\left[-\frac{4}{3}\,\omega^3/8 + \omega^3/2\right]$$

$$\frac{V_j^\circ}{2} = \frac{qK}{8\varepsilon}\left[-\frac{\omega^3}{6} + \frac{\omega^3}{2}\right]$$

$$\frac{V_j^\circ}{2} = \frac{qK}{8\varepsilon}\left[\frac{4\omega^3}{12}\right]$$

$$\Rightarrow \quad V_j^\circ/2 = \frac{qK}{8\varepsilon}\cdot\left(\frac{\omega^3}{3}\right)$$

$$\boxed{V_j^\circ = \left(\frac{qK}{12\varepsilon}\right)\cdot\omega^3} \quad \text{— ⑥}$$

$$Q = \frac{1}{2}\cdot\frac{\omega}{2}\cdot\left(\frac{qK\omega}{2}\right)\cdot A$$

$$Q = \frac{qKA}{8}\,\omega^2 \quad \text{— ⑦}$$

$$\frac{dQ}{dV_j^\circ} = \frac{qKA}{\cancel{8}_4}\,\cancel{2}\omega\,\frac{d\omega}{dV_j^\circ}$$

$$\frac{dQ}{dV_j^\circ} = \frac{qKA}{4}\cdot\omega\,\frac{d\omega}{dV_j^\circ} \quad \text{— ⑧}$$

Differentiate ⑥ wrt $V_j^\circ$

$$\Rightarrow \quad 1 = \frac{qK}{\cancel{12}_4\varepsilon}\,\cancel{3}\omega^2\,\frac{d\omega}{dV_j^\circ}$$

$$\Rightarrow \quad \frac{d\omega}{dV_j^\circ} = \frac{4\varepsilon}{qK\omega^2} \quad \text{— ⑨}$$

$$C_T \propto \frac{1}{V_j^{1/3}} \Rightarrow C_T \propto V_j^{-1/3}$$

$\Rightarrow$ $C_T = \dfrac{K}{V_j^{1/2}}$ for Non-linear Junction, where K is a constant.

$C_T = \dfrac{K}{V_j^{1/3}}$ for Linear Junction, where K is a constant.

$$\Rightarrow \boxed{C_T = \frac{K}{V_j^{n}}}$$

where $n = 1/2$ for non-linear junction
$n = 1/3$ for linear junction

$(\because V_j = V_0 + V_R)$

$$C_T = \frac{K}{V_j^n} = \frac{K}{(V_0+V_R)^n}$$

At $V_R = 0 \Rightarrow C_T = \dfrac{K}{V_0^n} \Rightarrow C_{T_0} = \dfrac{K}{V_0^n}$

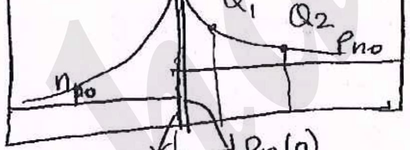
$$\Rightarrow K = C_{T_0} V_0^n$$

$$C_T = \frac{C_{T_0} \cdot V_0^n}{(V_0+V_R)^n} = \frac{C_{T_0} V_0^n}{V_0^n\left(1+\frac{V_R}{V_0}\right)^n} = \frac{C_{T_0}}{\left(1+\frac{V_R}{V_0}\right)^n}$$

$$\boxed{\therefore C_T = \frac{C_{T_0}}{\left(1+\frac{V_R}{V_0}\right)^n}} \quad ; \quad C_{T_0} = \frac{\varepsilon A}{\omega}$$

$C_T = \dfrac{C_{T_0}}{\left(1+\frac{V_R}{V_0}\right)^{1/2}}$ for non-linear junction

$C_T = \dfrac{C_0}{\left(1+\frac{V_R}{V_0}\right)^{1/3}}$ for linear junction forward bias, then it is called Diffusion capacitance.




$\rightarrow C_D = \frac{dQ}{dV}$

$dQ = Q_1 - Q_2$

→ $C_D$ ranges from nF to μF.

→ Diffusion capacitance is greater than transition capacitance.

$$C_D = \frac{dQ}{dV} \quad -① $$

$$I = Q/t$$

$$dI = dQ/t$$

$$\Rightarrow dQ = \tau dI \quad -② \quad (t = \tau)$$

Substitute ② in ①, $\Rightarrow C_D = \frac{\tau dI}{dV}$

$$\frac{dI}{dV} = g \Rightarrow C_D = \tau g$$

$\tau$ is the lifetime of charge carriers

$$g = \frac{I}{\eta V_T} \qquad \Rightarrow \boxed{C_D = \frac{\tau I}{\eta V_T}} \; ***$$

* Diffusion capacitance is proportional to current.

$$\boxed{\begin{gathered} C_D = \frac{\tau_p I_p + \tau_n I_n}{\eta V_T} \\ C_{D_p} = \frac{\tau_p I_p}{\eta V_T} \\ C_{D_n} = \frac{\tau_n I_n}{\eta V_T} \end{gathered}}$$

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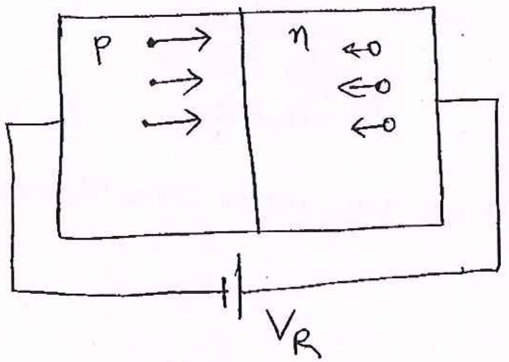
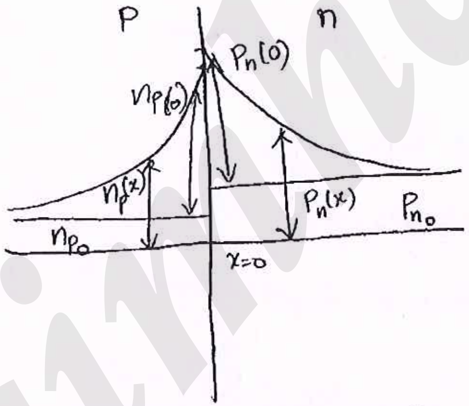
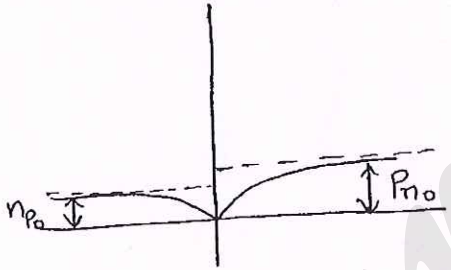
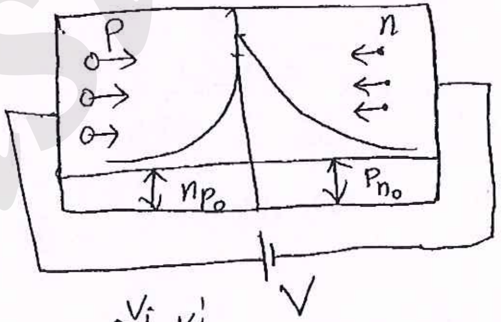
Reverse Bias.

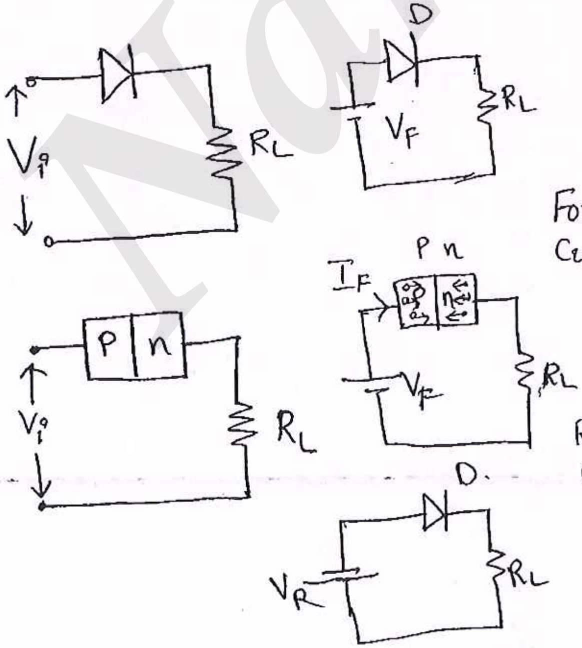


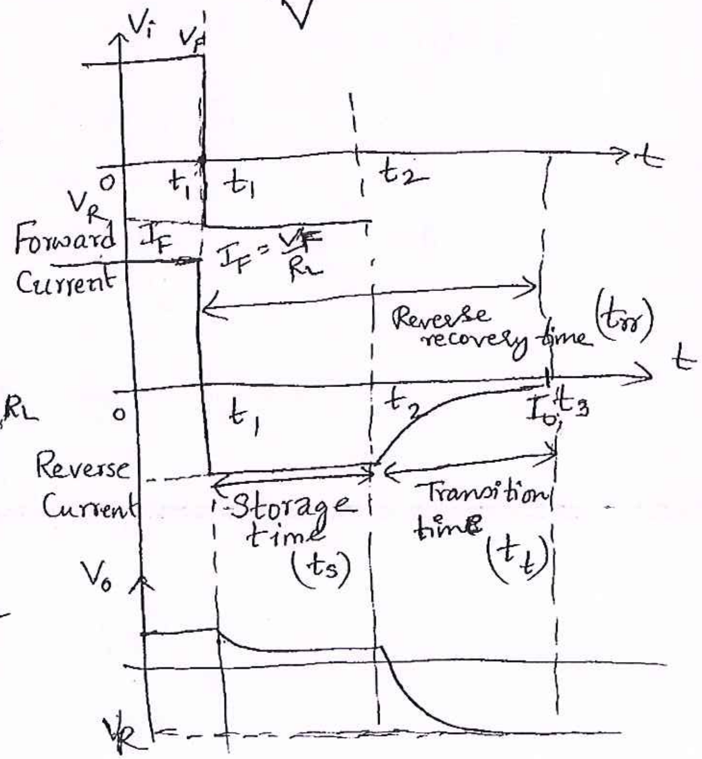

Forward Bias

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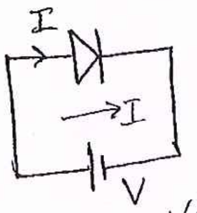
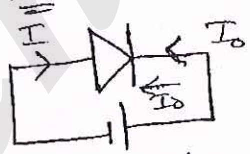
→ ON time < OFF time ( ... state)

→ Storage time $t_s = \tau \ln\left(1+\frac{I_F}{I_R}\right)$

FB




RB




$I = I_o\left[e^{V/\eta V_T}-1\right] \simeq I_o e^{V/\eta V_T}$

$I_F = I = I_o e^{V/\eta V_T}$

Current $I_F$ is in the order of mA

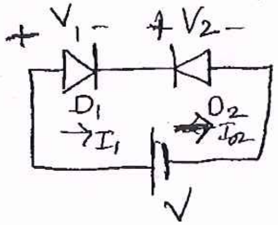
$I = I_o\left[e^{-V/\eta V_T}-1\right] \simeq -I_o$

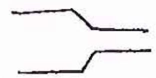
$I_R = I \simeq -I_o$

Q) For the circuit shown in the figure, show that $e^{qV_1/KT}+e^{-qV_2/KT} = 2$ if the diodes are identical and also made up of Ge.

$I = I_o\left[e^{V/\eta V_T}-1\right]$

$V_T = KT = \frac{T}{11600}$ $\quad \eta = 1$ for Ge



$-V + V_1 + V_2 = 0$

$V = V_1 + V_2$

$D_1$ is forward biased ($I_1$ flows)

$D_2$ is reverse biased ($I_{02}$ flows)

$I_1 = I_{02} = -I_2 \quad (\because I_2 = -I_{02} \Rightarrow I_{02} = -I_2)$

$I_{01}\left[e^{V_1/\eta V_T}-1\right] = -I_{02}\left[e^{-V_2/\eta V_T}-1\right]$

$I_o\left[e^{V_1/V_T}-1\right] = -I_o\left[e^{-V_2/V_T}-1\right]$

$I_o\left[e^{V_1/V_T}+e^{-V_2/V_T}\right] = 2I_o$

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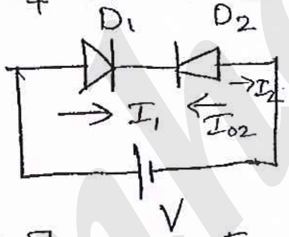
$$I_1 = I_{o2} = -I_{o2}$$




$$I_{o1}\left[e^{V_1/\eta V_T} - 1\right] = -I_{o2}\left[e^{-V_2/\eta V_T} - 1\right]$$

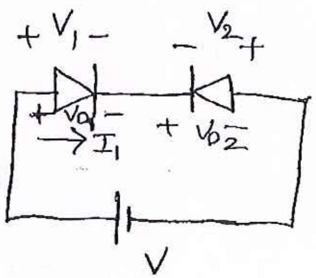
$$I_o\left[e^{V_1/\eta V_T} - 1\right] = -I_o\left[e^{-V_2/\eta V_T} - 1\right] \qquad \text{For Si, } \eta = 2$$

$$I_o\left[e^{V_1/2V_T} + e^{-V_2/2V_T}\right] = 2 I_o$$

$$\Rightarrow e^{V_1/2KT/q} + e^{-V_2/2KT/q} = 2$$

$$\Rightarrow \boxed{e^{qV_1/2KT} + e^{-qV_2/2KT} = 2}$$

→ For the circuit shown below, show that $e^{qV_1/2KT} + e^{qV_2/2KT} = 2$




$$I_1 = -I_{o1} = -I_2$$

$$I_1 = -I_2$$

$$I_{o1}\left[e^{V_{D1}/\eta V_T} - 1\right] = -I_{o2}\left[e^{-V_{D2}/\eta V_T} - 1\right]$$

$$e^{V_{D1}/\eta V_T} + e^{-V_{D2}/\eta V_T} = 2$$

$$V_{D1} = V_1 \; ; \; V_{D2} = -V_2$$

$$e^{V_1/\eta V_T} + e^{+V_2/\eta V_T} = 2$$

Si: $\eta = 2$; $V_T = \frac{KT}{q}$ $\Rightarrow \boxed{e^{qV_1/2KT} + e^{qV_2/2KT} = 2}$

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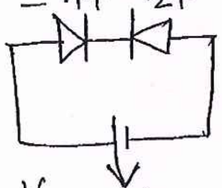
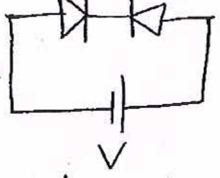
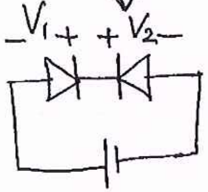


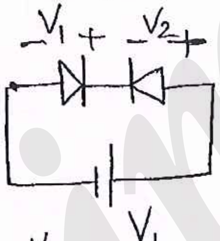
$e^{-qV_1/\eta KT} + e^{qV_2/\eta KT} = 2$




$e^{-qV_1/\eta KT} + e^{-qV_2/\eta KT} = 2$



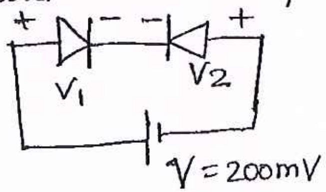

$e^{-qV_1/\eta KT} + e^{-qV_2/\eta KT} = 2$




$e^{-qV_1/\eta KT} + e^{qV_2/\eta KT} = 2$

These equations are applicable only when the diodes are identical

→ For the circuit shown in the figure, calculate voltage across each diode, If the diodes are identical and also madeup of Ge




$-V + V_1 - V_2 = 0$

$V_2 = V_1 \mp V = V_1 - 0.2V$

$e^{+V_1/\eta V_T} + e^{V_2/\eta V_T} = 2$

$e^{(2V_1 \mp V)/\eta V_T} = 2.$

$\frac{(2V_1 \mp V)}{V_T} = \ln 2$

$2V_1 \mp V = 0.0179$

$2V_1 = 0.0179 + 200 \times 10^{-3}$

$2V_1 = +0.2182$

$V_1 = +0.109V$

$V_2 = 0.11V.$

$V_2 = V_1 - 0.2$

$e^{V_1/V_T} + e^{V_2/V_T} = 2$

$e^{V_1/V_T} + e^{(V_1 - 0.2)/V_T} = 2$

$e^{V_1/V_T}\left[1 + e^{-\frac{0.2}{0.02586}}\right] = 2$

$e^{V_1/V_T} \simeq 2$

$V_1 = V_T \ln 2$

$= 0.02586 \ln 2$

$= 0.0179V$

$V_2 = 0.0179 - 0.2$

$= -0.182V$

Narasimha

$$e^{V_1/V_T} + e^{(V_1+25m-V)/V_T} = 2$$

$$e^{V_1/V_T}\left[1+e^{(25m-200m)/V_T}\right] = 2$$

$$e^{V_1/V_T}\left[1+e^{-175/26}\right] = 2$$

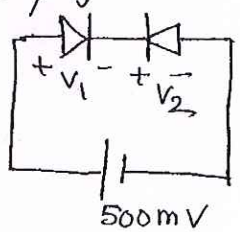
$$e^{V_1/V_T}\left[1+1.1\times10^{-3}\right] = 2$$

$$e^{V_1/V_T} = \frac{2}{\left[1+1.1\times10^{-3}\right]}$$

$$\Rightarrow V_1 = 0.0178\ V$$

$$V_2 = -0.1572\ V$$

→ For the circuit shown in the figure calculate voltage across the each diode, If the diodes are identical and made up of Si




$$e^{V_1/\eta V_T} + e^{-V_2/\eta V_T} = 2$$

$$e^{V_1/\eta V_T} + e^{-V_2/\eta V_T} = 2$$

$$-V + V_1 + V_2 = 0$$

$$V_1 + V_2 = 500mV$$

$$V_2 = 0.50 - V_1$$

$$e^{V_1/2V_T} + e^{-(0.5-V_1)/2V_T} = 2$$

$$e^{V_1/2V_T}\left[1+e^{-0.5/2V_T}\right] = 2$$

$$\frac{V_1}{2V_T} = \ln 2$$

$$e^{V_1/2V_T}\left[1+6.33\times10^{-5}\right] = 2$$

$$V_1 = 0.0358V$$

$$V_2 = 0.5 - 0.0358 = 0.464V$$

Narasimha

$$\frac{I_2}{I_{02}} = e^{\ldots} - 1$$

$$I_2 = I_{01} \qquad V_T \ln\left(1+\frac{I_2}{I_{02}}\right) = V_2$$

Applying KVL,

$$+V + V_1 - V_2 = 0$$

$$V_1 = V_2 - V = 0.0105 - 0.5$$

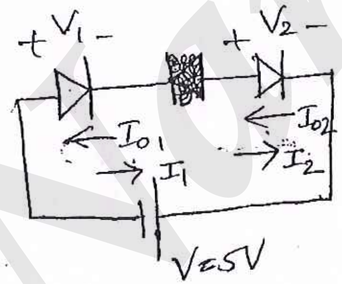
$$= -0.1895\,V$$

$$\Rightarrow V_2 = V_T \ln\left(1+\frac{I_2}{I_{02}}\right)$$

$$= 0.02586 \ln\left(1+\frac{I_{01}}{I_{02}}\right)$$

$$= 0.0105\,V$$

* When two diodes are connected in series back to back, it is not possible to calculate the voltage across the reverse biased diode first.

→ 


For the ckt shown in the figure, calculate voltage across the each diode $V_1$ & $V_2$ if the diodes are not identical and made up of Ge and also breakdown voltage of each diode is > 5V

Given $I_{01} = 5\mu A$ ; $I_{02} = 10\mu A$

$$I_1 = I_2$$

$$V + V_1 + V_2 = 0$$

$$V_1 = -V - V_2$$

$$I_1 = -I_{01}$$

$$I_2 = -I_{02}$$

$$I_2 = I_1 = -I_{01}$$

$$I_2 = I_{02}\left[e^{V_2/\eta V_T} - 1\right]$$

$$\frac{I_2}{I_{02}} = e^{V_2/\eta V_T} - 1$$

$$\frac{V_2}{\eta V_T} = \ln\left(1+\frac{I_2}{I_{02}}\right)$$

$$V_2 = V_T \ln\left(1+\frac{I_2}{I_{02}}\right)$$

$$V_2 = 0.02586 \ln\left(1+\left(-\frac{I_{01}}{I_{02}}\right)\right)$$

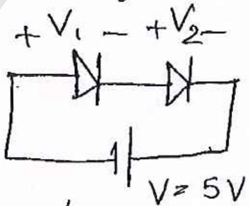
$$= 0.02586 \ln\left(1-\frac{5}{10}\right) = -0.018\,V$$

Narasimha

Narasimha

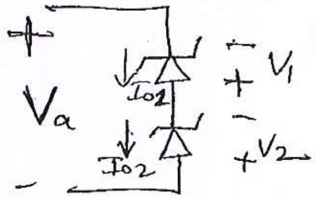
* When two diodes are connected in series in reverse bias, it is not possible to calculate the voltage across diode first which has least saturation current.

→ For the circuit shown in figure, calculate voltage across the each diode $V_1$ and $V_2$, if the diodes are identical and made up of Silicon and also breakdown voltage of each diode is greater than 5V.




$$V_1 = V_2 = -\frac{5}{2} = -2.5V$$

(Q) a) For the circuit shown in the figure, calculate voltage across each diode. $V_1$ and $V_2$ if the diodes are not identical and made up of Ge.




for a) $V_a = 9V$ Given $I_{01} = 5\mu A$

b) $V_a = 11V$ $I_{02} = 10\mu A$

$V_{Z1} = V_{Z2} = 10V$

$$I_2 = I_{02}\left[e^{V_2/\eta V_T} - 1\right]$$

$$\frac{I_2}{I_{02}} = e^{V_2/\eta V_T} - 1$$

$$\Rightarrow \frac{V_2}{\eta V_T} = \ln\left[1 + \frac{I_2}{I_{02}}\right]$$

$$V_2 = \eta V_T \ln\left[1 + \frac{I_2}{I_{02}}\right]$$

$$V_2 = \eta V_T \ln\left[1 - \frac{I_{01}}{I_{02}}\right]$$

$$\Rightarrow V_2 = 0.02586 \ln\left(1 - \frac{5}{10}\right)$$

$$= -0.018V$$

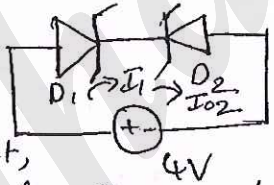
KVL ⇒

$$-V_a - V_1 - V_2 = 0$$

$$V_1 = -V_a - V_2$$

$$= -8.982V$$

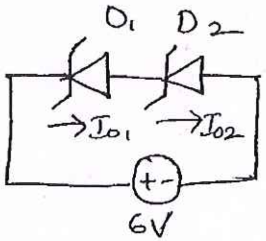
→ For the circuit shown in the figure, calculate overall current in the circuit, if the diodes are not identical and also the breakdown voltage of diode is 5V. Given $I_{01} = 25\mu A$, $I_{02} = 50\mu A$




a) $25\mu A$ clockwise  b) $25\mu A$ anticlockwise  c) $50\mu A$ clockwise ✓
d) $50\mu A$ anticlockwise.

$I_1 = I_{02} = 50\mu A$ clockwise

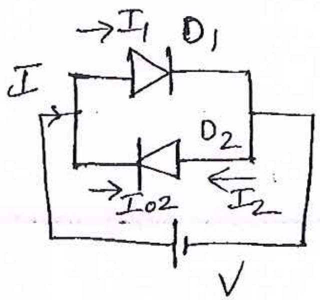
→ For the circuit shown in figure, calculate overall current in the circuit (Same as above Q)




6V > 5V ⇒ One diode gets breakdown
i.e, $D_1$ gets breakdown.
So current is $50\mu A$ clockwise

If it is 4V ⇒ Current is $25\mu A$ clockwise

→ For the circuit shown in the figure, find the relation between I and V if the diodes are identical




a) $I = I_0 \sinh V/\eta V_T$
b) $I = I_0 \cosh V/\eta V_T$
c) $I = 2I_0 \sinh V/\eta V_T$
d) $I = 2I_0 \cosh V/\eta V_T$

$$= I_0\left[e^{V/\eta V_T} - \cancel{1} - e^{-V/\eta V_T} + \cancel{1}\right]$$

$$I = I_0\left[e^{V/\eta V_T}\right] - I_0\left[e^{-V/\eta V_T}\right]$$

$$= 2I_0\left[\frac{e^{V/\eta V_T} - e^{-V/\eta V_T}}{2}\right]$$

$$\Rightarrow I = 2I_0 \sinh V/\eta V_T$$

$$\frac{V}{\eta V_T} = \ln\left(\frac{I}{I_0}\right)$$

$$\boxed{V = \eta V_T \ln\left(\frac{I}{I_0}\right)}$$

in terms of log.

→ In a uniformly doped abrupt pn junction, the doping level of the n-side is 4 times the doping level of the p side. The ratio of the depletion layer width of n-side vs p-side is.

$$N_A W_p = N_D W_n$$

$$\frac{W_n}{W_p} = \frac{N_A}{N_D} = \frac{N_A}{4N_A} = \frac{1}{4} = 0.25$$

→ The small signal capacitance of an abrupt $p^+n$ junction (non-linear) is 1nF at zero bias. If the built-in voltage is 1V, the capacitance at a reverse bias voltage of 99V is

$V_{bi} = V_0 = 1V$

$V_R = 99V$

$$C_T = \frac{C_{T0}}{\left(1 + \frac{V_R}{V_0}\right)^{1/2}}$$

$$= \frac{1nF}{\left(1 + \frac{99}{1}\right)^{1/2}} = \frac{1nF}{10} = 0.1nF$$

Narasimha

$$V_{j_2} = 0.8 + 7.2 = 8V$$

$$\omega_2 = ?$$

$$\frac{V_{j_2}}{V_{j_1}} = \frac{\omega_2^2}{\omega_1^2} \Rightarrow \omega_2 = \omega_1 \sqrt{\frac{V_{j_2}}{V_{j_1}}} = 2\mu m \sqrt{\frac{8}{2}}$$

$$\therefore \text{Width } \omega_2 = 4\mu m \qquad = 4\mu m$$

→ In an abrupt p-n junction, the doping concentration on p-side and n-side are $9 \times 10^{16}/cm^3$ and $1 \times 10^{16}/cm^3$. The p-n junction is reverse biased and the total depletion width is $3\mu m$. The depletion width on p-side is

$$N_A \omega_p = N_D \omega_n \qquad \text{(or) Use } \omega_p = \frac{N_A}{N_A + N_D} \cdot \omega$$

$$\omega_n = \frac{N_A}{N_D} \omega_p = \frac{9 \times 10^{16}}{1 \times 10^{16}} \times \omega_p$$

$$\Rightarrow \omega_n = 9\omega_p$$

$$\omega = \omega_n + \omega_p \Rightarrow \omega = 10\omega_p \Rightarrow \omega_p = 0.3\mu m //$$

→ Consider an abrupt p-n junction. Let $V_{bi}$ be the built-in potential of this junction and $V_R$ be the applied reverse bias. If the junction capacitance is 1pF for $V_{bi} + V_R = 1V$, then for $V_{bi} + V_R = 4V$, the junction capacitance will be?

$$C_T \propto \frac{1}{\sqrt{V_j}}$$

$$\frac{C_{T_2}}{C_{T_1}} = \sqrt{\frac{V_{bi_1} + V_{R_1}}{V_{bi_2} + V_{R_2}}} \Rightarrow C_{T_2} = C_{T_1} \sqrt{\frac{V_{j_1}}{V_{j_2}}} = 1P \times \sqrt{\frac{1}{4}} = 0.5pF$$

$$I_{Si} = I_{o\,Si}\left[e^{V/\eta V_T} - 1\right]$$

$$\frac{1}{1} = \frac{I_{o\,Ge}}{I_{o\,Si}}\left[\frac{(e^{0.1435/V_T} - 1)}{(e^{0.718/2V_T} - 1)}\right]$$

$$\frac{e^{0.718/2V_T} - 1}{e^{0.1435/V_T} - 1} = \frac{I_{o(Ge)}}{I_{o(Si)}} = \frac{\cancel{1069222.234}}{\cancel{2560.0098694}} \quad \cancel{393305.6}$$

$$\frac{I_{o(Ge)}}{I_{o(Si)}} = \frac{1069223.234}{256.008}$$

$$\frac{I_{o(Ge)}}{I_{o(Si)}} = 4176 \simeq 4 \times 10^3$$

→ A p-n junction is in series with a 100Ω resistor and is forward biased so that a current of 100 mA flows. If the voltage across this combination is instantaneously reversed at t=0, current through diode is approximately given by.

a) 0 mA  b) 100 mA  c) 200 mA  d) 50 mA

→ In a Ge p-n junction diode, $\sigma_p = 1\ S/cm$ and $\sigma_n = 0.1\ S/cm$ and $L_n = L_p = 0.15$ cm. Find the ratio of diffusion current due to holes to electrons.

$$J_p = -eD_p \frac{dp}{dx} \qquad \frac{I_{pn}(0)}{I_{np}(0)} = \frac{L_n \sigma_p}{L_p \sigma_n} = 10$$

$$J_n = eD_n \frac{dn}{dx}$$

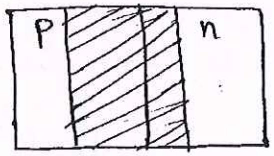
Narasimha

$$e^{-0.05/0.02586} - 1 \qquad \simeq 6.9$$

$$= \frac{5.9}{0.89}$$

$$= 6.9$$

→ Show that for an alloy p-n junction with $N_A << N_D$, the width of the depletion region is $w = \left[\frac{2\varepsilon \mu_p V_j}{\sigma_p}\right]^{1/2}$ where $V_j$ is the junction potential.




$$V_j = \frac{eN_A}{2\varepsilon} w^2$$

$$\Rightarrow w = \left[\frac{2\varepsilon V_j}{eN_A}\right]^{1/2}$$

$$\sigma_p = p\mu_p e \simeq N_A \mu_p e$$

$$\Rightarrow N_A e = \frac{\sigma_p}{\mu_p}$$

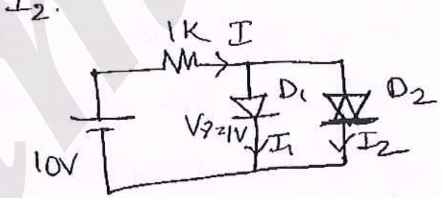
$$\Rightarrow w = \left[\frac{2\varepsilon V_j}{\frac{\sigma_p}{\mu_p}}\right]^{1/2}$$

$$\Rightarrow w = \left[\frac{2\varepsilon \mu_p V_j}{\sigma_p}\right]^{1/2}$$

Narasimha


$$I_2 = \frac{10-1-5}{2K+2K} = 1mA.$$

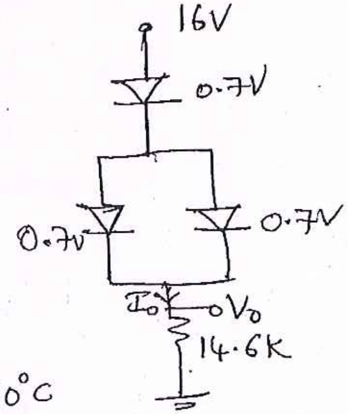
→ For the circuit shown in figure, diodes $D_1$ and $D_2$ are identical. Calculate currents $I_1$ & $I_2$.




$$I = \frac{10-1}{1K} = 9mA$$

$$I_1 = I_2 = \frac{9}{2} mA = 4.5mA$$

→ For the circuit shown in the figure, calculate $V_o$ and $I_o$




$$V_o = 16-0.7-0.7 = 14.6V$$

$$I_o = \frac{16-0.7}{14.6K} = 1mA.$$

→ Calculate the factor by which the reverse saturation current of diode is multiplied when temperature increases from 25°C to 80°C

$$I_{o2} = I_{o1} \times 2^{(T_2-T_1)/10}$$

$$= I_{o1} \times 2^{(80-25)/10}$$

$$= I_{o1} \times 2^{5.5}$$

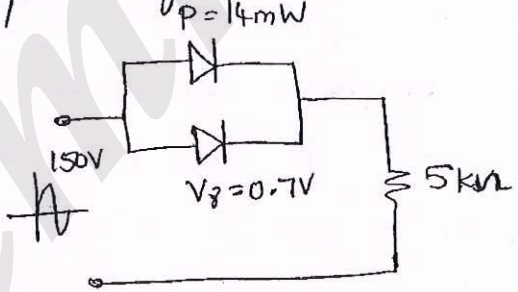
$$I_{o2} = 45.25\, I_{o1}$$

∴ Multiplying factor = 45.25

Narasimha

$= 0.0259\ cm$

→ In the circuit shown in figure, verify whether the diodes can withstand for maximum input signals or not.




$P = 14mW$

$I = \frac{P}{V} = 20mA$

$I = \frac{150 - 0.7}{5K} \simeq 30mA$

Current through each diode $= 15mA > 20mA$

∴ Diodes will withstand.

2/8/13

→ Consider a Si p-n junction at $T = 300K$ with doping concentrations of $N_A = 10^{16}/cm^3$, $N_D = 10^{15}/cm^3$ and built in potential $V_{bi} = 0.635$. Calculate Space charge width.

$$W = \sqrt{\frac{2\varepsilon}{e}(V_{bi})\left(\frac{1}{N_A} + \frac{1}{N_D}\right)}\ cm$$

$$= \sqrt{\frac{2 \times 8.854 \times 10^{-14} \times 0.635}{1.6 \times 10^{-19}}\left[\frac{1}{10^{16}} + \frac{1}{10^{15}}\right]}$$

$$= 0.96\ \mu m$$

Narasimha

$$= 2.86\ \mu m = \sqrt{\frac{2\times 8.854\times 10 \times 12}{1.6\times 10^{-19}}\left(0.635+5\right)\left(\frac{1}{10^{16}}+\frac{1}{10^{15}}\right)}$$

→ Consider the following parameters in Si p-n junction $N_A = N_D = 10^{16}/cm^3$, $n_i = 1.5\times 10^{10}/cm^3$, $D_n = 25\ cm^2/s$, $D_p = 10\ cm^2/s$, $\tau_p = \tau_n = 5\times 10^{-7}s$ and $\varepsilon_r = 11.7$. Calculate reverse saturation current density.

$$I_0 = Ae\left[\frac{D_p}{L_p N_D} + \frac{D_n}{L_n N_A}\right] n_i^2$$

$$L_p = \sqrt{\tau_p D_p}$$

$$L_n = \sqrt{\tau_n D_n}$$

$$\frac{I_0}{A} = n_i^2 e\left[\frac{D_p}{L_p N_D} + \frac{D_n}{L_n N_A}\right]$$

$$J_0 = n_i^2 e\left[\sqrt{\frac{D_p}{\tau_p}}\cdot\frac{1}{N_D} + \sqrt{\frac{D_n}{\tau_n}}\cdot\frac{1}{N_A}\right]$$

$$J_0 = 36\left[4.472\times 10^{-13} + 7.07\times 10^{-13}\right]$$

$$= 4.155\times 10^{-11}\ A/cm^2 = 41.55\ pA/cm^2$$

→ Calculate the barrier capacitance of a Ge p-n junction whose area is 1mm×1mm and space charge thickness is $2\times 10^{-4}$cm and $\varepsilon_r = 16$

Narasimha

$= 0.4 \times 10$

$= 0.07\, nF$

→ A Ge diode has a saturation current of 0.1 pA at 20°C. Find its current when it is forward biased by 0.55V. and also find the current in the same diode when the temperature raised to 100°C.

$$I = I_0 \left[ e^{V/\eta V_T} - 1 \right]$$

In Ge $\quad I = I_0 \left[ e^{V/V_T} - 1 \right]$

$$V_T = \frac{T}{11600} = \frac{273+20}{11600} = 0.025$$

$$= 0.1 \times 10^{-12} \left[ e^{0.55 / \frac{20+273}{11600}} - 1 \right]$$

$$= 0.286\, mA$$

At 100°C ⇒ T = 100°C ⇒ $V_T = \frac{100+273}{11600}$

$= 0.032$

$$I_0 \big|_{100°C} = 2^{(T_2 - T_1)/10} \times I_0 \big|_{20°C}$$

$$= 2^{(100-20)/10} \times 0.1 \times 10^{-12}$$

$$= 2^8 \times 0.1 \times 10^{-12}$$

$$= 25.6\, pA$$

$$I = I_0 \left[ e^{V/V_T} - 1 \right] = 25.6 \times 10^{-12} \left[ e^{0.55/0.032} - 1 \right]$$

$$= 7.4\, mA$$

11600

$$V_o = KT \ln\left(\frac{N_A N_D}{n_i^2}\right)$$

$$= V_T \ln\left(\frac{N_A N_D}{n_i^2}\right)$$

$$= 0.0256 \ln\left(\frac{10^{22} \times 1.2 \times 10^{21}}{(1.5 \times 10^{16})^2}\right)$$

$$= 0.632V$$

→ The capacitance of an abrupt p-n junction $1 \times 10^{-8}\ m^2$ in area measured at $-1V$ reverse bias is $5pF$. The built in voltage of this device is $0.9V$. When the diode is forward biased with $0.5V$, a current of $10mA$ flows. and the n-region minority hole life time is known to be $1\mu$second at $300K$. Calculate

(a) Depletion layer capacitance of this junction at $0.5V$ forward bias.

(b) Diffusion capacitance of the diode operating as in part (a) at $300K$.

Given $A = 1 \times 10^{-8} m^2$ $\quad V = 0.5V$

$V_R = -1V$ $\quad I = 10mA$

$C_T = 5pF$ $\quad \tau_p = 1\mu s.$

$V_o = 0.9V$

Narasimha

$= 10.89\ pF$

→ A step graded Ge p-n junction has $N_D = 500 N_A$ where $N_A$ corresponds to two acceptor atoms / $10^8$ Ge atoms. (a) Calculate contact potential at room temperature. (b) Repeat part (a) for Si p-n junction. It is given that the no: of atoms/$cm^3$ in Ge is $4.4\times10^{22}$ atoms/$cm^3$ and that in Si is $5\times10^{22}$ atoms/$cm^3$, $K = 1.38\times10^{-23}\ J/K$, $q = 1.6\times10^{-19}\ C$, $n_i$ for Ge is $2.5\times10^{13}/cm^3$ and $n_i$ for Si is $1.5\times10^{10}/cm^3$

(a)

$$V_o = KT \ln\left(\frac{N_A N_D}{n_i^2}\right)$$

$$KT = \frac{T}{11600} = 0.02586$$

$$N_A = 4.4\times10^{22} \times \frac{2}{10^8} = 8.8\times10^{14}/cm^3$$

$$N_D = 500 N_A = 44\times10^{16}/cm^3$$

$$V_o = 0.02586\left[\ln\left[\frac{8.8\times10^{14}\times44\times10^{16}}{(2.5\times10^{13})^2}\right]\right]$$

$$= 0.3449V$$

(b)

$$N_A = 5\times10^{22}\times\frac{2}{10^8} = 10^{15}/cm^3$$

$$N_D = 500 N_A = 5\times10^{17}/cm^3$$

$$V_o = 0.0258 \ln\left[\frac{10^{15}\times5\times10^{17}}{(1.5\times10^{10})^2}\right] = 0.735V$$

$$= 0.02586 \ln\left(\frac{10^{23} \times 10^{21}}{(1.5\times10^{16})^2}\right)$$

$$= 0.69$$

$$\omega = \sqrt{\frac{2\varepsilon V_0}{q}\left[\frac{1}{N_A}+\frac{1}{N_D}\right]}$$

$$= \sqrt{\frac{2\times 8.85\times10^{-12}\times 11.8}{1.6\times10^{-19}}\left[\frac{1}{10^{23}}+\frac{1}{10^{21}}\right]}$$

$$= 0.95\ \mu m$$

→ A Si abrupt pn junction at 300K has acceptor density $N_A = 10^{18}/cm^3$ and donor density $N_D = 10^{15}/cm^3$. If the intrinsic concentration $n_i = 1.5\times10^{10}/cm^3$ calculate built-in voltage. Derive the relations used.

$$V_0 = KT \ln\left(\frac{N_A N_D}{n_i^2}\right)$$

$$= 0.02586 \ln\left(\frac{10^{15}\times10^{18}}{(1.5\times10^{10})^2}\right)$$

$$= 0.753V$$

Narasimha

$$r_F = \frac{0.034}{0.011} = 3.07\,\Omega$$

$$r_r = \frac{0.034}{30\times10^{-6}} = 1.1\,K\Omega$$

→ A Si diode showed currents of 2mA and 10mA when the diode voltages were 0.6V and 0.7V. Estimate the operating temperature of the diode junction.

$I_1 = 2mA \qquad I_2 = 10\,mA \qquad \eta = 2$

$V_1 = 0.6V \qquad V_2 = 0.7V$

(neglect change in $I_0$)

$$I = I_0\left(e^{V/\eta V_T} - 1\right)$$

$$I_1 = 2 = I_0\left(e^{0.6/T_1/11600} - 1\right)$$

$$I_2 = 10 = I_0\left(e^{0.7/T_2/11600} - 1\right)$$

$$\frac{I_2}{I_1} = \frac{\left(e^{V_2/\eta V_T} - 1\right)}{\left(e^{V_1/\eta V_T} - 1\right)}$$

$$\frac{I_2}{I_1} \simeq \frac{e^{V_2/\eta V_T}}{e^{V_1/\eta V_T}} \Rightarrow e^{(V_2 - V_1)/\eta V_T} = 5$$

$$5\,e^{V_1/\eta V_T} = e^{V_2/\eta V_T}$$

$$\Rightarrow e^{(0.7-0.6)/2V_T} = 5$$

$$\Rightarrow e^{0.1/2V_T} = 5$$

$$\Rightarrow V_T = \frac{0.1}{2\ln(5)}$$

$$\frac{T}{11600} = 0.03106$$

$$\Rightarrow T = 360.374K$$

Narasimha

$\sigma_p = N_A \mu_p q \Rightarrow N_A = \dfrac{\sigma_p}{\mu_p q} = 1.25\times10^{18}$

$\Rightarrow N_D = \dfrac{\sigma_n}{\mu_n q} = 4.8\times10^{15}$

$$V_0 = KT \ln\left(\frac{N_A N_D}{n_i^2}\right)$$

$$= \frac{1.38\times10^{-23}\times300}{1.6\times10^{-19}} \ln\left(\frac{1.25\times10^{18}\times4.8\times10^{15}}{(1.5\times10^{10})^2}\right)$$

$$= 0.799V$$

→ A step graded Ge diode has a resistivity of $2\Omega$-cm on p-side and $1\Omega$-cm on n-side. Calculate the height of the barrier potential and also derive the famula used. $\mu_p = 1800\ cm^2/V\text{-sec}$, $\mu_n = 3800\ cm^2/V\text{-sec}$, $n_i = 2.5\times10^{13}/cm^3$ at 300K.

$\rho_p = 2\ \Omega\text{-cm} \Rightarrow \dfrac{1}{N_A \mu_p q} = 2 \Rightarrow N_A = \dfrac{1}{2\times1800\times1.6\times10^{-19}} = 8.22\times10^{14}$

$\rho_n = 1\ \Omega\text{-cm} \Rightarrow \dfrac{1}{N_D \mu_n q} = 1 \Rightarrow N_D = \dfrac{1}{1\times3800\times1.6\times10^{-19}} =$

$$C_j = \frac{C_{j_0}}{\left(1+\frac{V_R}{V_0}\right)^{1/2}}$$

$$= \frac{0.8p}{\left(1+\frac{5}{0.753}\right)^{1/2}}$$

$$= 2.2pF$$

Transition Capacitance ($C_T$) & Junction Capacitance ($C_j$)

Diffusion capacitance $C_D$

$$V_0 = KT\ln\left(\frac{N_A N_D}{n_i^2}\right)$$

$$= 0.02586 \ln\left(\frac{10^{16} \times 10^{17}}{1.5\times10^{10}}\right)$$

$$= 0.753$$

→ A Si p-n junction at T= 300K, has a reverse saturation current of $I_S = 2\times10^{-14}$ A. Determine required forward bias voltage to produce a current of a) $I_D = 50\mu A$ and b) $I_D = 1mA$.

$$I = I_0\left[e^{V/\eta V_T} - 1\right]$$

$I_D = 50\mu A \Rightarrow 10^{-6}\times50 = 2\times10^{-14}\left[e^{V/2\times0.02586} - 1\right]$

$$2.5\times10^{15} = e^{V/0.05172} - 1$$

$$\frac{V}{0.05172} = \ln\left(1 + 2.5\times10^{15}\right)$$

$$V = 1.12V$$

$$= 1.12\,V$$

b) $I_D = 1\,mA$

$$\Rightarrow V = 2 \times 0.02586 \ln\left[1 + \frac{10^{-3}}{2 \times 10^{-14}}\right]$$

$$= 1.27\,V$$

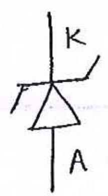
## Zener Diode:

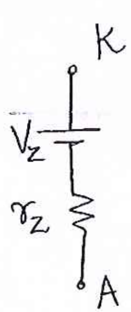
A diode which is designed with sufficient power dissipation capabilities and operates in breakdown region may be employed as a voltage reference or constant voltage source is called Zener diode.

→ Zener diode is a heavily doped p-n junction diode and its doping concentration is 1 impurity atom / $10^5$ Si & Ge atoms.

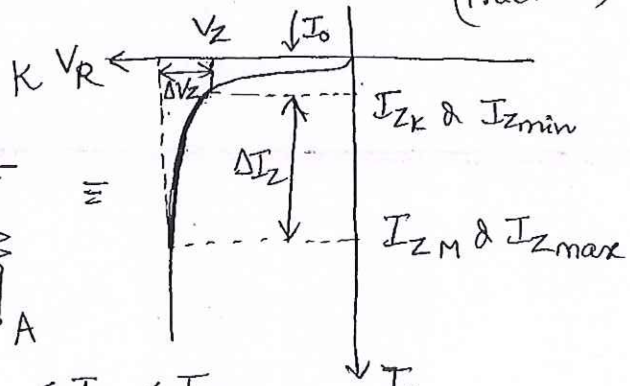
→ Zener diode always operates in reverse biased breakdown region.

Schematic Symbol.




V-I Characteristics:
(Practical)



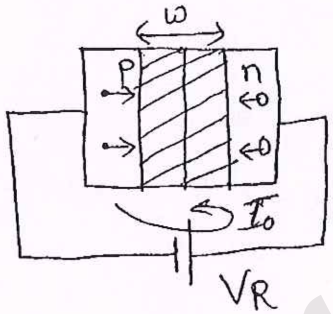

$$I_{ZK} \le I_Z < I_{ZM}$$

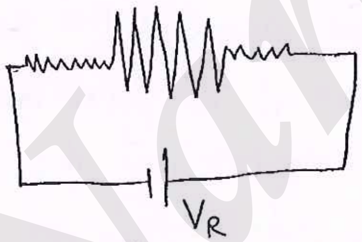
Narasimha

$\downarrow I_R$ →ON →OFF

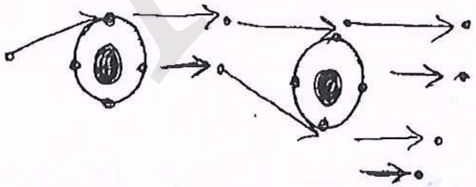
## Avalanche Break Down

→ happens in lightly doped junctions



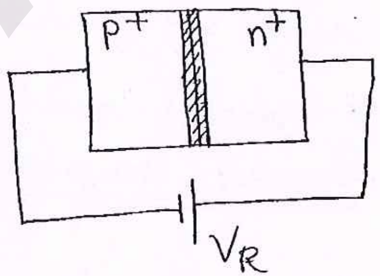




$$E = \frac{V_j}{\omega}$$



## Zener Break Down

→ happen in heavily doped junctions.




$$E = \frac{V_j}{\omega}$$

E is more because ω is small.

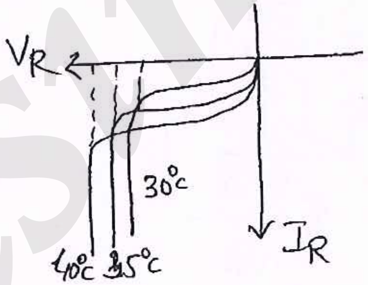
→ It is a cumulative process.

→ It happens due to collision of $e^-$ with the ions.

→ Low doping concentration.

→ Avalanche breakdown is having positive temperature coefficient i.e, as temperature increases, avalanche breakdown voltage increases.

→ Avalanche breakdown is a impact ionization process.




Zener Breakdown:

→ Initially available carriers do not acquire the sufficient energy to disturb the bonds but it is possible to initiate the breakdown through direct rupture of the bonds because of existence of strong electricfield at the junction.

→ It occurs at < 6eV

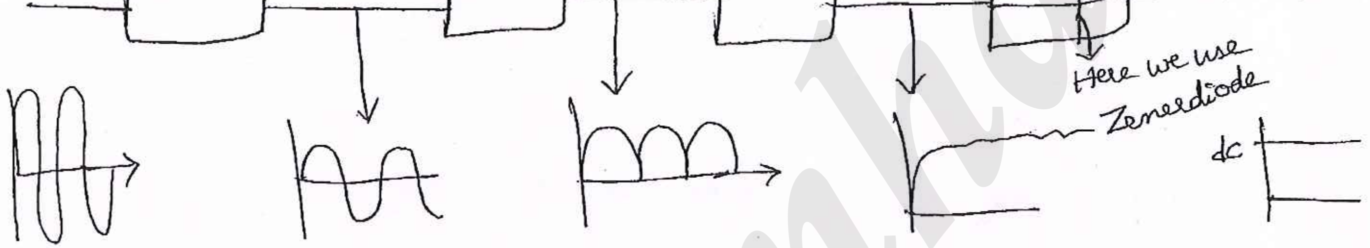
→ It is not a cumulative process

→ It happens due to direct rupture of the bonds because of existence of strong electric field at the junction.

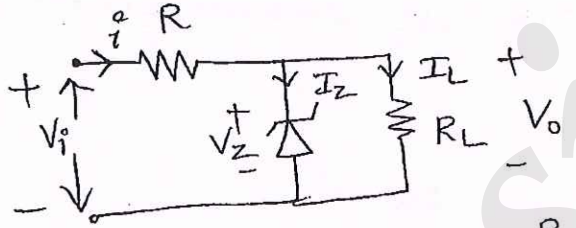
→ High doping levels.

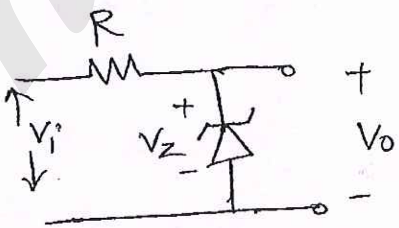
→ Zener breakdown voltage is having negative temperature coefficient i.e, as temperature increases, breakdown voltage decreases.

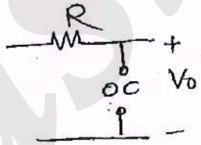
Narasimha



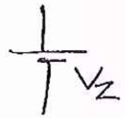

→

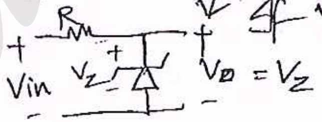


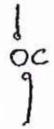



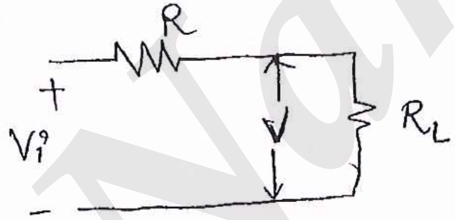

If $V_{in} \geq V_Z \Rightarrow$ ON




If $V_{in} < V_Z \Rightarrow$ OFF

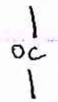



Calculate V

$$V = \frac{V_i R_L}{R + R_L}$$

(i) If $V < V_Z \Rightarrow$ OFF

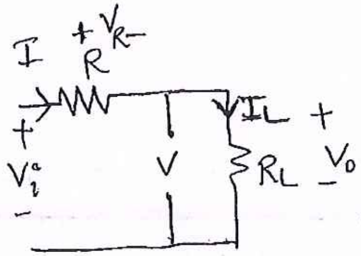



$I_Z = 0$

$I_L = I$

$V_0 = V$

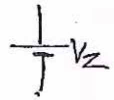
$V_R = IR = V_i - V$

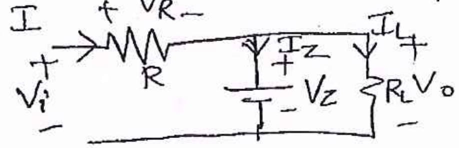



$$I = \frac{V_R}{R} = \frac{V_i - V}{R}$$

$P_Z = V_Z I_Z = 0$

(ii) If $V \geq V_Z \Rightarrow$ ON




$V_R = V_i - V_Z = IR$

$I = I_Z + I_L$

$$I = \frac{V_R}{R} = \frac{V_i - V_Z}{R}$$

$$\boxed{I_Z = I - I_L}$$


$V_R = V_i - V = 16 - 8 = 8V$

$I_Z = 0 \; ; \; P_Z = 0$

→ Repeat the above problem for $R_L = 3k\Omega$.

$V = \frac{16 \times 3K}{3K + 1K} = \frac{48}{4} = 12V > V_Z$ Zener diode is ON state

$V_o = \cancel{V_R} + V_Z = 10V$

$V_R = V_i - V_Z = 16 - 10 = 6V$

$I = \frac{V_R}{R} = \frac{6}{1K} = 6mA$

$I_Z = I - I_L = I - \frac{V_Z}{R_L}$

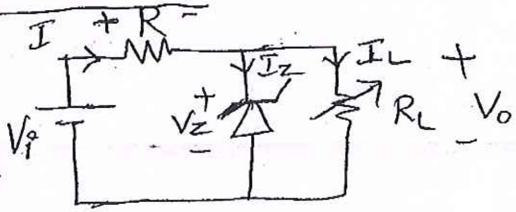
$= I - \frac{10}{3K}$

$\therefore I_Z = 6mA - 3.33mA$

$= 2.67 mA$

$P_Z = I_Z V_Z = 10 \times 2.67m = 26.7 mW$

→ Case(ii): $V_i$ fixed and $R_L$ varies




$R_L$ Fixed: $I^* = I_Z^* + I_L^* \Rightarrow V_o = I_L^* R_L^*$

$R_L\uparrow$ : $I^* = I_Z\uparrow + I_L\downarrow \Rightarrow V_o = I_L\downarrow R_L\uparrow$

$I^* = \frac{V_i^* - V_Z^*}{R^*}$ $\left[\because I_Z < I_{Zm} \text{ \& } I_Z < I_{Zmax}\right]$

$\therefore I = I_{Zm} + I_{Lmin}$ & $I_{Zmax} + I_{Lmin}$

$$\Rightarrow I_{L(max)} = I - I_{Z_K} = I - I_{Z(min)}$$

$$\boxed{R_{L(min)} = \frac{V_Z}{I_{L(max)}}}$$

$$I_{L_{max}} \simeq I = \frac{V_i - V_Z}{R}$$

$$P_{Z(max)} = V_Z I_{Z_{max}}$$

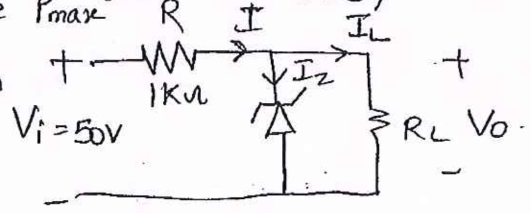
$$R_{L_{min}} = \frac{V_Z}{\frac{V_i - V_Z}{R}} = \frac{V_Z R}{V_i - V_Z}$$

$$P_{Z(min)} = V_Z I_{Z_{min}}$$

3/8/13

For the circuit shown in the figure find the range of load current and resistance that will maintain output voltage across zener diode fixed at 10V. and also calculate $P_{max}$

i.e, find $R_L$ min, $R_L$ max, $I_L$ min and $I_{L_{max}}$.




$$I = I_Z + I_L$$

$$V_o = I_L R_L$$

$$I = \frac{V_i - V_Z}{R}$$

$I_{Z_M} = 32\,mA$

$$V = \frac{50 \times R_L}{1K + R_L}$$

$I_L R_L = 10V \Rightarrow V_Z = 10V$

$$10 = \frac{50 R_L}{1K + R_L}$$

$I_{Z_{min}}$ is not given So take it as 0

$10K + 10R_L = 50R_L \Rightarrow R_L = 250\Omega$

$$R_{L_{min}} = \frac{V_Z R}{V_i - V_Z} = \frac{10 \times 1K}{50 - 10} = 250\Omega$$

$$I = \frac{V_i - V_Z}{R} = \frac{50 - 10}{1K} = 40mA$$

$$R_{L_{max}} = \frac{V_Z}{I_{L_{min}}} = \frac{10V}{8mA} = 1.25k\Omega$$

$$I_{L_{min}} = I - I_{Z_m} = 40 - 32 = 8mA$$

$$I_{L_{max}} = I - I_{Z_K} = I - I_{Z_{min}} \simeq I = 40mA$$

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$V_i \uparrow$ : $I = I_Z + I_L \Rightarrow V_0 = I_L R_L$ $\left[\because I_Z \leq I_{Zm} \;\&\; I_Z < I_{Zmax}\right]$

$$I_{max} = I_{Zmax} + I_L$$

$$\boxed{V_{i\,max} = V_{R\,max} + V_Z}$$

$$\Rightarrow V_{i\,max} = I_{max} R + V_Z$$

$V_i \downarrow$ : $I\downarrow = I_Z\downarrow + I_L^{*} \Rightarrow V_0 = I_L^{*} R_L^{*}$ $\left[\because I_Z \geq I_{Zk} \;(\&)\; I_Z \geq I_{Zmin}\right]$

$$I_{min} = I_{Zk} + I_L = I_{Zmin} + I_L$$

$\simeq I_L$ (when $I_{Zmin}$ is not given & $I_{Zmin} = 0$)

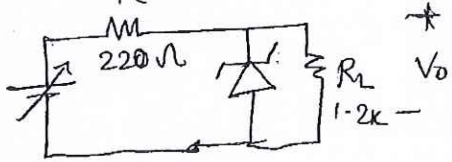
$$\boxed{V_{i\,min} = V_{R\,min} + V_Z}$$

$$\Rightarrow V_{i\,min} = I_{min} R + V_Z$$

$$I_{min} = I_{Zmin} + I_L \simeq I_L = \frac{V_Z}{R_L}$$

$$V_{i\,min} = \frac{V_Z}{R_L} \cdot R + V_Z = \left(1 + \frac{R}{R_L}\right) V_Z = \left[\frac{R_L + R}{R_L}\right] V_Z$$

→ For the circuit shown in the figure, find the range of input voltage that will maintain o/p voltage fixed at 20V.




$I_{ZM} = 60mA$.

$$V_{i\,min} = \left(1 + \frac{R}{R_L}\right) V_Z$$

$$= \left(1 + \frac{220}{1200}\right) 20$$

$$= 23.67V$$

$$I_L = \frac{V_Z}{R_L} = \frac{20}{1.2K} = 0.017A \approx 16.67mA$$

$$I_{max} = I_{Zmax} + I_L = 60m + 16.67m$$

$$= 76.67mA$$

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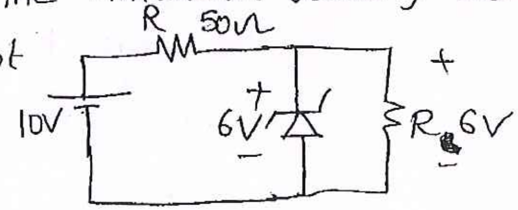
<u>$V_i$ Variable and $R_L$ fixed:</u>

$$\frac{V_{i\,min}-V_Z}{R} \geq I_{Z\,min}+I_L \Rightarrow \boxed{R \leq \frac{V_{i\,min}-V_Z}{I_{Z\,min}+I_L}}$$

<u>$V_i$ Variable and $R_L$ variable:</u>

$$\frac{V_{i\,min}-V_Z}{R} \geq I_{Z\,min}+I_{L\,max} \Rightarrow \boxed{R \leq \frac{V_{i\,min}-V_Z}{I_{Z\,min}+I_{L\,max}}}$$

→ A 6V Zener diode shown below has zero zener resistance and a knee current of 5mA. The minimum value of R so that the voltage across it does not fall below 6V is




$V_Z = 6V$, $I_{Z\,min} = I_{ZK} = 5mA$.

$$R_{min} = \frac{V_Z}{I_{L\,max}} = \frac{6}{75m} = 80\Omega$$

$I = I_L + I_Z$

$I_{L\,max} = I - I_{ZK}$

$I = \frac{10-6}{50} = \frac{4}{50} = 0.08A$
$= 80mA$

$I_{L\,max} = 80-5$
$= 75mA$

→ A Zener diode ~~shown~~ in a circuit shown in below figure has a knee current of 5mA and a maximum allowed power dissipation of 300mW. What are the min and max load currents that can be drawn safely from the circuit keeping the output voltage $V_o$ constant at 6V.

$V_Z = V_o = 6V$

$I_{Z_K} = 5mA$ $P_{max} = 300mW$ ~~$V_Z I_{Z}$~~ $P_{max} = V_Z I_{Z\,max}$

$\Rightarrow I_{Z\,max} = P_{max}/V_Z$

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$I_{Lmin} = \ldots - I_{Zmax}$

$= 60 - 50mA$

$= 10mA.$

$= 60 - 5$

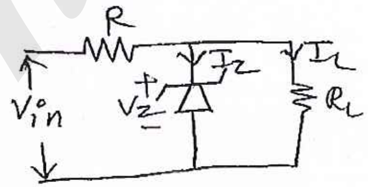
$= 55mA$

→ A Zener diode regulator as shown in the figure is to be designed to meet the following specifications.

$I_L = 10mA$, $V_o = 10V$, $V_i = 30$ to $50V$

$V_Z = 10V$ and $I_{Z_K} = 1mA$.

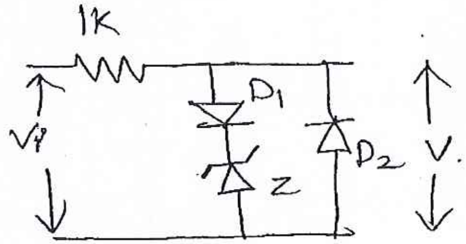
For proper operation of the circuit, the value of R is




$$I = I_Z + I_L$$

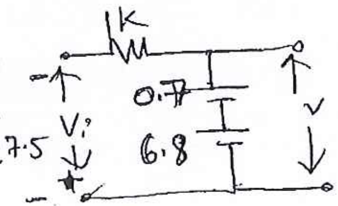
$$R \leq \frac{V_{i\,min} - V_Z}{I_{Z\,min} + I_L} = \frac{30-10}{1m + 10m} = \frac{20}{11m} = 1.8k\Omega$$

→ In the following limiter circuit, an input Voltage $V_i = 10 \sin 100\pi t$ is applied. Assume that the diode drop is 0.7V when it is forward biased and the zener break down voltage 6.8V. The max and minimum values of the output voltages are




$V_Z = 6.8V$, $V_{D_1} = V_{D_2} = 0.7V$

For +ve $V_i$ ⇒ Z is in reverse bias




$\therefore V_i \geq 7.5$

$\Rightarrow V_Z = 6.8 + 0.7 = 7.5V$

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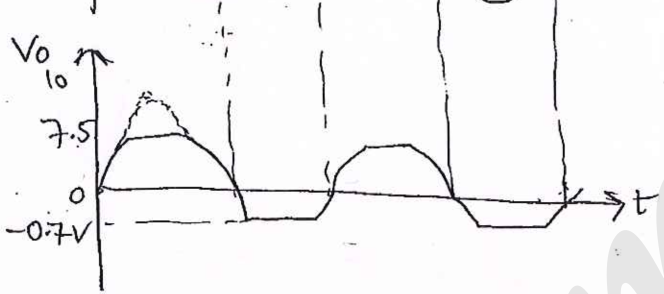
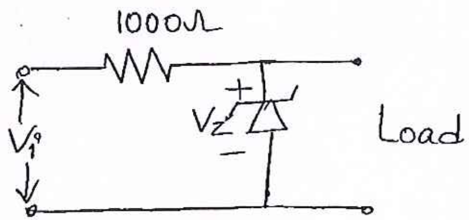



→ The Zener diode in the regulator circuit shown in the figure has Zener voltage of 5.8V and a knee current of 0.5mA. The maximum load current drawn from this circuit ensuring proper functioning over the input voltage range between 20 and 30 V is




$V_Z = 5.8V$

$I_{Z_K} = 0.5mA$

$V_i = 20 \text{ to } 30V$

$I_{L_{max}} = ?$

$$I_{R_{min}} = \frac{20-5.8}{1000} = 14.2mA$$

$$I_{R_{max}} = \frac{30-5.8}{1000} = 24.2mA.$$

$I = I_Z + I_L$

$$I_{L(max)} = I - I_{Z_K}$$
$$= 14.2 - 0.5$$
$$= 13.7mA$$

→ For the circuit shown below, assume that the Zener diode is identical with a breakdown voltage of 6V. The waveform observed across R is.

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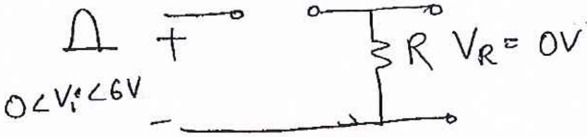
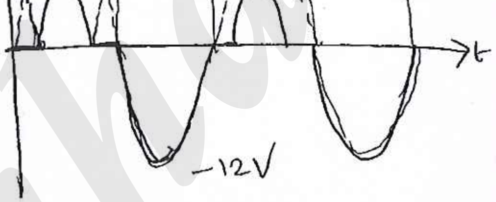
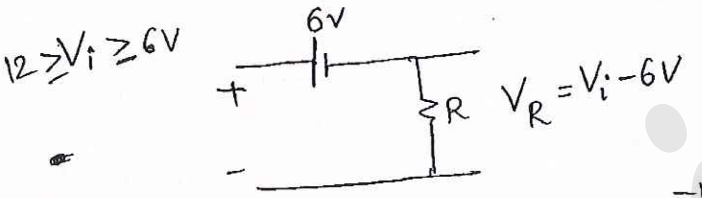
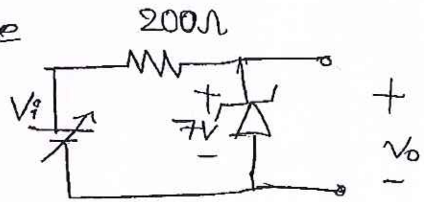




→ For the zener diode shown in figure, the Zener voltage at Knee is 7V. The knee current is negligible and the Zener dynamic resistance is 10Ω. If the input voltage $V_i$ range is from 10V to 16V, the output voltage $V_o$ range is

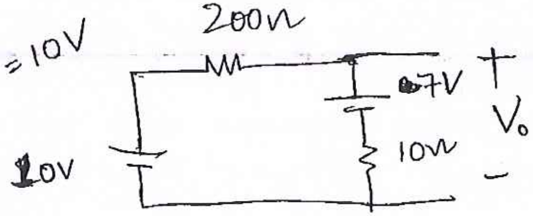



$V_Z = 7V$, $r_Z = 10\Omega$

$V_i = 10$ to $16$.

$$I = \frac{V_i - V_Z}{R} = \frac{10-7}{R+r_Z} = \frac{3}{210} = 0.014\,A = I_Z$$

i) $V_i = 10V$




$V_o = 7V + 10 \times 0.014$
$= 7 + 0.14$
$= 7.14\,V$

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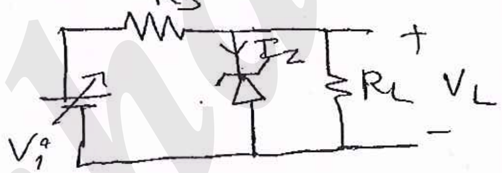



$V_i = 21$ to $27V$

$R_L = 250\Omega$ to $2k\Omega$

$V_Z = 16V$

$I_{Z_K} = 15mA.$

$$I_{L\max} = \frac{V_Z}{R_{L\min}} = \frac{16}{250}$$

$$= 0.064$$

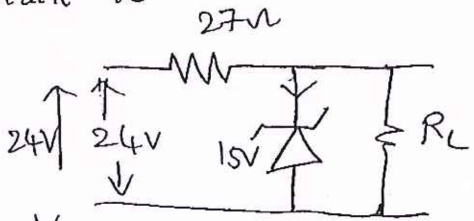
$$= 64mA$$

$$R \le \frac{V_{i\min} - V_Z}{I_{Z\min} + I_{L\max}}$$

$$= \frac{21-16}{15m + 64m}$$

$$= 0.063291k = 63.3\ \Omega$$

→ The circuit in figure shows Zener regulator DC power supply. The minimum value of $R_L$ down to which the output voltage remains constant is




$$I_R = \frac{24-15}{27} = 0.33A$$

$$I = I_Z + I_L$$

$$R_{L\min} = \frac{V_Z}{I_{L\max}}$$

$$I_{L\max} = I - I_{Z_K}$$

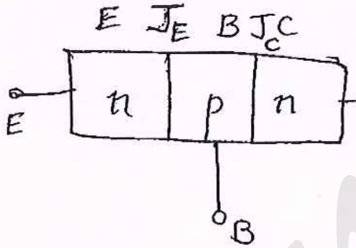
$$\le I = 0.33$$

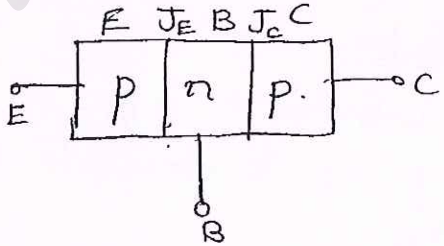
$$= \frac{15}{0.33} = 45\Omega$$

(∵ It ~~kar~~ will never get 0.6 V as $D_1$ is fwd biased at 0.2V) p-type Si is sandwiched between two n-type Silicon layers alternatively Junction transistor consists of Si & Ge Crystal in which a layer of n-type Si is sandwiched between two p-type Si layers. Former one is called npn transistor and later is called pnp transistor.

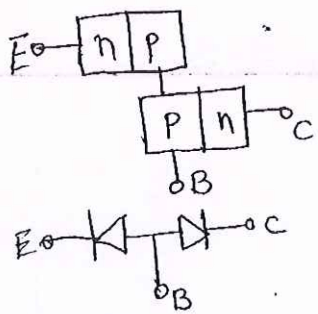
Depletion: n-channel DMOSFET, p-channel DMOSFET.
Enhancement: nchannel EMOSFET, pchanne EMOSFE

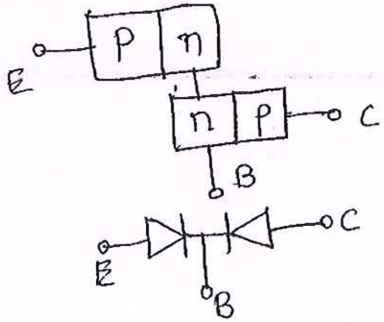
* Two diodes connected back to back will never act like transistor.




→ BJT consists of three layers & three regions (i.e, Emitter, Base and Collector), three terminals (i.e, Emitter terminal, Base terminal and Collector Terminal) and two junctions (i.e, Emitter to Base Junction & Emitter Junction and Collector to Base Junction & Collector Junction)



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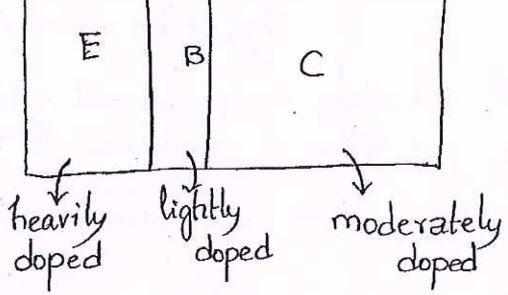



**Emitter:**

Emitter is heavily doped and medium in size because it has to emit the carriers.

**Collector:**

Collector is large in size and moderately doped because it has to dissipiate the power.

**Base:**

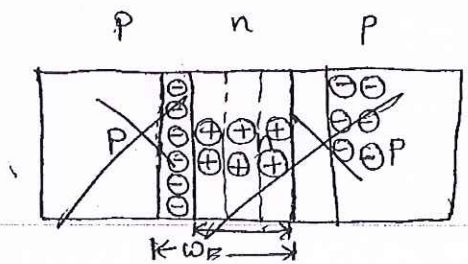
Base is lightly doped and thin in size because it has to reduce the recombinations.

→ In BJT, the diffusion length of the carrier should be $\boxed{L \gg w}$ where 'w' is basewidth.

→ We are transfelling current from one resistance path to another resistance path, hence the name transistor.

Transfer + Resistor ⇒ Transistor

**Unbiased BJT:**

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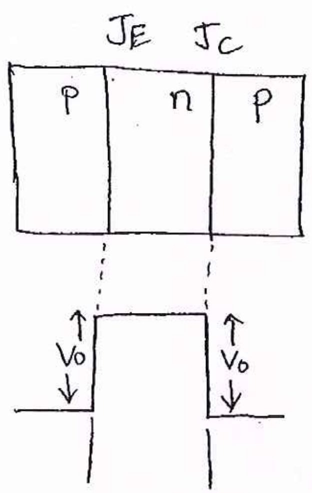
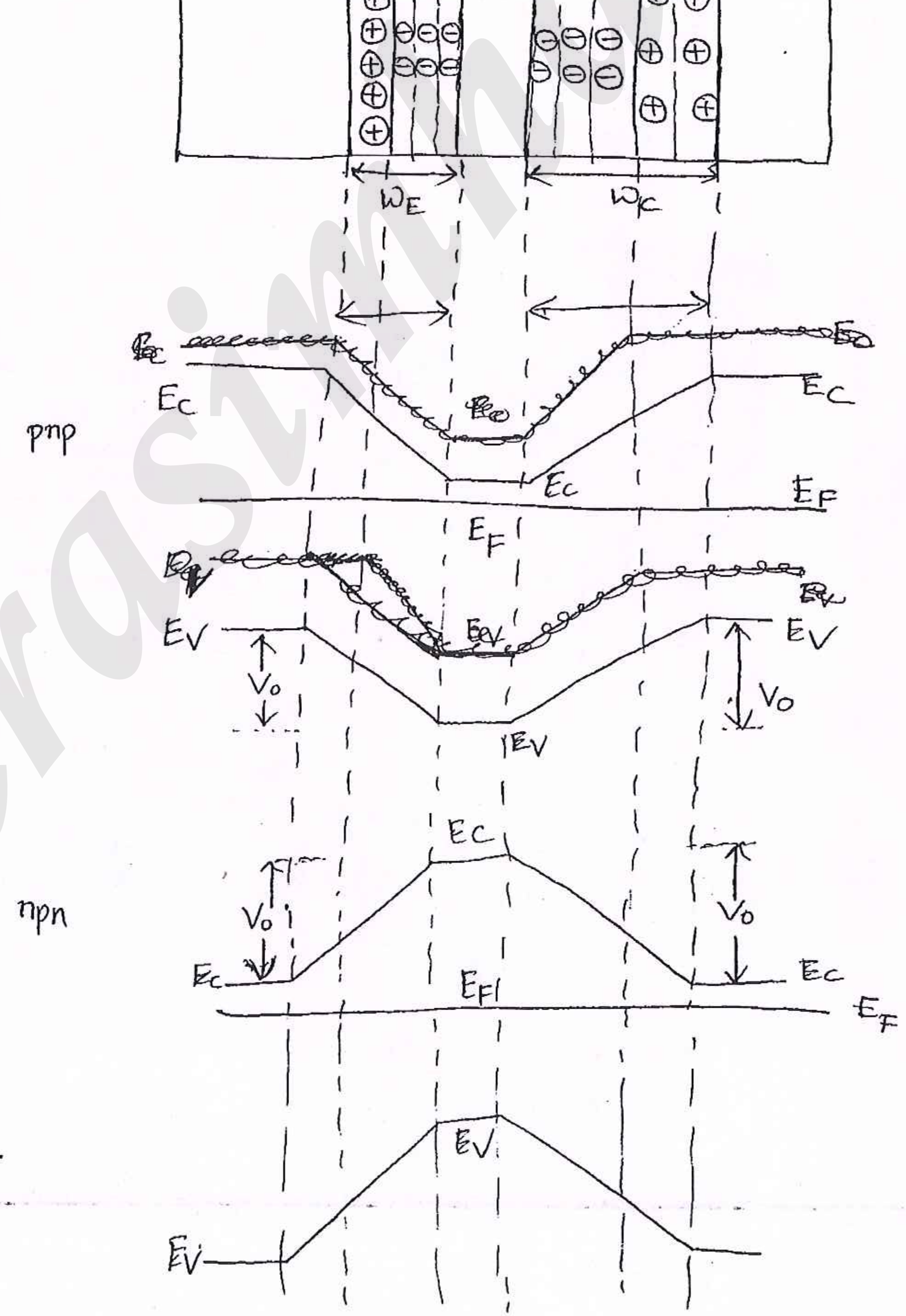

$J_E$ $J_C$
p n p
$V_0$
$V_0$


$W_E$
$W_C$
pnp
$E_C$
$E_C$
$E_C$
$E_F$
$E_F$
$E_V$
$E_V$
$E_V$
$V_0$
$V_0$
npn
$E_C$
$E_C$
$E_C$
$E_F$
$E_F$
$E_V$
$E_V$
$V_0$
$V_0$

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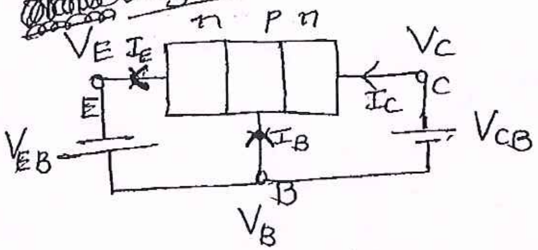
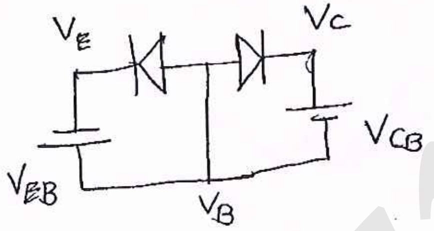
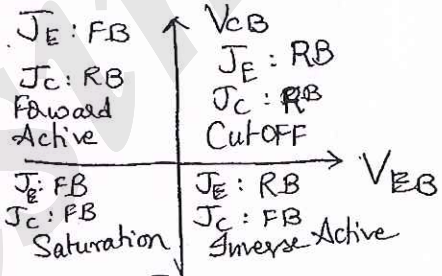
Inverse Active Region / Reverse Active Region    RB    FB    Attenuator

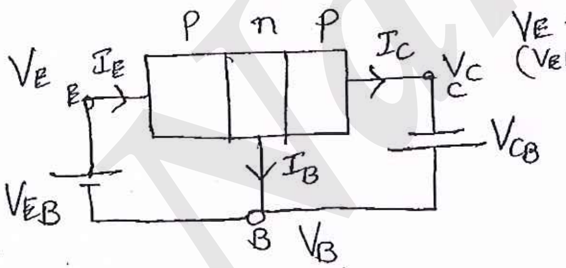
~~Active~~ Region

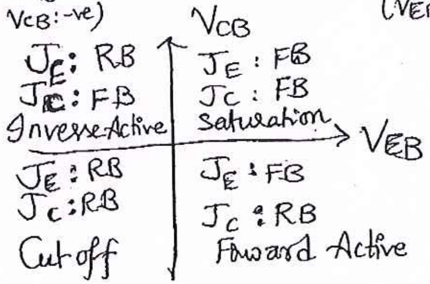


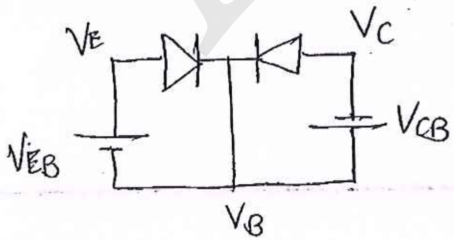



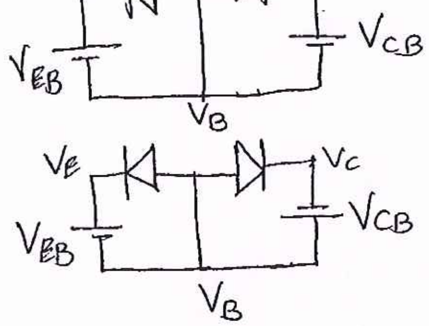

| Condition | Region |
|---|---|
| $V_E < V_B < V_C$ ($V_{EB}$ = -ve, $V_{CB}$ +ve) | Forward Active |
| $V_E < V_B$, $V_B > V_C$ ($V_{EB}$: -ve, $V_{CB}$: -ve) | Saturation |
| $V_E \geq V_B < V_C$ ($V_{EB}$: +ve $V_{CB}$: +ve) | Cutoff |
| $V_E > V_B$ $V_B > V_C$ ($V_{EB}$: +ve; $V_{CB}$ -ve) | Inverse Active |

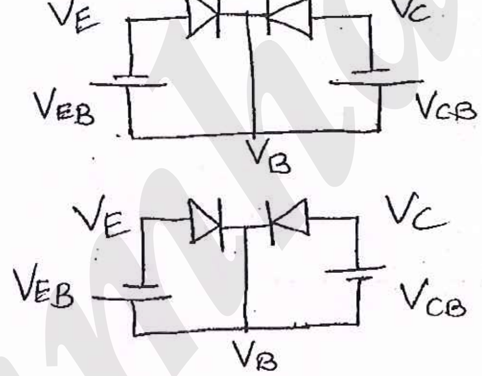


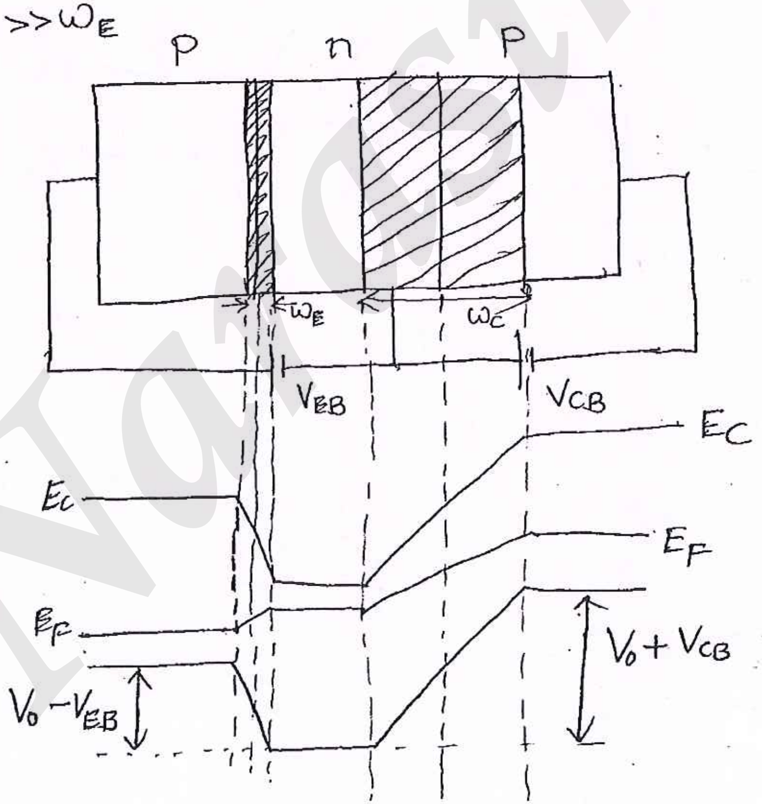




| Condition | Region |
|---|---|
| $V_E > V_B > V_C$ ($V_{EB}$ : +ve, $V_{CB}$ : -ve) | Forward Active |
| $V_E > V_B < V_C$ ($V_{EB}$ : +ve, $V_{CB}$ : +ve) | Saturation |
| $V_E < V_B > V_C$ ($V_{EB}$ : -ve, $V_{CB}$ : -ve) | Cutoff |
| $V_E < V_B < V_C$ ($V_{EB}$ : -ve ; $V_{CB}$ : +ve) | Inverse Active |




$\rightarrow \omega_C >> \omega_E$

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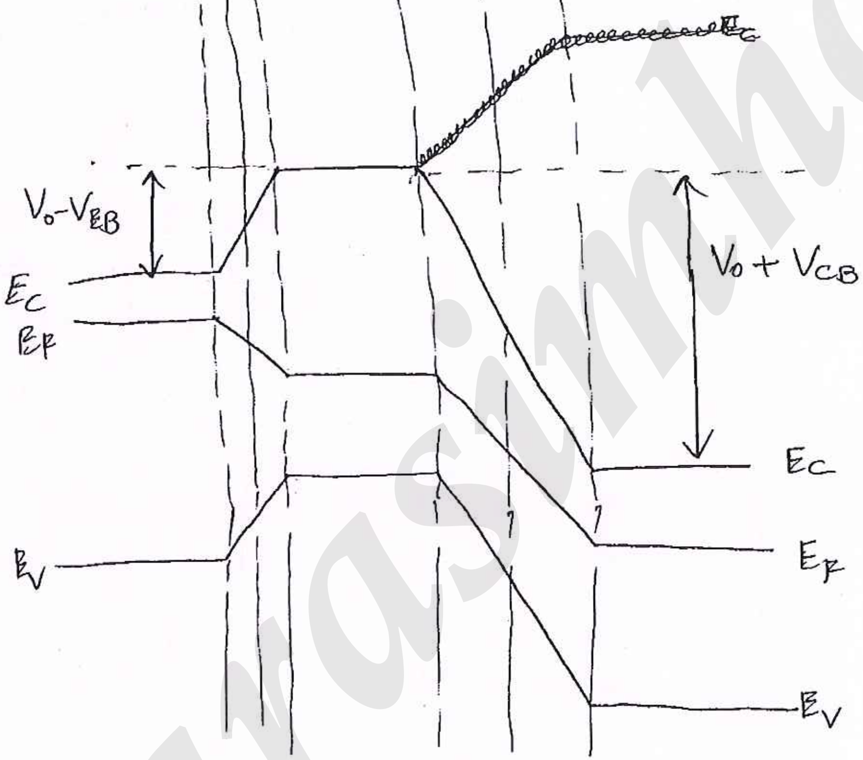
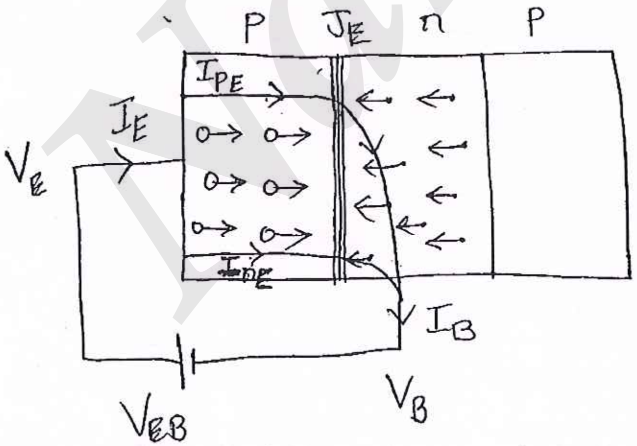
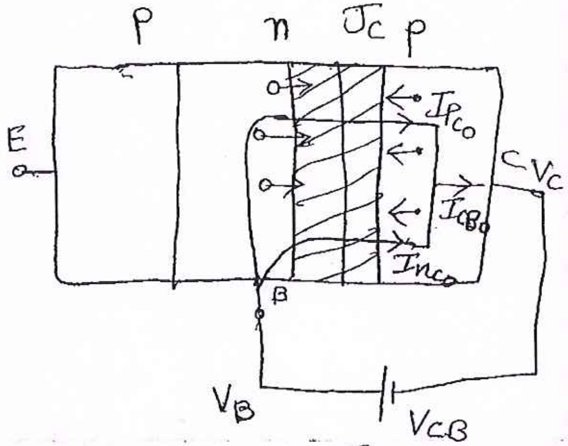
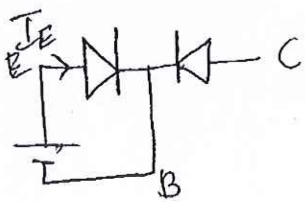


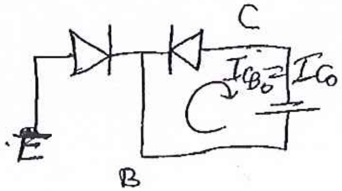




$V_E > V_B \Rightarrow I_E = I_{PE} + I_{nE}$

$V_B > V_C \Rightarrow I_C = I_{Co} = I_{CBo}$

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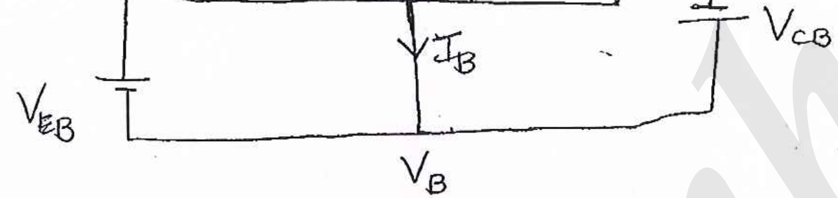
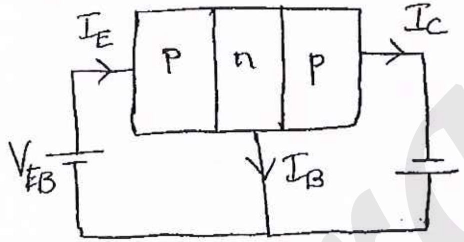
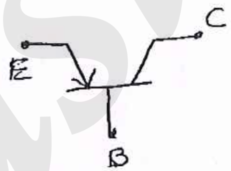
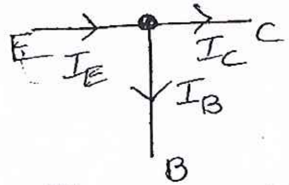



$V_C$ is more negative as compared to $V_B$. So holes moves to collector from Emitter.

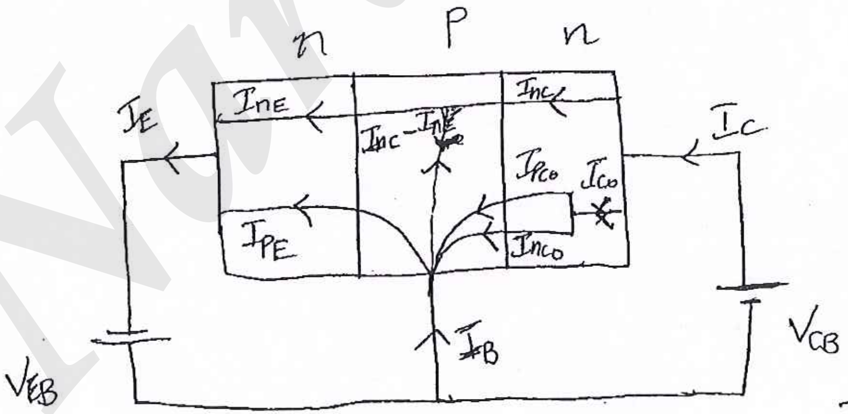
$$I_C = I_{P_C} + I_{C_0} = I_{P_C} + I_{CB_0}$$



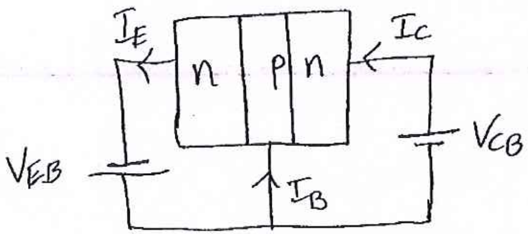



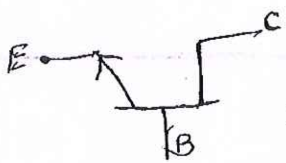



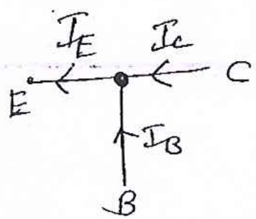

$$I_E = I_C + I_B$$




$$I_C = I_{nC} + I_{CB_0}$$
$$= I_{nC} + I_{C_0}$$




$$I_E = I_C + I_B$$

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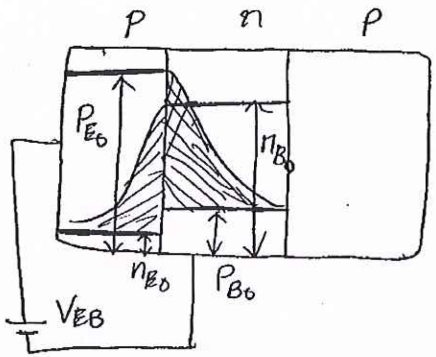


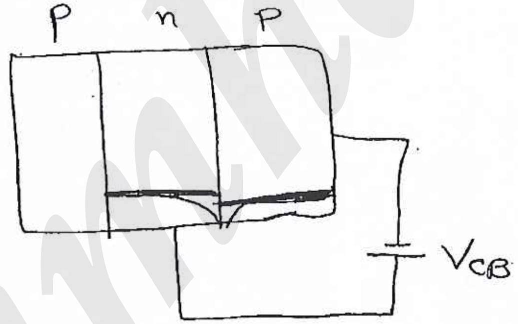


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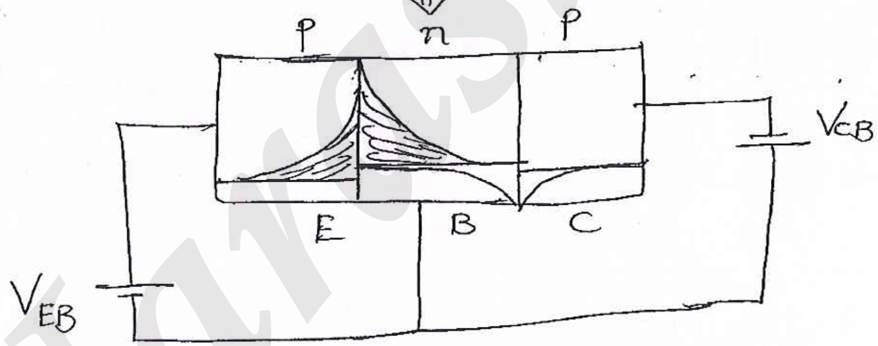
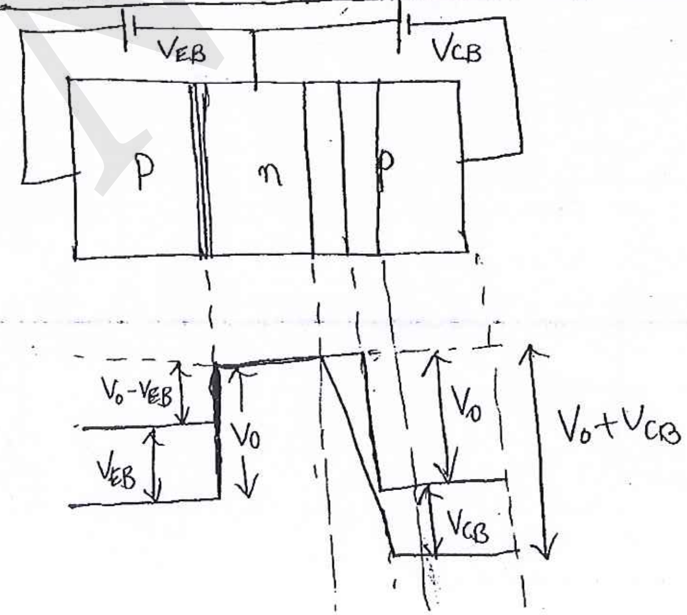



Potential Distribution for biased BJT across the junctions:

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$$\frac{\ldots \text{ at } J_E}{\text{Total Emitter Current}} \quad \sqrt{B}$$

$$= \frac{I_{PE}}{I_E} = \frac{I_{PE}}{I_{PE}+I_{nE}}. \qquad \gamma^* = \frac{I_{nE}}{I_{PE}+I_{nE}} \text{ for } (npn)$$

$$\gamma^* \simeq \frac{I_{PE}}{I_{PE}} = 1$$

## Base Transport Factor ($\beta^*$):

It is the ratio of injected carrier current reaching at collector junction to injected carrier current at emitter junction.

$$\beta^* = \frac{\text{Injected carrier current reaching at } J_C}{\text{Injected carrier current reaching at } J_E}$$

$$= \frac{I_{PC}}{I_{PE}}. \qquad \beta^* = \frac{I_{nC}}{I_{nE}} \text{ for } (npn)$$

## Large Signal Current Gain ($\alpha$): (0.95 to 0.998)

It is the ratio of injected carrier current reaching at collector junction to the total emitter current.

$$\alpha = \frac{\text{Injected carrier current reaching at } J_C}{\text{Total Emitter Current}}$$

$$\alpha = \frac{I_{PC}}{I_E} \Rightarrow \alpha = \frac{I_C - I_{Co}}{I_E} \qquad \alpha = \frac{I_{nc}}{I_E} \text{ for } (npn)$$

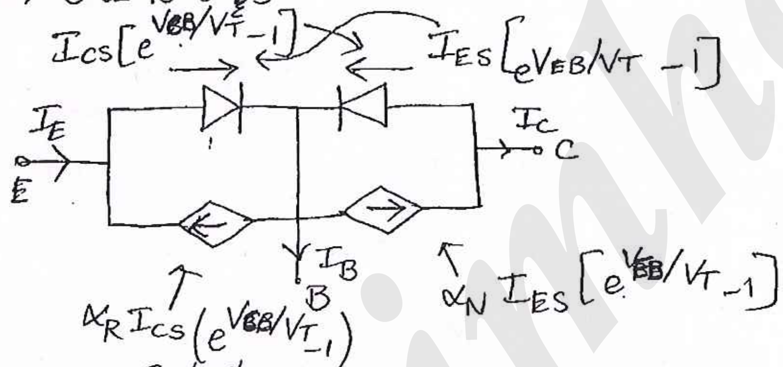
$$I_C = I_{PC} + I_{Co}$$

$$\Rightarrow I_{PC} = I_C - I_{Co}$$

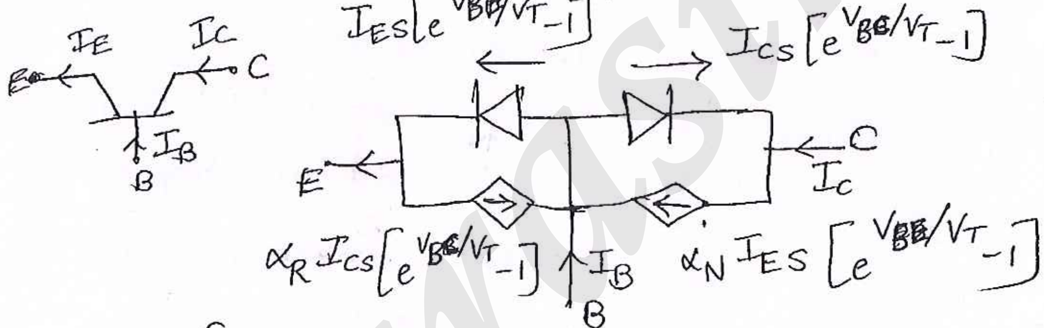
$$\beta^* \gamma^* = \frac{I_{PC}}{I_{PE}} \times \frac{I_{PE}}{I_E} = \frac{I_{PC}}{I_E} = \alpha$$

$$\boxed{\therefore \alpha = \beta^* \gamma^*}$$

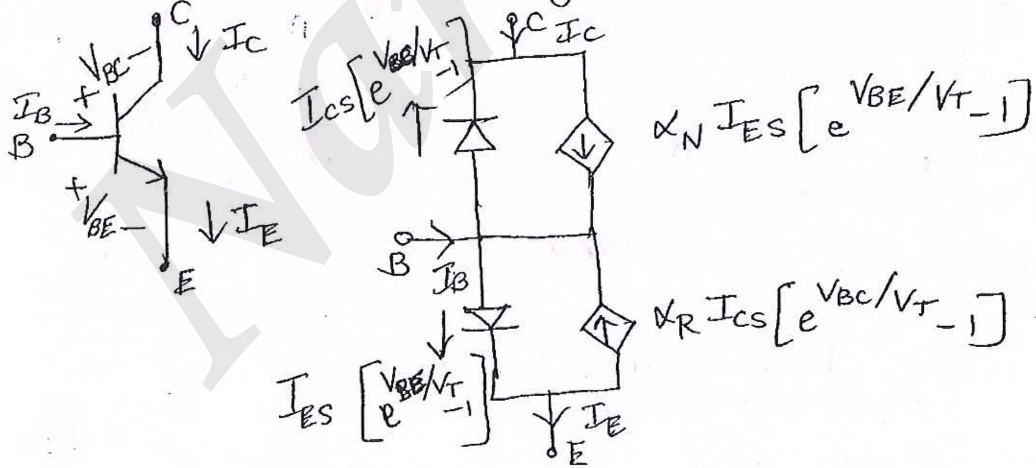
$\alpha_R \rightarrow 0.02$ to $0.05$




for pnp




for npn




for npn transistor

EBORS MOLL MODEL relates the terminal ~~volt~~ currents interms of junction voltages where $I_{ES}$ is the emitter junction saturation current and $\alpha_N$ is the Normal mode current transfer ratio.

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$$\underline{\underline{I_E}} = I_{ES}\left[e^{V_{BE}/V_T}-1\right] - \alpha_R I_{CS}\left[e^{V_{BC}/V_T}-1\right]$$

$$\underline{\underline{I_C}} = -I_{CS}\left[e^{V_{BC}/V_T}-1\right] + \alpha_N I_{ES}\left[e^{V_{BE}/V_T}-1\right]$$

$$I_B = I_E - I_C$$

$$= I_{ES}\left[e^{V_{BE}/V_T}-1\right] - \alpha_R I_{CS}\left[e^{V_{BC}/V_T}-1\right] - \alpha_N I_{ES}\left[e^{V_{BE}/V_T}-1\right] + I_{CS}\left[e^{V_{BC}/V_T}-1\right]$$

$$\Rightarrow \underline{\underline{I_B}} = I_{ES}\left[e^{V_{BE}/V_T}-1\right]\left[1-\alpha_N\right] + I_{CS}\left[e^{V_{BC}/V_T}-1\right]\left[1-\alpha_R\right]$$

<u>Normal Mode</u>: $J_E$ is FB; $J_C$ is RB. $\Rightarrow V_{BE}$ +ve, $V_{BC}$ -ve

$$I_E = I_{ES}\left[e^{V_{BE}/V_T}-1\right] - \alpha_R I_{CS}\left[e^{-V_{BC}/V_T}-1\right]$$

$$= I_{ES}\left[e^{V_{BE}/V_T}-1\right] - \underbrace{(\alpha_R I_{CS})}_{\text{neglected}}$$

$\because \alpha_R \simeq 0.02$

$I_{CS}$ is reverse saturation current

$e^{-V_{BC}/V_T} << 1$

$$\Rightarrow I_E = I_{ES}\left[e^{V_{BE}/V_T}-1\right]$$

$$I_C = \alpha_N I_{ES}\left[e^{V_{BE}/V_T}-1\right] - \underbrace{I_{CS}\left[e^{-V_{BC}/V_T}-1\right]}_{\text{neglected}}$$

$$= \alpha_N I_{ES}\left[e^{V_{BE}/V_T}-1\right]$$

$$I_B = I_E - I_C$$

$$= I_{ES}\left[e^{V_{BE}/V_T}-1\right] - \alpha_N I_{ES}\left[e^{V_{BE}/V_T}-1\right]$$

$$= \left[I_{ES}\left[e^{V_{BE}/V_T}-1\right]\right]\left[1-\alpha_N\right]$$

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$\alpha_N = 0.98$ to $0.998$

If $\alpha_N = 0.99 \Rightarrow \beta_N = \frac{\alpha_N}{1-\alpha_N} = 99.$

$$\frac{I_C}{I_E} = \frac{\alpha_N I_{ES}\left[\cancel{e^{V_{BE}/V_T}-1}\right]}{I_{ES}\left[\cancel{e^{V_{BE}/V_T}-1}\right]} = \alpha_N$$

$$\boxed{\alpha_N = \frac{I_C}{I_E}}, \quad \boxed{\alpha = \frac{I_C}{I_E}}$$

$$\frac{I_E}{I_B} = \frac{\cancel{I_{ES}}\left[\cancel{e^{V_{BE}/V_T}-1}\right]}{(1-\alpha_N)\, I_{ES}\left(\cancel{e^{V_{BE}/V_T}-1}\right)} = \frac{1}{1-\alpha_N} = \gamma_N$$

$$= 1+\beta_N$$

$$\therefore \boxed{\gamma_N = \frac{1}{1-\alpha_N}} \quad \boxed{\gamma = \frac{1}{1-\alpha}}$$

$$\boxed{\gamma_N = 1+\beta_N} \quad \boxed{\gamma = 1+\beta}$$

**Reverse Mode:** $J_E$ : RB ; $J_C$ : FB $\Rightarrow V_{BE} = -ve$, $V_{BC} = +ve$

$$I_E = I_{ES}\left[e^{-V_{BE}/V_T}-1\right] - \alpha_R I_{CS}\left[e^{V_{BC}/V_T}-1\right]$$

$$I_E = -\alpha_R I_{CS}\left[e^{V_{BC}/V_T}-1\right]$$

$$I_C = \alpha_N I_{ES}\left[e^{-V_{BE}/V_T}-1\right] - I_{CS}\left[e^{V_{BC}/V_T}-1\right]$$

$$= -I_{CS}\left[e^{V_{BC}/V_T}-1\right]$$

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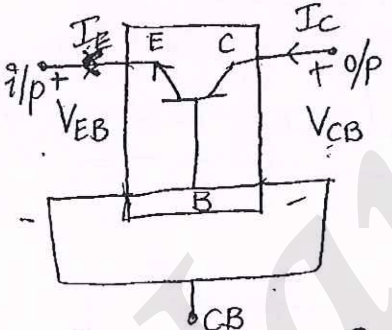
$$\beta_R = \frac{-I_E}{I_B} = \frac{\alpha_R}{1-\alpha_R}$$

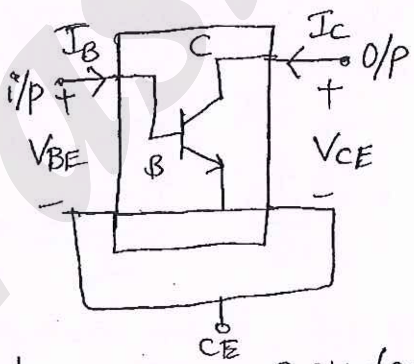
$\alpha_R = 0.02$ to $0.5 \Rightarrow \beta_R = 0.02$ to $1$

i.e, It is acting as attenuator. Hence we will not use reverse mode

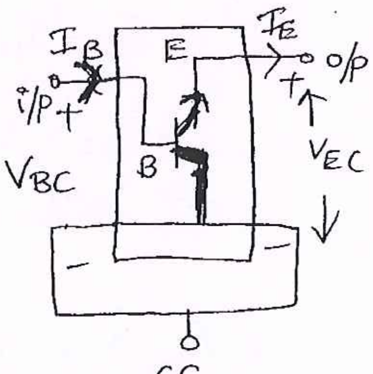
→ Inorder to take BJT as any amplifier, we need only two terminals hence we take ~~either~~ one terminal as common. Hence CE, CB and CC.



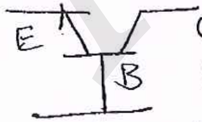

Common Base Configuration (CB)




Common Emitter (CE) Configuration




Common collector (CC) Configuration




$V_{EB}, I_C$ : dep

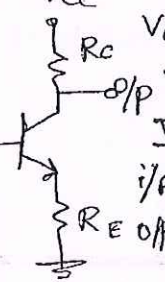
$V_{CB}, I_E$ : Indep

$V_{BE} = Q_1(V_{CB}, I_E)$

$I_C : Q_2(I_E, V_{CB})$

i/p char: $V_{EB}$ vs $I_E / V_{CB}$

o/p char: $I_C$ vs $V_{CB}/I_E$




$V_{BE}, I_C$ : dep

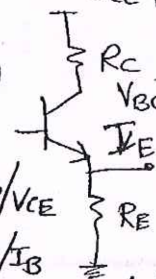
$V_{CE}, I_B$ : Ind

$V_{BE} = Q_1(I_B, V_{CE})$

$I_C = Q_2(I_B, V_{CE})$

i/p char: $V_{BE}$ vs $I_B/V_{CE}$

o/p char: $I_C$ vs $V_{CE}/I_B$




$V_{BC}, I_E$ : dep

$V_{EC}, I_B$ : Ind

$V_{BC} = Q_1(I_B, V_{EC})$

$I_E = Q(I_B, V_{EC})$

i/p char: $V_{BC}$ vs $I_B/V_{EC}$

o/p char: $I_E$ vs $V_{EC}/I_B$

In transistor,

$V_1, I_2$ are Dependent

$I_1, V_2$ are Independent

$V_1 = Q(I_1, V_2)$  $V_1 = h_{11}I_1 + h_{12}V_2$

$I_2 = Q(I_1, V_2)$  $I_2 = h_{21}I_1 + h_{22}V_2$

So we use h-parameters in BJT

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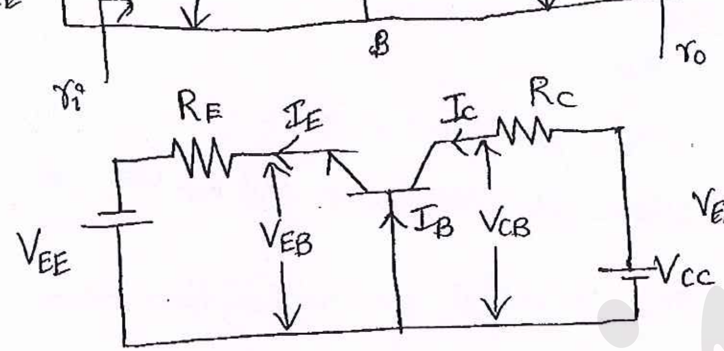
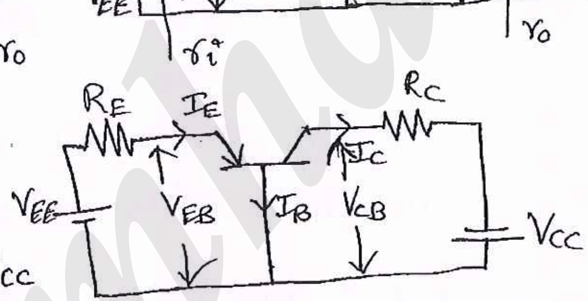



$\alpha = \frac{I_{PC}}{I_E}$

$I_C = I_{PC} + I_{CBo} = I_{PC} + I_{Co}$

$\Rightarrow I_{PC} = I_C - I_{Co} = I_C - I_{CBo}$

$I_{PC} = \alpha I_E \Rightarrow \alpha = \frac{I_{PC}}{I_E} = \frac{I_C - I_{CBo}}{I_E}$

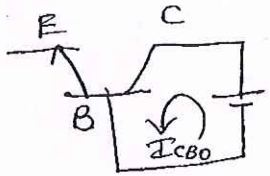
$\alpha I_E = I_C - I_{CBo}$

$$\boxed{\begin{aligned} &\Rightarrow I_C = \alpha I_E + I_{CBo} \\ &\Rightarrow I_C = \alpha I_E + I_{Co} \end{aligned}}$$

→ $I_{CBo}$ & $I_{Eo}$ : depends on temperature

: Increases by 7% /°C

: doubles /10°C




$I_{CBo}$ & $I_{Co}$ is of order of nA

$I_C \simeq \alpha I_E$

$\Rightarrow \alpha = \frac{I_C}{I_E}$ where '$\alpha$' is the current gain in CB configuration.

$\alpha_{dc} = \frac{I_C}{I_E}$

$\alpha_{ac} = \frac{\Delta i_c}{\Delta i_e}$

$$\boxed{\alpha_{DC} = \alpha_{AC} = \alpha}$$

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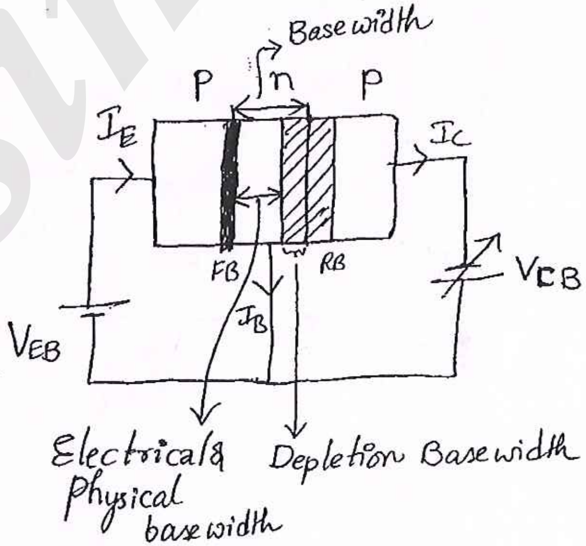
→ In CB configuration, as collector to base junction reverse bias voltage increases, emitter current increases due to early effect (Base width modulation effect)
Therefore the slope of the i/p characteristic curves are increasing

→ Early effect is also called Base width modulation.

## Early Effect:




Total Basewidth

= Electrical Basewidth + Depletion Basewidth

As $V_{CB}\uparrow$, EBW $\downarrow$, DBW $\uparrow$
and total basewidth remains constant

TBW = EBW$\downarrow$ + DBW$\uparrow$

Since the base width is varying wrt $V_{CB}$, we call it as Basewidth modulation

As EBW $\downarrow$, more holes reach from E to C as recombination $\downarrow$ in B.

* As Collector to Base junction reverse bias voltage increases, the width of the collector junction depletion region increases. Due to this the electrical & physical base width decreases, i.e, as collector junction reverse bias voltage varies, the width of the base is varying. Therefore, it is called base width modulation or early effect.

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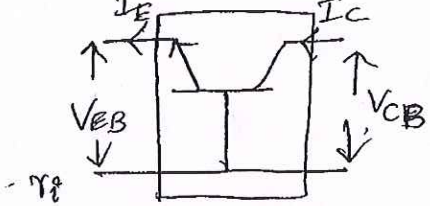
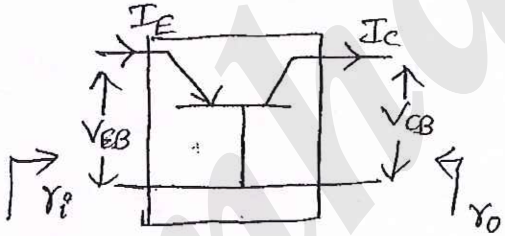



It is the ratio of change in Emitter to Base voltage to the change in emitter current (or) It is the reciprocal of the slope of the input characteristics.

$$\text{Slope} = \left.\frac{\Delta I_E}{\Delta V_{EB}}\right|_{V_{CB}}$$

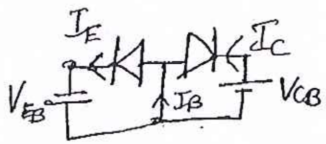
$$r_i = \frac{1}{\left.\frac{\Delta I_E}{\Delta V_{EB}}\right|_{V_{CB}}} = \left.\frac{\Delta V_{EB}}{\Delta I_E}\right|_{V_{CB}}.$$

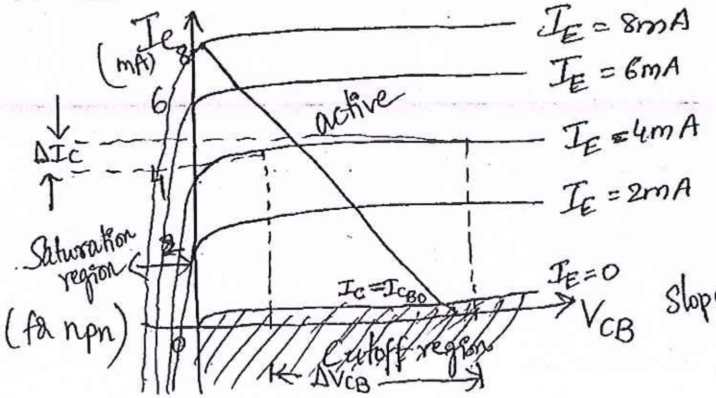
$$r_i = r_e = \frac{\eta V_T}{I_E}$$ $r_i \Rightarrow low$, $r_i \simeq 10\Omega$

$$r_i = r_e = \frac{26}{I_E}$$

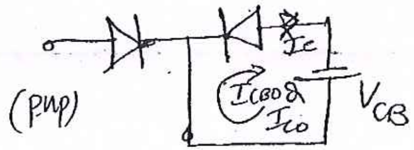
$I_E \rightarrow mA$

## Output Characteristics: $I_C$ vs $V_{CB}\big|_{I_E}$




$I_C = I_{CB} = I_{CBO}$




$$I_C = \alpha I_E + I_{C_0}$$

$\text{Slope} = \left.\frac{\Delta I_C}{\Delta V_{CB}}\right|_{I_E}$ $I_C \simeq I_E$ ($I_{C_0} \rightarrow nA$, $\alpha \simeq 1$)

bias.

→ In cutoff region, collector current $I_C = I_{CBO} = I_{CO}$

→ It can be used as a OFF switch in cutoff region.

## Saturation Region:

→ Saturation region is the region left side to $V_{CB} = 0$ line.

→ In saturation region, emitter and collector junctions are in forward bias

→ In saturation region, collector current increases exponentially.

→ It can be used as ON switch in saturation region.

## Active Region:

→ Active Region is the region between saturation and cutoff regions.

→ In active region, Emitter junction is FB and collector junction is RB.

→ In active region, $I_C = \alpha I_E + I_{CBO}$ (This equation is applicable only in active region).

→ It can be used as an amplifier in the active region.

## Output Resistance:

It is the ratio of change in collector to base voltage to the change in collector current($\alpha$) it is the reciprocal of the slope of the output characteristics.

$$r_o = \frac{1}{\Delta I_C / \Delta V_{CB}} \Big|_{I_E} = \frac{\Delta V_{CB}}{\Delta I_C} \Big|_{I_E}$$

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(As $V_{CB}$ is increased, at a particular value of $V_{CB}$, the basewidth disappears)

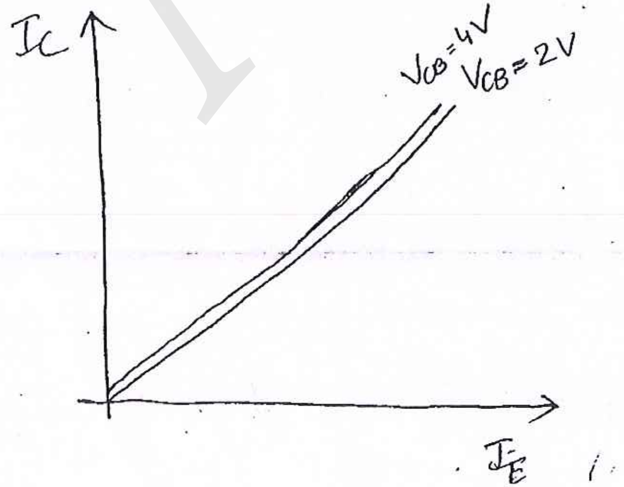
→ As collector to base junction reverse bias voltage increases, the width of the collector junction depletion region increases..

→ At a particular value of $V_{CB}$, this collector junction depletion region penetrates through emitter junction. It is called Punchthrough effect.

→ Punch through is also called Reachthrough effect.

## Transfer Characteristics:

BJT is a current controlled current source. Hence transfer characteristics are plotted b/n $I_C$ Vs $I_E$.




$I_C \simeq \alpha I_E$

As $V_{CB}$ ↑, small slope will be there in o/p characteristics because of small ↑ in $I_C$.

Hence As $V_{CB}$ ↑, the graph shifts left in Transfer characteristics

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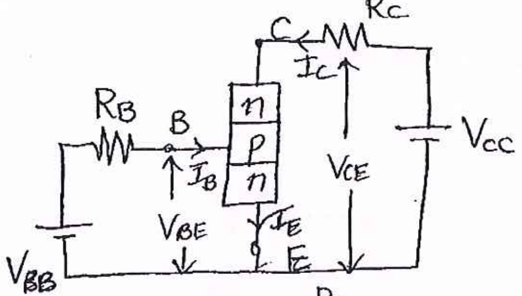


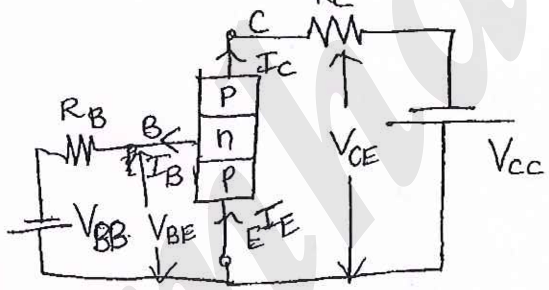


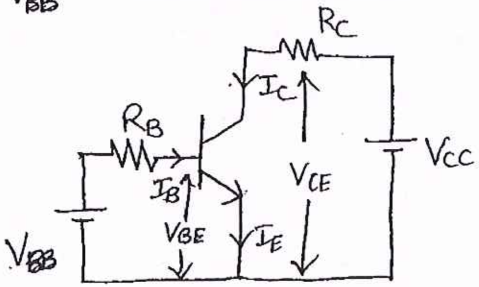


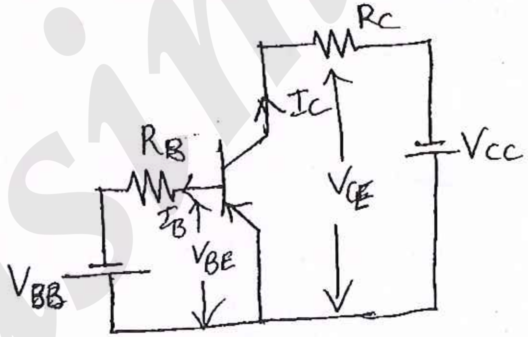


$$\alpha = \frac{I_{pC}}{I_E} = \frac{I_C - I_{CBO}}{I_E} = \frac{I_C - I_{C_0}}{I_E}$$

$$I_C = \alpha I_E + I_{CBO} = \alpha I_E + I_{C_0}$$

$$I_E = I_C + I_B$$

$\beta$ : 50 to 500

$$I_C = \alpha(I_C + I_B) + I_{C_0}$$

$$\Rightarrow \frac{I_C[1-\alpha] - I_{C_0}}{\alpha} = I_B.$$

$$\Rightarrow \quad I_B = \frac{1-\alpha}{\alpha} I_C - \frac{1}{\alpha} I_{C_0}$$

$$I_C = \frac{\alpha}{1-\alpha} I_B + \frac{1}{1-\alpha} I_{C_0}$$

$$\boxed{I_C = \beta I_B + (1+\beta) I_{C_0}} \qquad \beta = \frac{\alpha}{1-\alpha} \; ; \; \alpha = \frac{\beta}{1+\beta}$$

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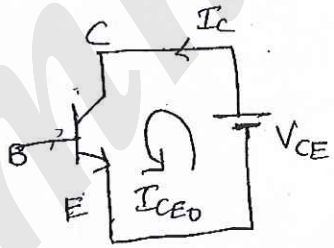
$\therefore I_{CEo} = I_{CBo}$

Hence biasing is needed in CE configuration to protect transistor from thermal runaway.




$$I_C \simeq \beta I_B$$

$$\Rightarrow \beta = \frac{I_C}{I_B}$$

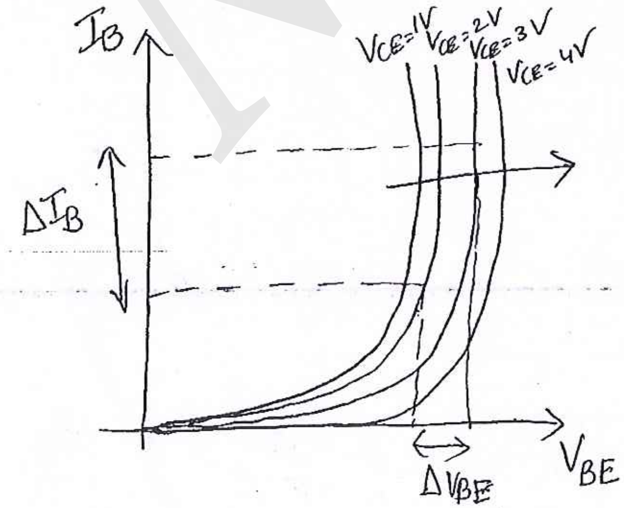
$\beta$: Current gain in CE configuration

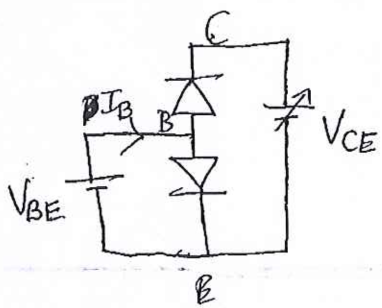
$$\beta_{dc} = \frac{I_C}{I_B}$$

$$\beta_{ac} = \frac{\Delta i_c}{\Delta i_b}$$

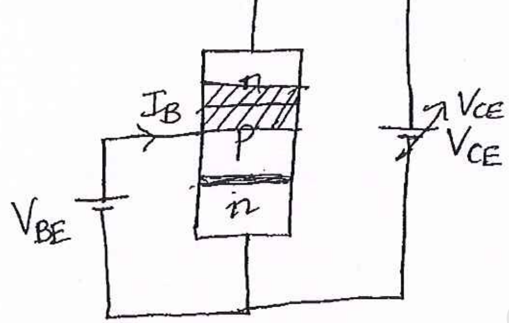
$$\boxed{\beta_{dc} = \beta_{ac} = \beta}$$

## Input Characteristics: $I_B$ vs $V_{BE} \big|_{V_{CE}}$




$$\text{Slope} = \frac{\Delta I_B}{\Delta V_{BE}}$$




## Input Resistance ($r_i$):

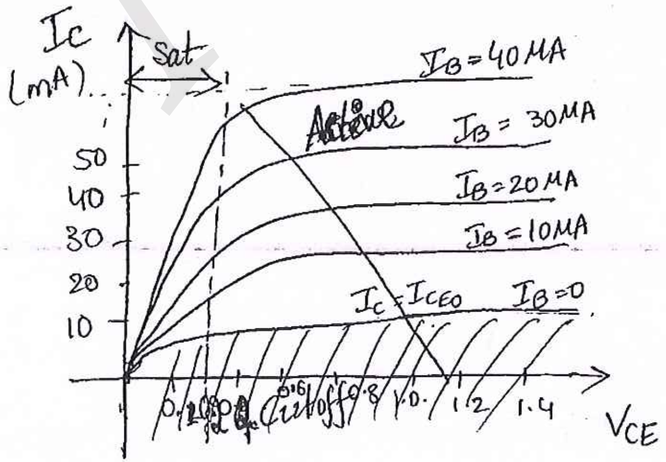
It is the ratio of change in base to emitter voltage to the change in base current (or) It is the reciprocal of the slope of the input characteristics.

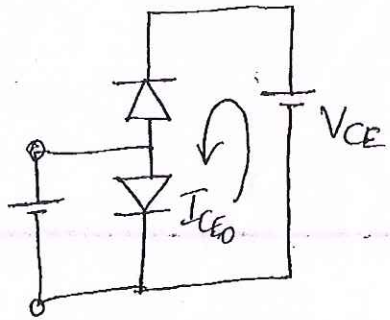
$$r_i = \frac{1}{\frac{\Delta I_B}{\Delta V_{BE}}}\Bigg|_{V_{CE}} = \frac{\Delta V_{BE}}{\Delta I_B}\Bigg|_{V_{CE}}$$

In a BJT
$I_B \rightarrow \mu A$
$I_C, I_E \rightarrow mA$
$I_{CEO}, I_{CBO} \rightarrow nA$

$r_i <$ medium $\simeq 1K\Omega$

## Output Characteristics: $I_C$ vs $V_{CE}\,\big|_{I_B}$




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

$$I_C = \beta I_B + I_{CEO}$$

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→ It can be used as a OFF switch in cut off region

## Saturation Region:

→ Saturation region is the region left side to $V_{CE}=0.2V$ line.

→ In saturation region, emitter junction and collector junction are in forward bias.

→ In saturation region, $I_C$ increases exponentially

→ In saturation region, $\boxed{V_{CE} \leq V_{CE(sat)}}$

→ It can be used as a ON switch in saturation region

$$V_{CE} = 0.2V \text{ or } 0.3V \text{ for Si transistor}$$

$$V_{CE} = 0.1V \text{ for Ge transistor}$$

## Active Region:

→ Active region is the region between saturation and cutoff regions.

→ In active region, emitter junction is FB and collector junction is RB.

→ Collector Current in active region, $I_C = \beta I_B + (1+\beta) I_{CBO}$

$$I_C = \beta I_B + I_{CEO}$$

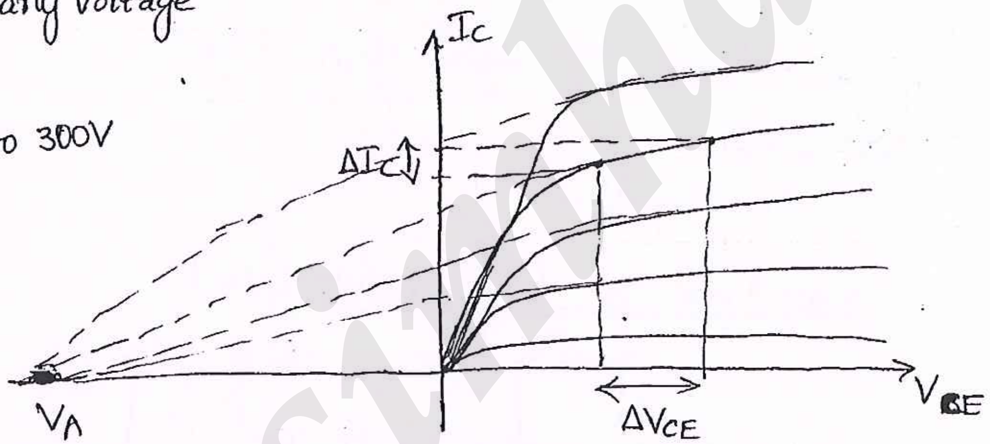
→ In active region, $V_{CE} > V_{CE(sat)}$ and $V_{CE} < \frac{V_{CC}}{2}$

$$\therefore V_{CE(sat)} < V_{CE} < \frac{V_{CC}}{2}$$

→ It can be used as an amplifier in the ~~saturation~~ active region.

$V_A$ : Early Voltage

$V_A$ : 100 to 300V



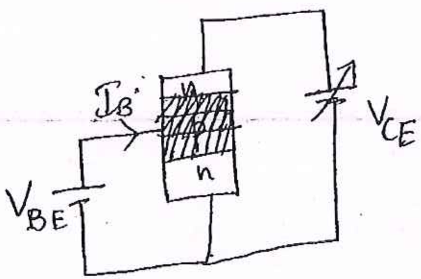

## Output Resistance:

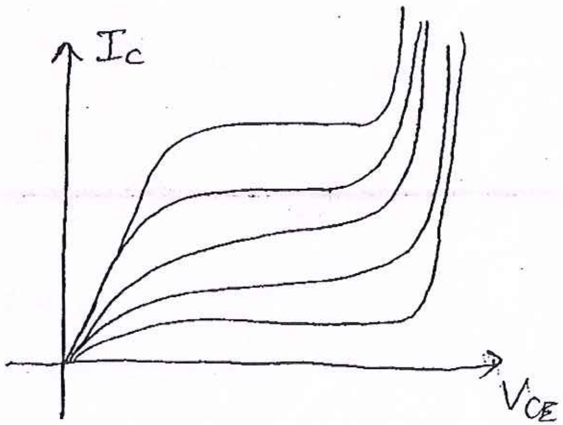
It is the ratio of change in Collector to Emitter voltage to the change in collector current (or) It is the reciprocal of the slope of the output characteristics

$r_o >$ Medium $\simeq 10K\Omega$

$$r_o = \frac{1}{\left.\frac{\Delta I_C}{\Delta V_{CE}}\right|_{I_B}} = \left.\frac{\Delta V_{CE}}{\Delta I_C}\right|_{I_B}$$

## Punchthrough:

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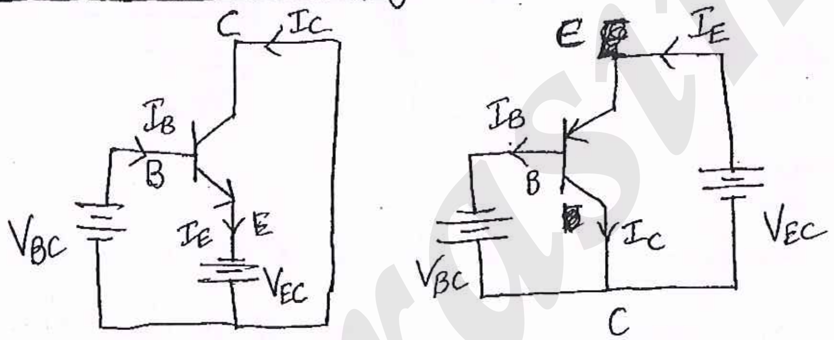
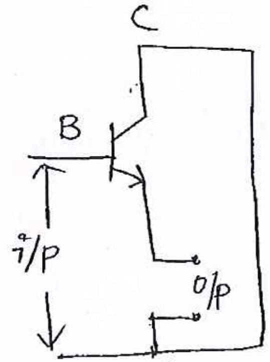
| | $r_i$ | $r_o$ | $A_I$ | $A_V$ | $A_P$ |
|---|---|---|---|---|---|
| CE | < Medium | > Medium | High | High | High |

**Applications:**

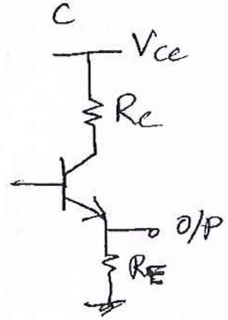
→ AF amplifier

## Common Collector Configuration: (CC)




$$\alpha = \frac{I_{PC}}{I_E} = \frac{I_C - I_{CBo}}{I_E} = \frac{I_C - I_{Co}}{I_E}$$




$$I_C = \alpha I_E + I_{CBo} = \alpha I_E + I_{Co}$$

$$I_E = I_C + I_B \Rightarrow I_C = I_E - I_B$$

$$I_E - I_B = \alpha I_E + I_{CBo}$$

$$(1-\alpha) I_E = I_B + I_{CBo}$$

$$\Rightarrow I_E = \frac{1}{1-\alpha} I_B + \frac{1}{1-\alpha} I_{CBo}$$

$$* \boxed{I_E = (1+\beta) I_B + (1+\beta) I_{CBo}} \qquad \boxed{\gamma = 1+\beta = \frac{1}{1-\alpha}}$$

$$* \boxed{I_E = \gamma I_B + \gamma I_{CBo}}$$

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(CC) $\gamma = \dfrac{I_E}{I_B}$

$$\boxed{\gamma_{ac} = \gamma_{dc} = \gamma}$$

$$\alpha \cdot \gamma = \frac{I_C}{I_E} \cdot \frac{I_E}{I_B} = \frac{I_C}{I_B} = \beta$$

$$\boxed{\therefore \alpha\gamma = \beta}$$

$\beta = \alpha\gamma$ Also $\alpha = \beta^* \gamma^*$

$\alpha\gamma \rightarrow$ Current gains.

$\beta^*\gamma^* \rightarrow$ transport factors & emitter efficiency

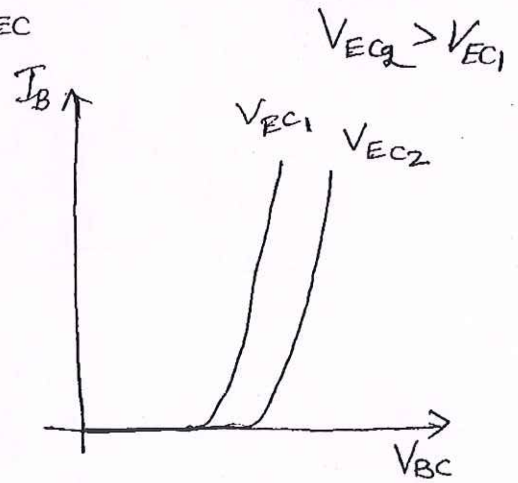
## Input Characteristics: $I_B$ vs $V_{BC}\big|_{V_{EC}}$

Input resistance ($r_i$)

$$r_i = \frac{\Delta V_{BC}}{\Delta I_B}$$

$r_i$ = High

$r_i \simeq 100\,k\Omega$




## Output Characteristics: $I_E$ Vs $V_{EC}\big|_{I_B}$

$I_C \simeq I_E$

$V_{CE} = -V_{EC}$

Similar to CE o/p characteristics

but are present in 2nd Quadrant

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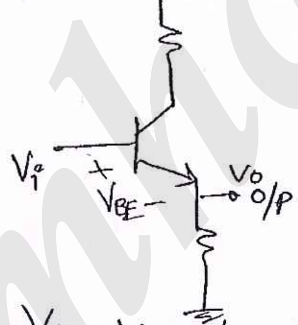
$\Delta I_E \,|\, I_B$

$r_o$ : Low

$r_o \simeq 10\Omega$



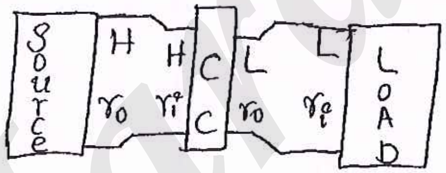

$V_o = V_i - V_{BE}$

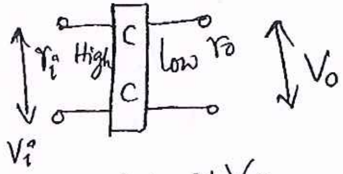
$\Rightarrow V_o \simeq V_i \Rightarrow A_V = 1$

| | $r_i$ | $r_o$ | $A_I$ | $A_V$ | $A_P$ |
|---|---|---|---|---|---|
| CC : | High | Low | High | $\simeq 1$ | Low |

__Applications:__

→ Buffer.




$V_o \simeq V_i$

| | $A_I$ | $A_V$ |
|---|---|---|
| CB | $\simeq 1$ | High |
| CE | High | High |
| CC | High | $\simeq 1$ |

__Voltage Gain ($A_V$):__

$A_{V_{CC}} \simeq 1$

$A_{V_{CB}} > A_{V_{CE}}$

$\boxed{A_{V_{CB}} > A_{V_{CE}} > A_{V_{CC}}}$ $\boxed{A_{V_{CC}} < A_{V_{CE}} < A_{V_{CB}}}$

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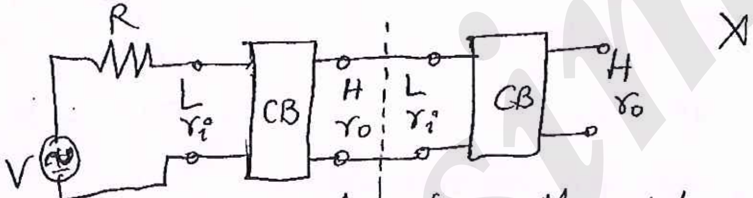
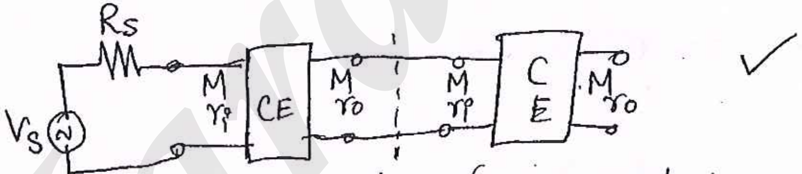
→ For high voltage gain cascaded CB configuration can be taken as. $A_{VCB}$ is high. But it is not preferred because there is impedance mismatch between two CB stages.




Impedance Mismatch.

In place of CB, we can take cascading of CE configuration.




Impedance matched.

## Why CE?:

→ CE configuration has voltage as well as current gains. Therefore its power gain is high.

→ It has medium input and output impedances.

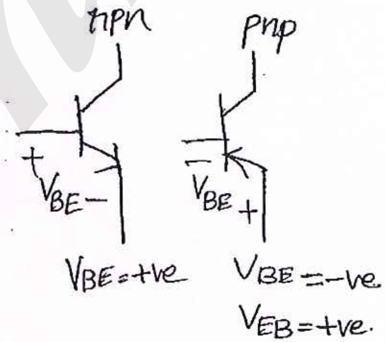
Therefore we prefer CE configurations than other configurations.

## Typical npn transistor junction voltages at room temperature:

$V_{CE(sat)} = 0.3V$ & $0.2V$ for Si
$= 0.1V$ for Ge

$V_{BE(active)} = 0.7V$ for Si
$= 0.2V$ for Ge

$V_{BE(sat)} = 0.8V$ or $0.7V$ for Si
$= 0.3V$ for Ge




* Change the polarities for $\boxed{\text{pnp}}$ transistor.

→ $V_{BE}$ depends on temperature

$$\frac{dV_{BE}}{dT} = -2.5\,mV/^\circ C$$

$$\frac{V_{BE_2} - V_{BE_1}}{T_2 - T_1} = -2.5\,mV/^\circ C$$

$$V_{BE_2} - V_{BE_1} = -2.5(T_2 - T_1)\,mV/^\circ C$$

$$\boxed{V_{BE_2} = V_{BE_1} - (T_2 - T_1)\,2.5\,mV/^\circ C}$$

Q) If $I_E$ is doubled, for $10^\circ C$ then what is $V_{BE}$.
→

$$I_{E_1} = I_S e^{V_{BE_1}/V_T}$$

Ans is increases by 20mV

$$2I_{E_1} = I_S e^{V_{BE_2}/V_T}$$

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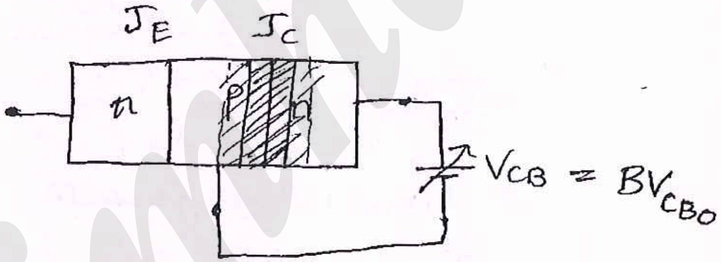
## Avalanche Breakdown

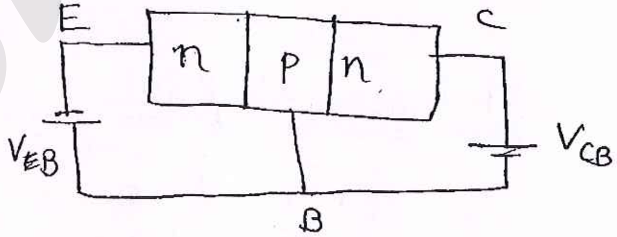
$BV_{CBO} \Rightarrow$ (CB Configuration) Breakdown voltage in CB configuration when the emitter is open.




(or) Collector to Base voltage when emitter is open. (CBO)

**Multiplication factor (M):**

It is a cumulative breakdown.




(CB configuration)

$$M = \frac{1}{1 - \left(\frac{V_{CB}}{BV_{CBO}}\right)^n}$$

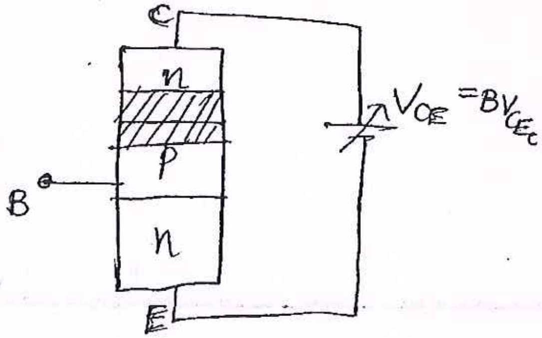
n: 2 to 10 and depends on type of semiconductor

(CE Configuration)

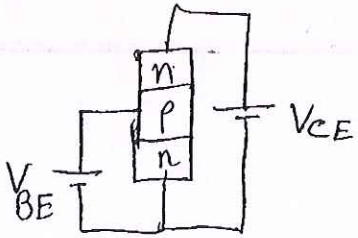
$BV_{CEO} \Rightarrow$ Collector to Emitter Voltage when Base is Open

(or) Breakdown voltage in CE configuration when the Base is open.

(CE configuration)




$$M = \frac{1}{1 - \left(\frac{V_{CE}}{BV_{CEO}}\right)^n}$$

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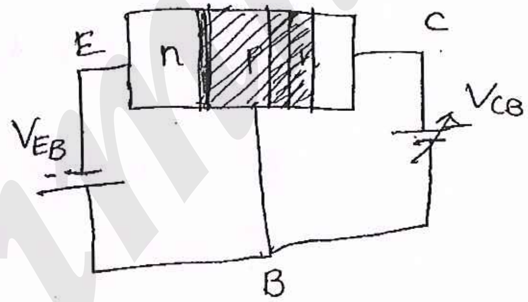
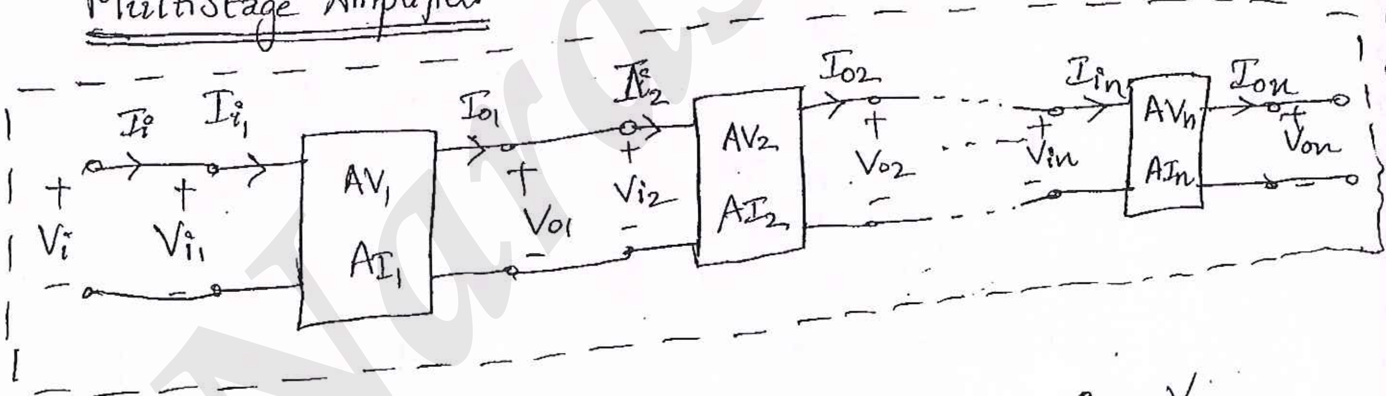
$$\boxed{BV_{CBO} > BV_{CEO}}$$

## Punchthrough:

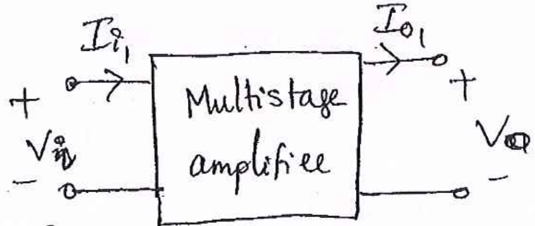
The Base-Collector junction penetrates through the Emitter Base junction.

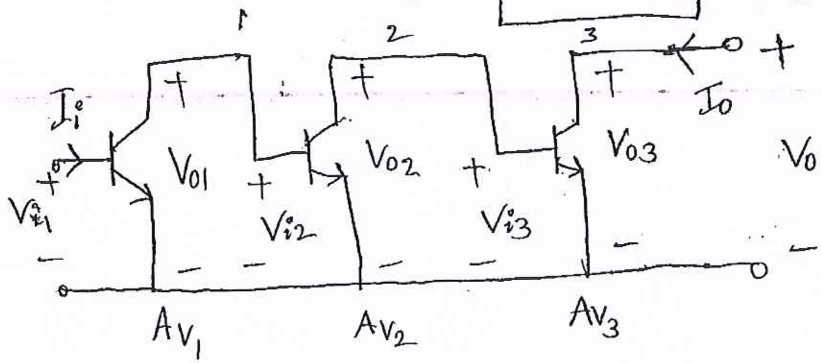



## Multistage Amplifier:




$$A_V = \frac{V_o}{V_i}$$

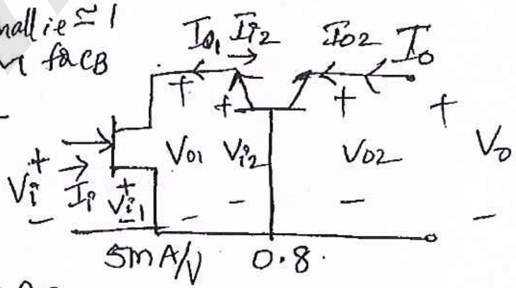


$$A_V = \frac{V_o}{V_i} = A_{V_1} \cdot A_{V_2} \cdot A_{V_3} \cdot \ldots \cdot A_{V_n}.$$

Q) For the circuit shown in the figure, FET has a transconductance of 5mA / volts and BJT has a common base current gain of 0.8. Calculate overall transconductance of the composite amplifier.

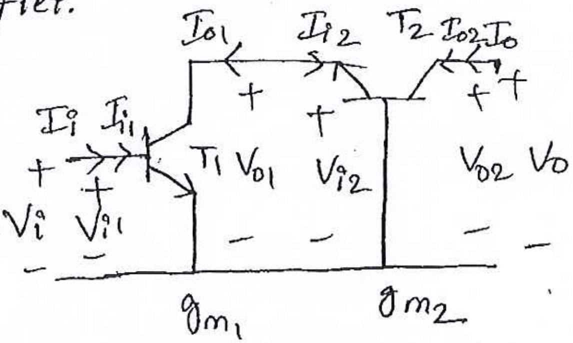
$$g_m = \frac{I_o}{V_i} = \underbrace{\frac{I_o}{I_{o2}}}_{1} \cdot \underbrace{\frac{I_{o2}}{I_{i2}}}_{0.8} \cdot \underbrace{\frac{I_{i2}}{I_{o1}}}_{1} \cdot \underbrace{\frac{I_{o1}}{I_{i1}}}_{\text{small ie} \simeq 1 \text{ for CB}} \cdot \underbrace{\frac{I_{o1}}{V_{i1}}}_{5mA/volt} \cdot \underbrace{\frac{V_{i1}}{V_i}}_{1}$$




$$= 0.8 \times 5 = 4 \text{ mA/V}$$

Q) For the circuit shown in the figure, transistors $T_1$ and $T_2$ are having transconductances of $g_{m_1}$ and $g_{m_2}$. Calculate the overall transconductance of the amplifier.

$$g_m = \frac{I_o}{V_i} = \underbrace{\frac{I_o}{I_{o2}}}_{1} \cdot \underbrace{\frac{I_{o2}}{I_{i2}}}_{1} \cdot \underbrace{\frac{I_{i2}}{I_{o1}}}_{1} \cdot \underbrace{\cancel{\frac{I_{o1}}{I_{i1}}}}_{1} \cdot \underbrace{\frac{I_{o1}}{V_{i1}}}_{g_{m_1}} \cdot \underbrace{\frac{V_{i1}}{V_i}}_{1}$$




a) $g_{m_1} \cdot g_{m_2}$

b) $g_{m_1} // g_{m_2}$

~~c)~~ $g_{m_1}$

d) $g_{m_2}$

$g_m = g_{m_1}$

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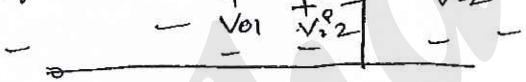
$V_i^a \quad I_{o2} \quad V_{i2} \quad V_{o1}$




$$\underbrace{\frac{V_{o1}}{V_{i1}}}_{1} \cdot \underbrace{\frac{V_{i1}}{V_i}}_{1} = g_{m2}.$$

(CC)

If $g_{m1} = g_{m2} = g_m$ then $g_m = \frac{g_m}{2}$

Q) In a certain npn transistor, $10^8$ holes/$\mu$sec moved from Base to emitter and $10^{10}$ $e^-$/$\mu$sec moved from emitter to base. An ~~emitter~~ ammeter reading gives the base current of 16 $\mu$A, calculate emitter and collector currents.

$$I_B = 16\,\mu A$$

$$\cancel{\alpha = \frac{I_{pc}}{I_B}} = \frac{10^8}{10^8+10^{10}} = \frac{1}{1+10^2} = 9.9 \times 10^{-3}.$$

$$\beta = \frac{\alpha}{1-\alpha}$$

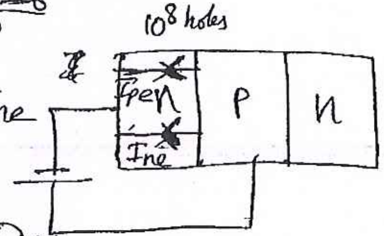
$$= \frac{1}{1-9.9\times10^{-3}}$$

$$= 10.8\times10^{-3}$$

$$\cancel{I_C = \beta I_B}$$

$$= \cancel{16 \times 10 \times 10^{-3} \times 10^{-6}}$$

$$I_E = I_{pe} + I_{ne}$$




$$I_E = \frac{Q_p}{T} + \frac{Q_n}{T} = \frac{p\cdot q}{T} + \frac{n\cdot q}{T}$$

$\Rightarrow 10^8$ holes/$\mu$s $\times 1.6\times10^{-19}$ $+ 10^{10}$ holes/$\mu$s $\times 1.6\times10^{-19}$

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$I_B = 16 \mu A$

$= 0.016 mA$

$I_E = I_B + I_C \Rightarrow I_C = I_E - I_B$

$\Rightarrow I_C = 1.616 - 0.016$

$= 1.6 mA.$

$$\boxed{\begin{aligned} \therefore I_B &= 0.016mA \\ I_C &= 1.6mA \end{aligned}}$$

Q) In a certain transistor, emitter current is 1.02 times as large as that of collector current. If the emitter current is 12mA, Find its base current

$I_E = 1.02 I_C$

$\Rightarrow \frac{12m}{1.02} = I_C \Rightarrow I_C = 11.764 mA.$

$I_E = I_B + I_C \Rightarrow I_B = 12m - 11.764m$

$= 0.235 mA.$

Q) For the above problem, calculate $\alpha, \beta, \gamma$.

$I_C = \beta I_B$

$\beta = \frac{I_C}{I_B} = 50.06$

$I_C = \alpha I_E$

$\Rightarrow \alpha = \frac{I_C}{I_E}$

$= \frac{11.764}{12} = 0.98$

$\gamma = \frac{I_E}{I_B}$

$= 49.05$

(or)

$\beta = \frac{\alpha}{1-\alpha}, \gamma = \frac{1}{1-\alpha} = 1 + \beta$

$I_C = \beta I_B + I_{CBO}(1+\beta)$ | $I_E = I_B + I_{CBO}$

$= 99(25\mu) + (200\times10^{-9})(100)$

$= 2.495\,mA.$

$I_E = I_B + I_C = 2.52\,mA. = 2.520\,mA$

Neglecting the leakage current,

$I_C = \beta I_B = 2.475\,mA.$

$I_E' = I_B + I_C = 2.5\,mA.$

% Percentage Error in $I_E = \dfrac{I_E - I_E'}{I_E} \times 100$

$= \dfrac{2.52 - 2.5}{2.52} \times 100$

$= 0.79$

Q) The DC current gain ($\beta$) of a BJT is 50. Assuming that the emitter injection efficiency is 0.995. Then the base transport factor is.

$\gamma^* = 0.995$

$\beta = 50$

$\Rightarrow \alpha = \dfrac{\beta}{1+\beta} = \dfrac{50}{51} = 0.98$

$\alpha = \beta^* \gamma^*$

$\beta^* = \dfrac{\alpha}{\gamma^*} = 0.985$

$I_{E_2} = 2 I_{E_1}$

$$\frac{②}{①} \Rightarrow 2 = \frac{e^{V_{BE2}/V_T}}{e^{V_{BE1}/V_T}}$$

$$\Rightarrow 2 = e^{(V_{BE_2} - V_{BE_1})/V_T}$$

$$\Rightarrow (\ln 2) = \frac{V_{BE_2} - V_{BE1}}{V_T}$$

$$\Rightarrow V_{BE_2} - V_{BE_1} = 26m(\ln 2)$$

$$= 18.018\,mV \simeq 20\,mV$$

$\simeq$ increases by 20mV

$$\boxed{\Delta V_{BE} = V_{BE_2} - V_{BE_1} = V_T \ln\left(\frac{I_{E_2}}{I_{E_1}}\right)}$$

Q) The base to emitter voltage $V_{BE}$ of a Si BJT has a temperature coefficient of approximately $-2.2\,mV/^{o}C$. If the transistor $V_{BE}$ is 0.7V at 25°C, Calculate its value at 50°C

$$V_{o2} - V_{o1} = -2.2(T_2 - T_1) \qquad \frac{dV_o}{dT} = -2.2\,mV/^{o}C$$

$$V_{o2} = 0.7 - \left((2.2)(25)\right) \times 10^{-3}$$

$\Rightarrow$ ~~$V_{o2}$ = [illegible]~~

$$\therefore V_{o2} = 0.7 - 0.0077 = 0.623V$$

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$1-\alpha$ $1-0.98$

$$I_C = \beta I_B + (1+\beta) I_{C_0}$$

$$= 49(20\mu) + (50)(0.6\mu)$$

$$= 1.01 \times 10^{-3}$$

$$= 1.01\,mA.$$

Q) The reverse saturation current of the collector base junction of a BJT is found to be 10nA at lower collector voltages. The low voltage current amplification factor ($\alpha$) is 0.98. Find reverse saturation current with base open.

$$\alpha = 0.98 \Rightarrow \beta = \frac{\alpha}{1-\alpha} = 49$$

$$I_{CB_0} = 10nA$$

$$I_{CE_0} = (1+\beta) I_{CB_0}$$

$$= 50 \times 10nA$$

$$= 500nA$$

$$= 0.5\mu A$$

Q) A transistor has a current gain of 0.99 in CB mode. Its current gain in CC mode is

$$\alpha = 0.99$$

$$\gamma = \frac{1}{1-\alpha} = \frac{1}{0.01} = 100$$

Narasimha

$\alpha = 0.99$

$$\beta = \frac{\alpha}{1-\alpha} = \frac{0.99}{1-0.99} = 99$$

Q) A BJT is in saturation region given $V_{cc} = 10V$, $R_c = 1k\Omega$, $h_{fe} = 100$ and $V_{CE(sat)} = 0.3V$. What is the collector current in saturation

$\beta = 1 + h_{fe}$

$$I_C = \frac{V_{CC} - V_{CE(sat)}}{R_C} = 9.7\,mA.$$

$$= \frac{10-0.3}{1K} = 9.7mA$$

Q) The reverse leakage current of the transistor when connected in CB configuration is $0.1\mu A$. While it is $16\mu A$, when the same transistor is connected in CE configuration. Calculate $\alpha, \beta, \gamma$

$I_{CBo} = 0.1\mu A$

$I_{CEo} = 16\mu A$

$I_{CEo} = (1+\beta) I_{CBo}$

$$\Rightarrow \beta = \frac{I_{CEo}}{I_{CBo}} - 1$$

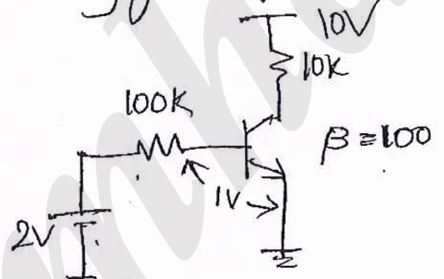
$\Rightarrow \beta = 159$

$$\alpha = \frac{\beta}{1+\beta} = \frac{159}{160} = 0.99$$

$\gamma = 1+\beta$

$\Rightarrow \gamma = 160$

Q) For the circuit shown in the figure, find the region of operation




$V_{BE} = 2V$

$V_{CC}$ — $I_B$ $\quad -2 + 100k I_B + 1 = 0$

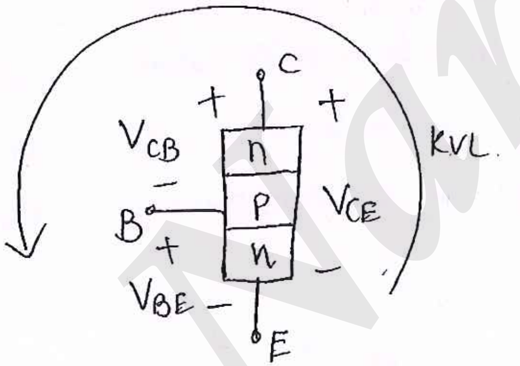
$I_B = \frac{+1}{100k} = +0.01 mA$ & $I_E = \quad I_C = \beta I_B$

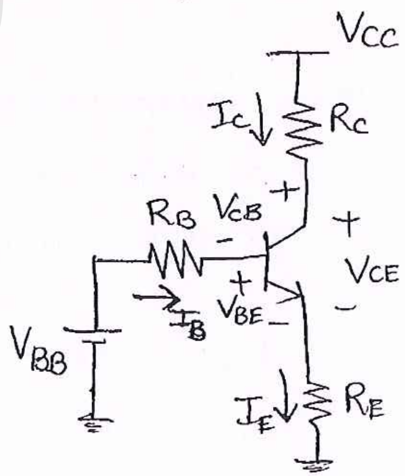
$\doteq 100 \times 0.01 m$

$\Rightarrow 1mA$

$V_{CE} = 0 \Rightarrow V_{CE} < 0.2 \Rightarrow$ Saturation Region

## Regions of Operation:




$-V_{CE} + V_{CB} + V_{BE} = 0$

$\Rightarrow V_{CE} = V_{CB} + V_{BE}$

$V_{CB} = V_{CE} - V_{BE}$

Narasimha

## Cutoff Region:

→ If $I_E = 0$

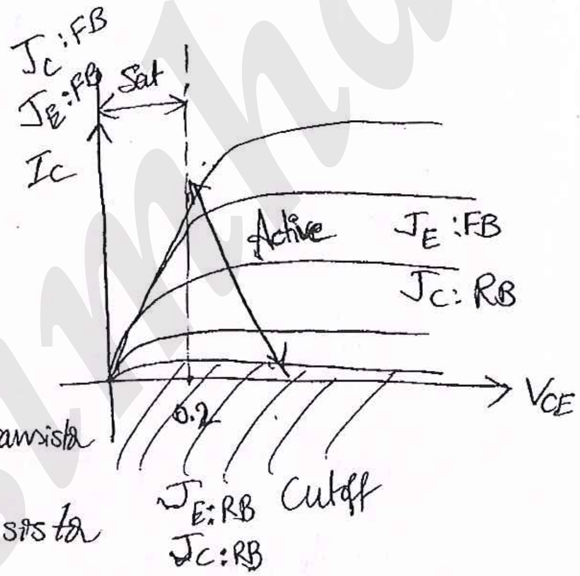
→ If $I_B = 0$

→ If $V_{BE} \leq 0$ for Si Tx

$V_{BE} \leq -0.1$ for Ge Tx

→ If $V_{BB}$ is negative for npn transistor

→ If $V_{BB}$ is +ve for pnp transistor




## Saturation Region:

(Current Method)

→ If $I_B \geq \frac{I_{C(sat)}}{h_{fe}}$ & $I_B \geq \frac{I_{C(sat)}}{h_{fe}}$

KVL at I/P side ⇒ $-V_{BB} + I_B R_B + V_{BE} + I_E R_E = 0$

$$\Rightarrow V_{BB} - V_{BE} = I_B R_B + I_E R_E$$

$$\Rightarrow I_B R_B + (I_C + I_B) R_E = V_{BB} - V_{BE}$$

$$\Rightarrow I_B (R_B + R_E) + I_C R_E = V_{BB} - V_{BE}$$

$\boxed{I_C = h_{fe} I_B}$ ⇒ $I_B (R_B + R_E + h_{fe} R_E) = V_{BB} - V_{BE}$

$$\Rightarrow \boxed{I_B = \frac{V_{BB} - V_{BE}}{R_B + (1 + h_{fe}) R_E}}$$

$$\Rightarrow I_C = \frac{V_{CC} - V_{CE}}{\left(R_C + R_E + \frac{R_E}{h_{fe}}\right)}$$

$$\Rightarrow \boxed{I_C = \frac{V_{CC} - V_{CE}}{R_C + R_E + \frac{R_E}{h_{fe}}}}$$

$$\boxed{I_{C(sat)} = \frac{V_{CC} - V_{CE(sat)}}{R_C + R_E + \frac{R_E}{h_{fe}}}}$$

Condition for Saturation:

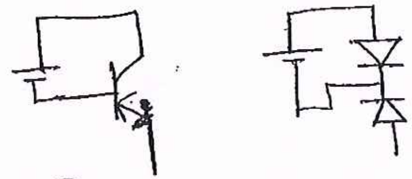
$$h_{fe} I_B \geq I_C(sat)$$

$h_{fe} = \beta$

$$* \quad \boxed{h_{fe}\left[\frac{V_{BB} - V_{BE}}{R_B + (1+h_{fe})R_E}\right] \geq \frac{V_{CC} - V_{CE(sat)}}{R_C + R_E + \frac{R_E}{h_{fe}}}} \quad \text{— (1)}$$

$$\boxed{h_{fe}\left[\frac{V_{BB} - V_{BE}}{R_B + h_{fe} R_E}\right] \geq \frac{V_{CC} - V_{CE(sat)}}{R_C + R_E}} \quad \text{— (2)} \qquad (\because h_{fe} \gg 1)$$

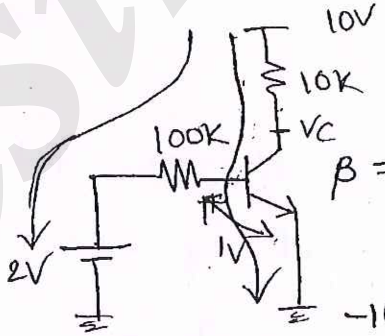
③ Cutoff RB RB



## Active Region:

If it is not satisfying ① and $V_{BB} > V_{BE}$, then it operates in active region.

Q)




$\beta = 100$

→ ① Verification

$$100\left[\frac{2-1}{100K+0}\right] \geq \left[\frac{10-0.3}{10K+0}\right]$$

$$\frac{100}{100K} \geq \frac{9.7}{10K}$$

$1m \geq 0.97m$ (Condition is satisfied)

$-10 + 10K(1m) + V_{CB} + 1 = 0$

$V_{CB} = 10 - 2 = 8V$

Transistor operates in saturation region.

Voltage Method:

npn transistor

$I_C = 1mA$

$I_B = 0.01mA$.

$\frac{V_{CC} - V_C}{10K} = 1m$

$V_C = V_{CC} - 10 = 0$.

$V_B = 1V$

$V_{CB} = V_C - V_B = 0 - 1 = -1V$

$\boxed{V_{CB} = -1V}$

$-10 + 10 + V_{CE} = 0$

$V_{CE} = 0$

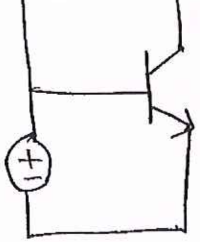
$V_{CB} = V_{CE} - V_{BE}$

$= -1V$

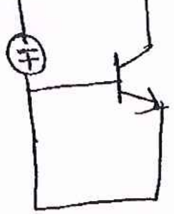
$-V_{CC} + 10K(1m) + 100K(0.01m) + 2 + V_{CB} = 0$

$10 - 10 - 1 + 2 = V_{CB} = -ve$

Narasimha



$J_E$ : FB
$J_C$ : RB
(Forward Active)



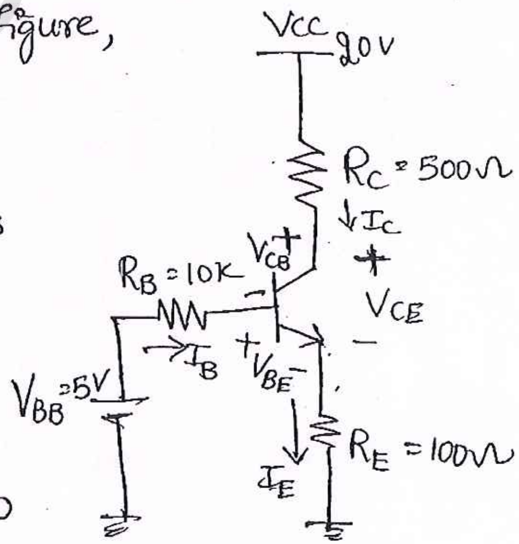

$J_E$ : RB
$J_C$ : FB
(Reverse Active)

$J_E$ : RB
$J_C$ : RB
(cutoff)

Q) For the circuit shown in the figure,

$V_{BE} = 0.7V$ and $h_{fe} = 100$

(Part a) Calculate $I_B$, $I_C$, $I_E$, $V_{CE}$ and $V_{CB}$




KVL at Input loop

$$-V_{BB} + I_B R_B + V_{BE} + I_E R_E = 0$$

$$\Rightarrow -5 + 10K\, I_B + 0.7 + I_E(100) = 0$$

$$10K\, I_B + 100\, I_E = 4.3$$

$$I_E = I_B + I_C$$

$$I_C = \beta I_B$$

$$\Rightarrow I_E = (1+\beta) I_B$$

$$\Rightarrow 10K\, I_B + 100(101) I_B = 4.3$$

$$\Rightarrow I_B = \frac{4.3}{10K + 10.1K}$$

$$= 2.14 \times 10^{-4}\ A$$

$$= 0.214\ mA$$

$$I_C = \beta I_B \Rightarrow 100 \times 0.214\ mA$$

$$= 21.4\ mA$$

Narasimha

$V_{CB} = V_{CE} - V_{BE}$

$= 6.4386V$

(or). $I_B = \dfrac{V_{BB} - V_{BE}}{R_B + (1+h_{fe})R_E} \simeq \dfrac{V_{BB} - V_{BE}}{R_B + h_{fe}R_E} = 2.15$

Region of operation: $V_{CE} > 0.2 \Rightarrow$ Active Region

Part(b) $\dfrac{I_C}{h_{fe}} = \dfrac{21.5m}{100} = 2.153 \times 10^{-4}$ $I_B = 0.214$

$I_B < I_C/h_{fe}$ Hence no saturation region

If $V_{BB}$ is varied while maintaining other parameters unchanged in part (a), what is the minimum $V_{BB}$ required to drive the transistor into saturation. Assume $V_{CE(sat)} = 0.3V$

$$\cancel{\left( I_B = \frac{V_{BB} - V_{BE}}{R_B + h_{fe}R_E} \simeq \frac{V_{BB} - V_{CE(sat)}}{R_C + R_E} \right)}$$

~~$V_{CE(sat)} = 0.3$~~V

$$h_{fe}\left[\frac{V_{BB} - V_{BE}}{R_B + h_{fe}R_E}\right] \geq \frac{V_{CC} - V_{CE(sat)}}{R_C + R_E}$$

$$100\left[\frac{V_{BB} - 0.7}{10K + 10K}\right] \geq \frac{20 - 0.3}{500 + 100}$$

$\Rightarrow V_{BB} \geq 7.26V$

$\Rightarrow V_{BB_{min}} = 7.26V$

Narasimha

$$\ldots R_B + h_{fe} R_E \Big] \qquad R_C + R_E$$


$$R_E = R_L$$

$$\Rightarrow 100\left[\frac{12-0.8}{200K+100R_L}\right] \geq \frac{10-0.2}{0+R_L}$$

$$\frac{1120}{200K+100R_L} \geq \frac{9.8}{R_L}$$

$$1120R_L \geq 1960000 + 980R_L$$

$$140R_L \geq 1960000$$

$$\Rightarrow R_L \geq 14K\Omega$$

$$R_{L_{min}} = 14K\Omega$$

(b) Determine Voltage $V_o$ at saturation for $R_L = R_{L_{min}}$

$$V_{CE} = V_{CE(sat)}$$

$$V_o = V_{CC} - V_{CE(sat)}$$
$$= 10 - 0.2$$
$$= 9.8V$$

(or)

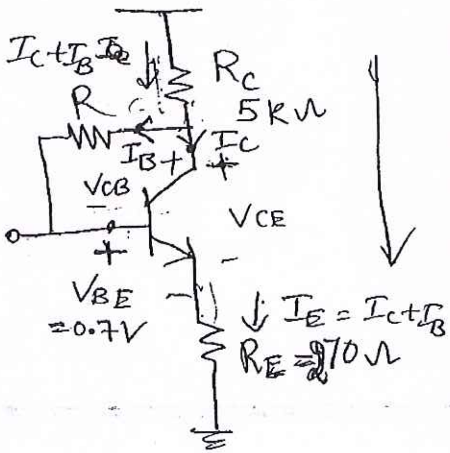
$$V_o = V_{CC} - I_{C(sat)}R_L$$

---

Q) → $h_{fe} = \beta = 50$, $V_{BE} = 0.7V$, ~~$V_{CE} = 5V$~~

For the circuit shown in the figure transistor has above values

If $V_{CE} = 5V$, find the value of R.




Sol: Applying KVL at the o/p side

$$-V_{CC} + I_C R_C + V_{CE} + I_E R_E = 0$$

$$V_{CC} = I_C R_C + V_{CE} + I_E R_E \qquad ~~+V_{BE}~~$$

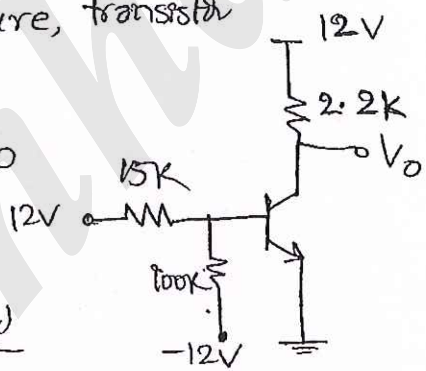
$$V_{CB} = V_{CE} - V_{BE}$$

$$R = \frac{V_{CB}}{I_B} = \frac{5-0.7}{I_B} = \frac{4.3}{I_B}$$

Narasimha

18/8/15

Q) For the circuit shown in the figure, transistor has $\beta = 30$, $V_{BE} = 0.7V$, $V_{CE(sat)} = 0.2V$. Find the region of operation and also calculate $V_o$.



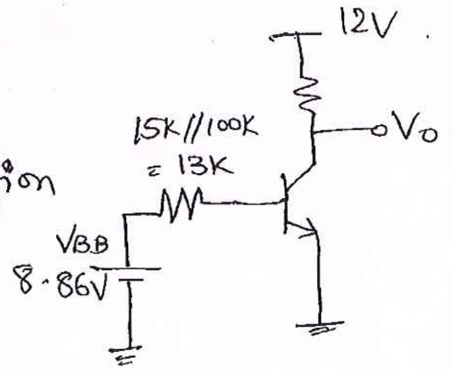

$$h_{fe}\left(\frac{V_{BB} - V_{BE}}{R_B + h_{fe} R_E}\right) \geq \frac{V_{CC} - V_{CE(sat)}}{R_C + R_E}$$

$$30\left(\frac{\cancel{886}\ 8.86 - 0.7}{13K + 0}\right) \geq \frac{12 - 0.2}{2.2K}$$

~~4 Vce~~

$$18.83m \geq 5.36m.$$

Region of operation is Saturation region

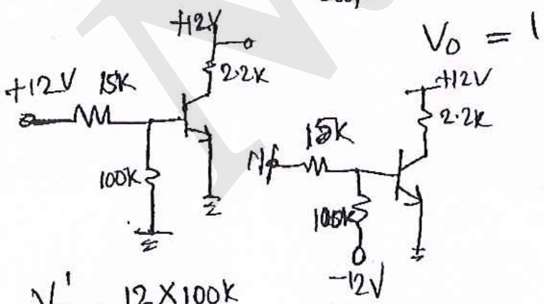



$$-12 + I_{C_{sat}}(2.2k) + V_o = 0$$

$$V_o = 12 - I_{C_{sat}}(2.2k)$$

$$V_o = V_{CE(sat)}$$

$$= 0.2V$$




$$\therefore V_o = 0.2V$$

$$V'_{BB} = \frac{12 \times 100K}{15K + 100K} \qquad V''_{BB} = \frac{-12 \times 15K}{15K + 100K}$$

$$V_{BB} = V'_{BB} + V''_{BB}$$

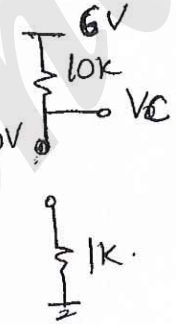
$$= \frac{12}{115K}[100K - 15K] = 8.86V$$

Narasimha

For $\underline{V_B = 0V}$

$V_B = 0V \Rightarrow I_B = 0 \Rightarrow$ ~~$I_{cc} \approx I_{EE}$~~. Cut off

~~$I_C = \frac{6-0}{10K+1K} =$~~




Transistor is in cutoff

$V_C = 6V, \quad I_C = 0, \quad I_E = 0$

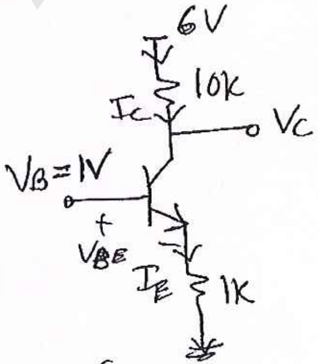
For $\underline{V_B = 1V}$

$V_B = 1V \Rightarrow \qquad I_E = \frac{V_B - V_{BE}}{1K}$

~~$10K(I_C)$~~

$= \frac{1-0.7}{1K}$

$I_E \approx I_C = 0.3mA \qquad = 0.3mA$




(active)

($V_{CB}$ is +ve)

or $I_C = \alpha I_E$ where $\alpha = \frac{\beta}{1+\beta}$

$-6 + 10K I_C + V_C = 0$

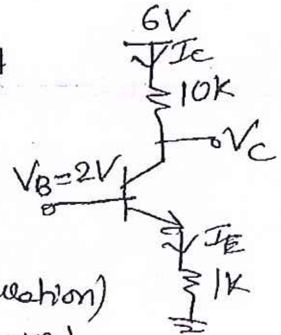
$\Rightarrow V_C = 6 - (10K)(0.3m)$

$= 6 - 3 = 3V$

For $\underline{V_B = 2V}$

$I_E = \frac{V_B - V_{BE}}{1K} = \frac{2-0.7}{1K} = 1.3mA$

$I_C \simeq I_E = 1.3mA$




So these are wrong values

$V_C = 6 - (10K)(1.3m)$

$= 6 - 13 = -7V$ (Saturation)

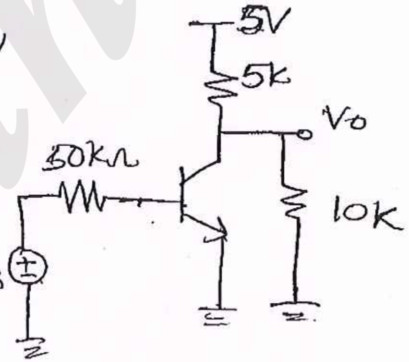
($V_{CB}$ is -ve)

Narasimha

$= 0.2 + (0.52)(1K)$

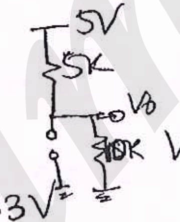
$\cong 0.8V$

Q) For the circuit shown in the figure, transistor has $\beta = 75$. Calculate $V_0$ for $V_{BE} = 0V, 1V$ and $2V$




For $V_B = 0V$

Transistor is in Cutoff




$\Rightarrow V_0 = \frac{5V \times 10K}{5K + 10K} = 3.33V$

For $V_B = 1V$,

$I_B = \frac{V_B - V_{BE}}{50k} = \frac{1 - 0.7}{50k} = 6\mu A$

$\frac{5 - V_0}{5k} = I_C + \frac{V_0}{10k}$

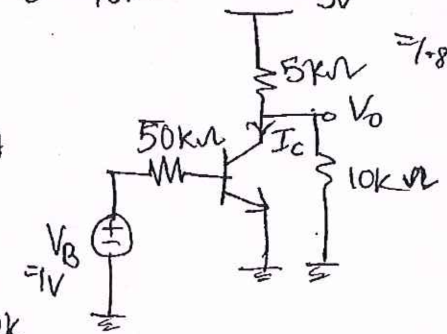
$\Rightarrow V_0 = 0.55 \times \frac{4}{3} = 1.833$

$I_L = \frac{V_0}{10K}$

$I_E = I_B + I_C$

$\Rightarrow$ ~~$I_E \approx 0 \Rightarrow I_B \approx I_C$~~

$I_C = \beta I_B = 75 \times 6\mu A = 0.45\,mA$




$V_C = 5 - 5k(0.45m)$
$= 2.75V$

$V_0 = \frac{2.75 \times 10k}{10k + 5k} = 1.83V$

For $V_B = 2V$

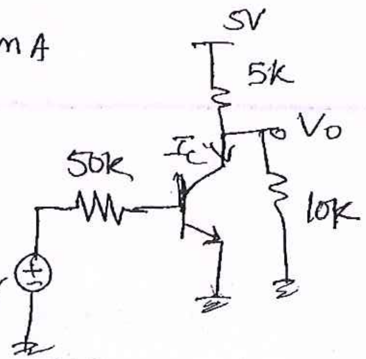
$I_B = \frac{V_B - V_{BE}}{50k} = \frac{2 - 0.7}{50k} = 0.026\,mA = 26\mu A$

$\frac{5 - V_0}{5K} = I_C + \frac{V_0}{10K}$

$\Rightarrow -0.95m = \frac{3V_0}{10K}$

$\Rightarrow V_0 = \frac{-0.95 \times 10}{3} = -3.1667V$

$I_C = \beta I_B = 1.95\,mA$



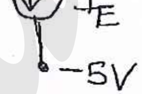

$V_C = 5 - 5k(1.95m)$
$= -4.75V \Rightarrow$ Saturation region

$V_0 = -3.1667V$

$\Rightarrow V_0 = V_{CE(sat)} = 0.2V$

Narasimha

$1+\beta \quad 151$




$I_C = 0.099 \text{ mA}.$

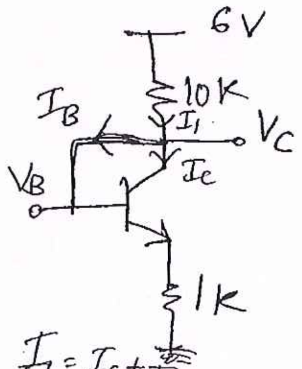
$V_0 = 5 - (0.099)\, 5K = 4.5V$

For $I_E = 0.5 \text{mA}$

$I_C = \alpha I_E = 0.4967 \text{ mA}$

$V_0 = 5 - (2.4835) = 2.5165V$

Q) For the circuit shown in the figure, $V_B = V_C$ and $\beta = 50$. Calculate $V_{BE}$




$I_1 = I_C + I_B$

$\left( I_C = I_E \Rightarrow I_E = \dfrac{6-0}{11K} = 0.545 \text{mA} \right.$

$V_C = 0.55$

$V_C = V_B = 0.55 \Rightarrow -0.55 + V_{BE} + (0.545m)(1k) = 0\,)$

$\cancel{\Rightarrow V_{BE} =}$

KVL at o/p side $\Rightarrow$ $6V = 10K\, I_1 + V_{BE} + 1K(I_1)$

$\Rightarrow 6V - V_{BE} = 11K\, I_1$

$\Rightarrow I_1 = \dfrac{6V - 0.7V}{11K}$

$= \dfrac{5.3}{11K} = 0.4818 \text{ mA}.$

$V_C = 6 - 10k(0.4818m)$

$= 6 - 4.818$

$= 1.182 \simeq 1.2V$

Narasimha

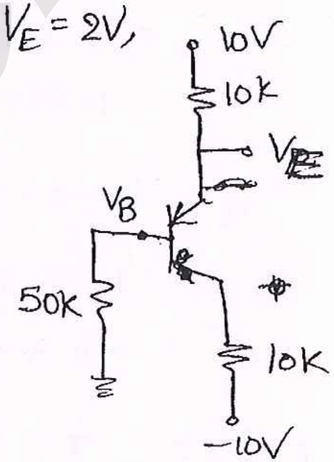
$1+\beta$   $101$

$= 0.99$

$\cancel{= 0.89\,mA}$

$$I_E = \frac{1}{\alpha} I_C = \frac{0.90}{0.99} = 0.909\,mA.$$

Q) For the circuit shown in the figure, $V_E = 2V$, Calculate $\alpha$ value.




$V_E = 2 \Rightarrow I_E = \frac{V_{EE} - V_E}{10K}$

$= \frac{10-2}{10K} = 0.8\,mA.$

$I_C = \alpha I_E$

$I_C = \alpha I_E$

$V_{CE}$

$I_E = 0.8\,mA$

$\alpha = 0.96$

$V_{CC} = -10V$

$V_{EB} = 0.7$

$I_B = \frac{\cancel{0-1.3}}{\cancel{50K}} = \frac{-0+1.3}{50K} = 26\,\mu A$

$V_E - V_B = 0.7$

$V_B = V_E - 0.7$

$= 2 - 0.7$

$= 1.3\,V.$

$I_E = I_B + I_C$

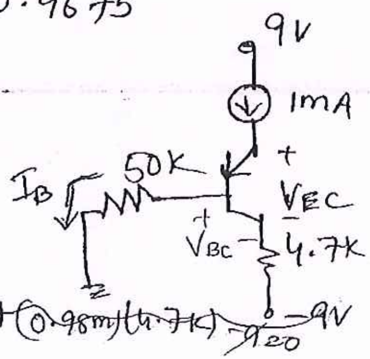
$\Rightarrow I_C = I_E - I_B$

$= 0.774\,mA$

$\alpha = \frac{I_C}{I_E}$

$= 0.9675$

Q) For the circuit shown in the figure, transistor has $\beta = 50$. Calculate $V_{EC}$




$I_E = 1mA$

$\alpha = \frac{\beta}{1+\beta} = 0.98$

$I_C = \alpha I_E = 0.98\,mA$

$V_{EC} =$ $\cancel{+9 + V_{EC} + (0.98m)(4.7K) - 9 = 0}$

$V_{EB} = V_E - V_B$ $\Rightarrow$ $V_{EC} = 6.07V$

$V_E = V_{EB} + V_B$

$= 0.7 + 50K(20\mu)$

$= 0.7 + 0.020 \times 50$

$= 1.68V$

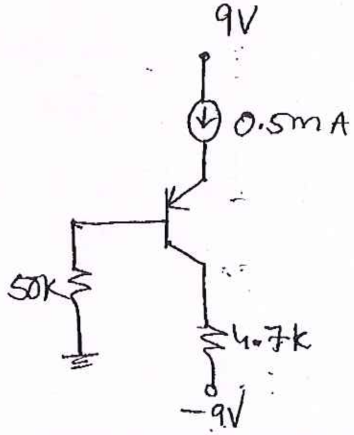
$V_C = 4.7K \times I_C - 9$

$= 4.7k \times 0.98m - 9$

$= -4.394V$

$V_{EC} = V_E - V_C = 1.68 - (-4.394) = 6.07V$

Q) For the circuit shown in the figure, transistor has $\beta = 50$, Calculate power dissipated in the transistor




$pnp \Rightarrow P_d = V_{EC} \times I_C$

$I_E = 0.5mA$

$\alpha = 0.98$

$I_C = \alpha I_E = 0.49mA$

$I_B = I_E - I_C$

$= 0.5 - 0.9$

$= 10\mu A$

$V_{EB} = V_E - V_B$

$V_E = V_{EB} + V_B$

$= 0.7 + (50K)(10\mu)$

$= 1.2$

$V_C = 4.7K \times I_C - 9$

$= 4.7K \times 0.49m - 9$

$= -6.697$

$V_{EC} = V_E - V_C$

$= 1.2 + 6.697$

$= 7.897V$

$P_d = V_{EC} \times I_C = 3.869 mW$

Narasimha

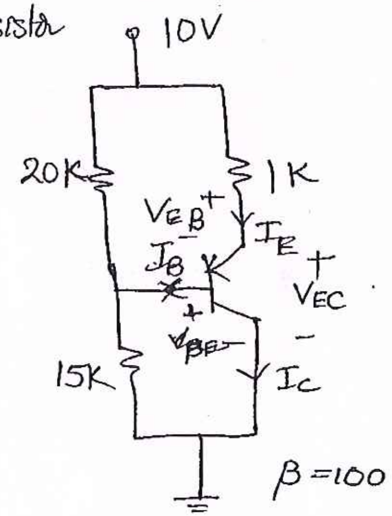
$$I_C = \beta I_B \Rightarrow I_B = \frac{I_C}{\beta} = 33.3\,\mu A$$

$$-24 + I_B R_B + V_{BE} = 0$$

$$R_B = \frac{24-0.7}{33.3\mu}$$

$$= 0.7\,M\Omega \simeq 699\,k\Omega$$

Q) For the circuit shown in the figure, transistor has $\beta = 100$, Calculate $V_B$.




$\times\ (\cancel{-10 + I_E(1k) + V_{EC} = 0}$

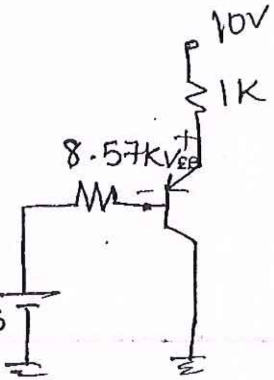
$\cancel{20k(I_B) - V_{EB} - I_E(1k) = 0})\times$

$$I_C = \alpha I_E$$

$$\alpha = \frac{\beta}{1+\beta} = \frac{100}{1+100} = \frac{100}{101} = 0.99$$

$$V_{Th} = \frac{10 \times 15K}{20K + 15K} = 4.285$$

$$R_{TH} = 8.57K$$




$\times\ (\cancel{I_B = \frac{V_{BB} - V_B}{8.57k}}$

$\Rightarrow \cancel{V_B = -I_B(8.57k) + V_{BB}})\times$

$I_B =$

$\times\ (\cancel{-10 + (1K + 8.57k) I_E + V_{EB} + 4.285 = 0}$

$\Rightarrow \cancel{I_C = \frac{10 - 4.285 - 0.7}{9.857k} = 0.5087\,mA})\times$

Narasimha

$$V_B = V_{BB} + I_B R_B$$

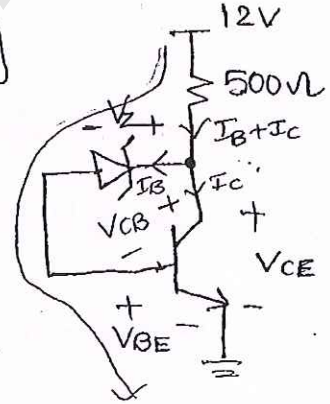
$$= 4.286 + (45.8\mu)(8.57k)$$

$$= 4.67V$$

Q) The transista circuit shown in the figure, $V_Z = 5V$ and $\beta = 100$

→ Calculate $V_{CE}$ and $I_C$

$\boxed{V_{CB} = V_Z}$




$$-12 + I_C(500\,\Omega) + 5 + 0.7 = 0$$

$$\Rightarrow I_C = \frac{12 - 5 - 0.7}{500}$$

$$= 12.6mA$$

$$-12 + I_C R_C \bar{+} 5 + V_{CE} = 0$$

$$V_{CE} = 12 - 6.3 + 5 \text{ (a)}$$

$$\text{(a) } = 5.7V$$

$V_{CE} = V_Z + V_{BE}$

$= 5 + 0.7$

$= 5.7V$

$$-12 + 500(I_C + I_B) + V_{CE} = 0$$

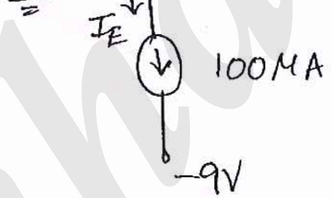
$$\Rightarrow (101) I_B = \frac{12 - 5.7}{500}$$

$$= 0.0126mA$$

$$\therefore I_C = 12.6mA.$$

Narasimha

$$I_E = I_S e^{+V_{BE}/V_T}$$




$$V_{BE} = V_T \ln\left(\frac{I_E}{I_S}\right)$$

$$= 26m \ln\left(\frac{100\mu}{10^{-16}}\right)$$

$$= 0.718\ V$$

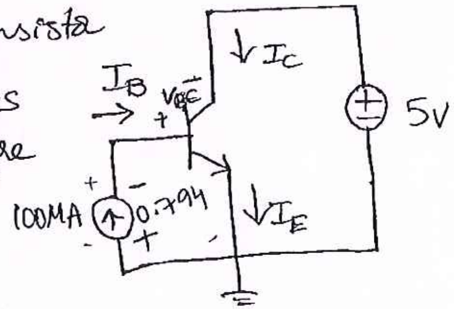
$\alpha = 0.95$

$I_S = 10^{-16} A.$

$$I_C = \alpha I_E = 95\mu A = 0.095\ mA.$$

$$I_B = I_E - I_C = 100 - 95 = 5\mu A = 0.005\ mA.$$

Q) Calculate & $I_E, I_C, I_B$ currents and also calculate $V_{BE}$, $V_{BC}$ voltages fo the transista biased by a base current source as shown in the figure




$I_B = 100\mu A$

$$I_C = I_S e^{V_{BE}/V_T}$$

$$\beta = \frac{\alpha}{1-\alpha} = 19$$

$\alpha = 0.95$

$I_S = 10^{-16} A.$

$$I_C = \alpha I_E$$

$$I_C = \beta I_B = 1900\mu A = 1.9 mA$$

$$I_E = I_C + I_B$$

$$\Rightarrow I_E = 1900\mu + 100\mu = 2 mA$$

$$I_C = I_S e^{V_{BE}/V_T}$$

$$\Rightarrow V_{BE} = 26m \ln\left(\frac{1.9m}{10^{-16} A}\right) = 0.794 V$$

$$-V_{100\mu A} + V_{BE} = 0$$

$$\Rightarrow V_{100\mu A} = +0.794 V$$

$$-5 + V_{BC} + 0.794 = 0$$

$$\Rightarrow V_{BC} = \cancel{0.794V}\ 4.206 V$$

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$$I_C = \frac{12-6}{10K} = 0.6\,mA$$

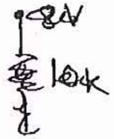
$$R_C = \frac{18 - I_C 10K}{I_C} = 20K\Omega$$

$$I_E = \frac{I_C}{\alpha} = \frac{0.6\,m}{0.987} = 0.608\,mA$$

$$\alpha = \frac{\beta}{1+\beta} = 0.987$$

$$I_E = \frac{12-6}{10K} = 0.6\,mA$$

$$I_C = \alpha I_E = \Big] \times$$




$$V_{EB} = V_E - V_B = -0 + V_E = V_E - 0$$

$$\Rightarrow V_E = V_{EB} = 0.7$$

$$I_E = \frac{12-0.7}{10K} = 1.13\,mA$$

$$I_C = \alpha I_E = \frac{\beta}{1+\beta} I_E \Rightarrow I_C = 1.115\,mA$$

KVL at o/p

$$-12 + 10K(1.13m) + 6 + I_C R_C - 12 = 0$$

$$\Rightarrow R_C = \frac{24 - 6 - 11.3}{1.115m} = 5.82\,k\Omega \simeq 6\,k\Omega$$

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$$\Rightarrow I_B = \frac{\quad}{10K + 760K}$$

$$= 0.012\,mA$$

$$= 12.07\,\mu A$$

$$I_C = \beta I_B$$

$$= 75 \times 12.07\mu = 0.9\,mA.$$

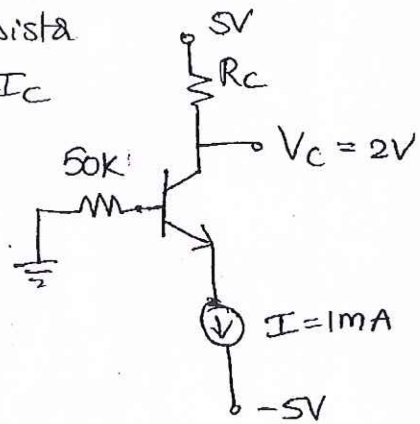
$$I_E = I_B + I_C \Rightarrow \cancel{I_C} \; I_E = I_B + I_C$$

$$= 0.912\,mA.$$

$$-8 + 9.12 + V_{EC} + 2.7 - 8 = 0$$

$$\Rightarrow V_{EC} = 4.18V$$

Q) For the circuit shown in the figure, transista has $\beta = 75$ and $V_{BE} = 0.7V$. Calculate $I_C$ and $R_C$ values




$$I_E = 1mA \qquad\qquad I_C = \alpha I_E$$

$$I_C = \frac{5-2}{R_C} \qquad\qquad \alpha = \frac{\beta}{1+\beta} = \frac{75}{76}$$

$$I_B = \frac{V_B - 0}{50K} \qquad\qquad = 0.98$$

$$I_C = 0.98\,mA$$

$$R_C = \frac{5-2}{0.98m} = \frac{3}{0.98m} = 3.06\,K\Omega.$$

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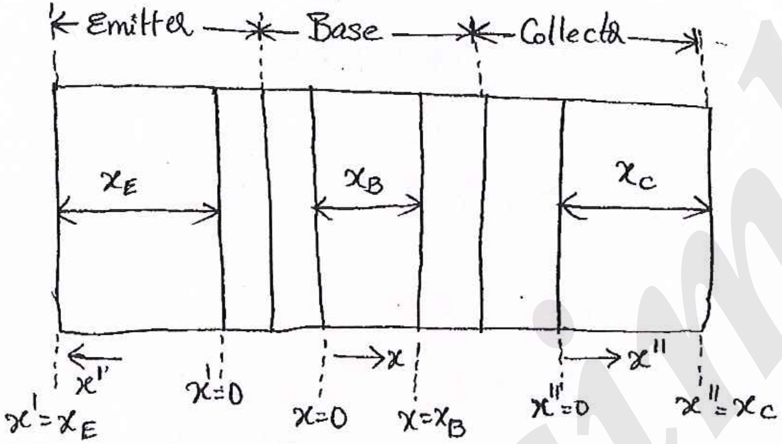


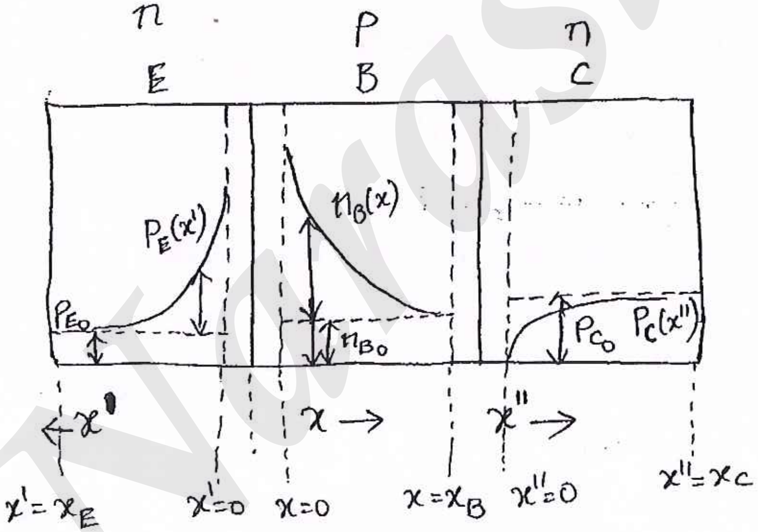


$$I_C = I_S e^{V_{BE}/V_T}$$

$$I_o = \frac{AeD_{p}p_{n_0}}{L_p} + \frac{AeD_n}{L_n} n_{p_0}$$

$$n_B(x)\Big|_{x=0} = n_{B_0} e^{V_{BE}/V_T}$$

$$P_E(x')\Big|_{x'=0} = P_{E_0} e^{V_{BE}/V_T}$$

If EB junction is forwardbiased

$$I_S = \frac{A_{BE}\, q D_n}{x_B} n_{B_0}$$

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Q) The parameters in the base region of an npn bipolar transistor are as follows:

npn

$D_n = 20\,cm^2/s$

$n_{B_0} = 10^4/cm^3$

$x_B = 1\,\mu m$

$A_{BE} = 10^{-4}\,cm^2$

① If $V_{BE} = 0.5V$ then the collector current $I_C$ is

$$I_S = \frac{A_{BE}\, q D_n}{x_B} n_{B_0} = \frac{10^{-4} \times 1.6\times10^{-19} \times 20}{10^{-4}} \times 10^4$$

$$= 3.2\times10^{-14}$$

$$I_C = I_S e^{V_{BE}/V_T} = 3.2\times10^{-14} \times e^{0.5/0.02586}$$

$$= 7.98\times10^{-6} A$$

$$= 7.98\,\mu A \quad \text{(Cut-off Region)}$$

② If $V_{BE} = 0.7V$, then the collector current $I_C$ is

$$I_C = I_S e^{V_{BE}/V_T}$$

$$= 3.2\times10^{-14} \times e^{0.7/0.02586}$$

$$= 18.24\,mA \quad \text{(Forward biased)}.$$

Q) In a bipolar transistor biased in the forward active region the base current $I_B = 50\,\mu A$ and the collector current $I_C$ is $2.7mA$. Then the $\alpha$ value is

$\beta = \frac{\alpha}{1-\alpha}$

$I_C = \beta I_B$

$\beta = \frac{I_C}{I_B} = 54$

$$\alpha = \frac{\beta}{1+\beta} = \frac{54}{55} = 0.982$$

Narasimha

$$\ln n_{B0} = \ln n_B(x) - \frac{V_{BE}}{V_T}$$

$$\Rightarrow n_{B0} = 1.7 \times 10^4 / cm^3$$

$$\ln P_{E0} = \ln P_E(x) - \frac{V_{BE}}{V_T}$$

$$\Rightarrow P_{E0} = )$$

$$n_{B0} = \frac{n_i^2}{N_B} \qquad P_{E0} = \frac{n_i^2}{N_E} \qquad P_{C0} = \frac{n_i^2}{N_C}$$

$$n_i = 1.5 \times 10^{10} / cm^3$$

$$n_{B0} = \frac{(1.5\times10^{10})^2}{10^{16}} = 2.25 \times 10^{4} / cm^3$$

$$P_{E0} = \frac{(1.5\times10^{10})^2}{5\times10^{17}} = 450 / cm^3$$

$$P_{C0} = \frac{(1.5\times10^{10})^2}{10^{15}} = 2.25 \times 10^5 / cm^3$$

Q) A uniformly doped Si pnp transistor is biased in the forward active mode. The transistor doping concentrations are $N_E = 10^{18}/cm^3$, $N_B = 5\times10^{16}/cm^3$, $N_C = 10^{15}/cm^3$. For $V_{EB} = 0.6V$, $P_B$ at $x=0$ is

$$P_B(x) = P_{B0} \cdot e^{V_{EB}/V_T} \qquad P_{B0} = \frac{n_i^2}{N_B}$$

$$= 4500 \times e^{0.6/0.02586} \qquad = \frac{(1.5\times10^{10})^2}{5\times10^{16}} = 4500 / cm^3$$

$$P_B(0) = 5.366 \times 10^{13} / cm^3$$

Q) An npn bipolar transistor having uniform doping of
→ $N_E = 10^{18}/cm^3$, $N_B = 10^{16}/cm^3$, $N_C = 6\times10^{15}/cm^3$ is operating in the inverse active mode with $V_{BE} = -2V$ and $V_{BC} = 0.6V$.

① The minority carrier concentration at $x = x_B$ is

$$n_{B_0} = \frac{n_i^2}{N_B} = \frac{(1.5\times10^{10})^2}{10^{16}} = 2.25\times10^4/cm^3$$

$$n_B(x_B) = 2.25\times10^4 \times e^{0.6/0.02586}$$

$$= 2.68\times10^{14}/cm^3$$

② The minority carrier concentration at $x'' = 0$ is

$$P_{C_0} = \frac{n_i^2}{N_C}$$

$$= 37500/cm^3$$

$$P_C(x) = P_{C_0}\, e^{V_{BC}/V_T}$$

$$= 37500 \times e^{0.6/0.02586}$$

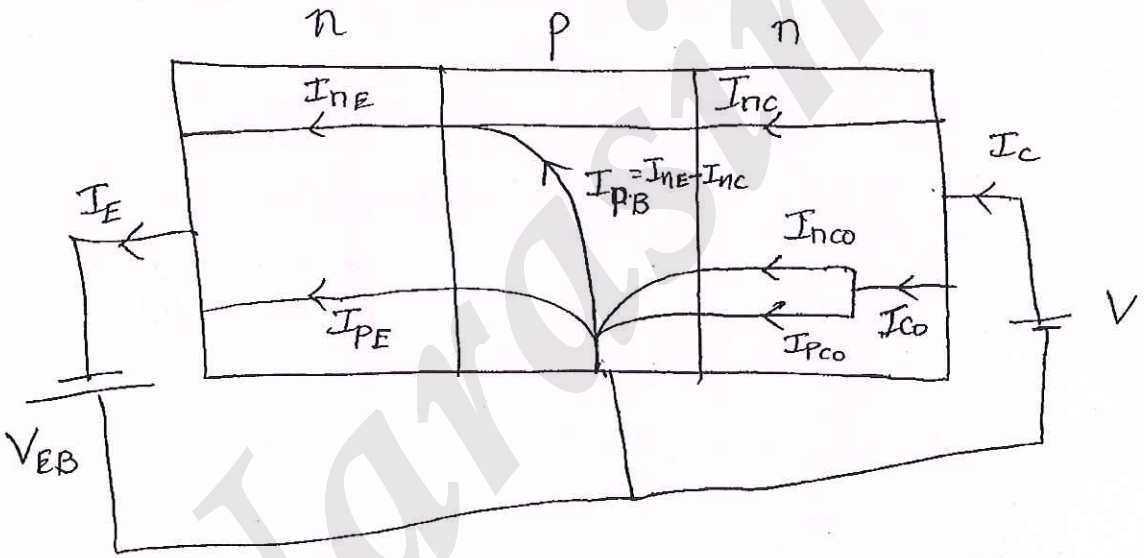
$$= \cancel{4.49}\times10^{14}/cm^3$$

$$= 4.47\times10^{14}/cm^3$$

Narasimha

$$\beta^* = \frac{I_{nC}}{I_{nE}} = \frac{1.18\,m}{1.2\,m} = 0.983$$

$$\alpha = \beta^* \gamma^* = 0.907$$




$$\gamma^* = \frac{I_{nE}}{I_E} = \frac{I_{nE}}{I_{nE} + I_{PE}}$$

$$\beta^* = \frac{I_{nC}}{I_{nE}}$$

$$\alpha = \frac{I_{nC}}{I_E} = \frac{I_{nC}}{I_{nE} + I_{PE}}$$

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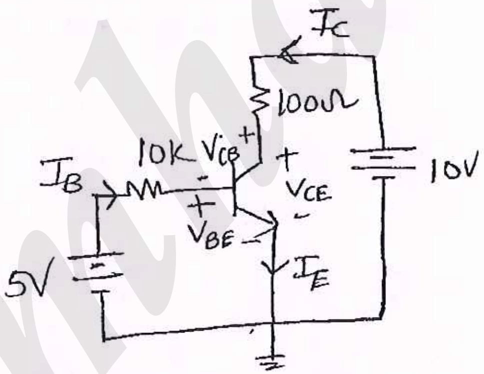
$I_B$, $I_C$, $I_E$, $V_{BE}$, $V_{CB}$.

Given $V_{BE} = 0.7V$.

$\beta = 150$




$$-5 + 10k I_B + V_{BE} = 0$$

$$\Rightarrow I_B = \frac{5-0.7}{10k}$$

$$= \frac{4.3}{10k} = 0.43mA.$$

$$I_C = \beta I_B$$
$$= 150(0.43)$$
$$= 64.5\ mA.$$

$$-10 + 100 I_C + V_{CE} = 0$$

$$V_{CE} = 10 - 100(64.5m)$$

$$= 3.55V$$

$$I_E = I_B + I_C$$
$$= 0.43 + 64.5mA$$
$$= 64.93\ mA.$$

$$V_{CE} = V_{BE} + V_{CB}$$

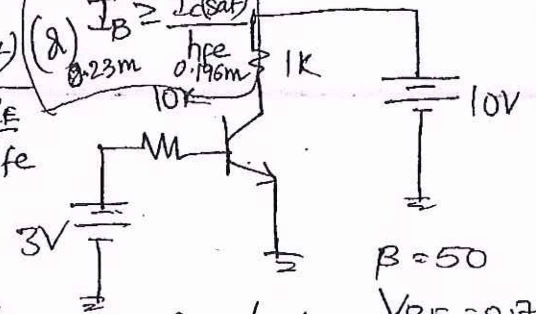
$$\approx \cancel{0.7+3.55}$$

$$= \cancel{4.25V}$$

$$\Rightarrow V_{CB} = V_{CE} - V_{BE}$$
$$= 3.55 - 0.7 = 2.85V$$

Q) The transistor circuit shown in the figure. Find the region of operation. Assume $V_{CE(sat)} = 0.2V$

(or) $I_B \geq \frac{I_{C(sat)}}{h_{fe}}$ 0.23m 0.196m




$$h_{fe}\left[\frac{V_{BB} - V_{BE}}{R_B + (1+h_{fe})R_E}\right] \geq \frac{V_{CC} - V_{CE(sat)}}{R_C + R_E + \frac{R_E}{h_{fe}}}$$

$$\Rightarrow 50\left[\frac{3-0.7}{10k + 51(0)}\right] \geq \frac{10 - 0.2}{1k + 0}$$

$0.0115 \geq 0.0098$ Transistor is in saturation.

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~~from~~ is ~~$V_{CC} - V_{CE}$~~


$\beta = 100$

$V_{BE} = 0.7V$

$$I_B = \frac{5-0.7}{22K} = 0.195mA$$

$$I_C = \beta I_B = 19.5mA$$

$$19.5m = \frac{V_{CC} - V_{CE(max)}}{R_C} \Rightarrow V_{CC} = 19.5m(1K) + 15$$

$$= 34.5V$$

(2)

$$V_{CC(max)} = V_{CE(max)} + V_{RC}$$

$$= 15 + 19.5 = 34.5V$$

$I_C$ is independent of $V_{CC}$. It depends on $\beta$ and $I_B$ values

If $V_{CC} > V_{CC(max)}$ then remaining drop will come across transistor that will damage the transistor

$$P_D = V_{CE(max)} \times I_C$$

$$= 15 \times 19.5m = 292.5mW < P_{D(max)}$$

→ $V_{CE(max)}$ and $I_{C(max)}$ will not be taken at a time. When Voltage is max, Current is min and vice versa to achieve max power rating.

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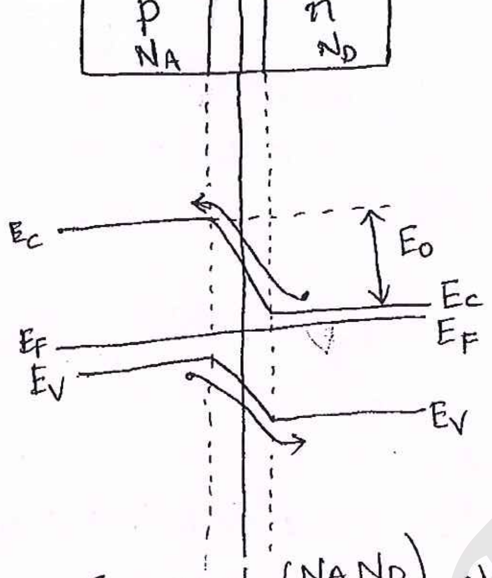



$E_C - E_F = KT\ln\left(\frac{N_C}{N_D}\right)$ → $N_C > N_D$

$E_F - E_V = KT\ln\left(\frac{N_V}{N_A}\right)$ → $N_V > N_A$.

$N_C = 4.82\times10^{15}\left(\frac{m_n}{m}\right)^{3/2} \cdot T^{3/2} / cm^3$

$N_V : 4.82\times10^{15}\left(\frac{m_p}{m}\right)^{3/2} \cdot T^{3/2} / cm^3$

$N_D$: Donor Concentration

$N_A$: Acceptor concentration

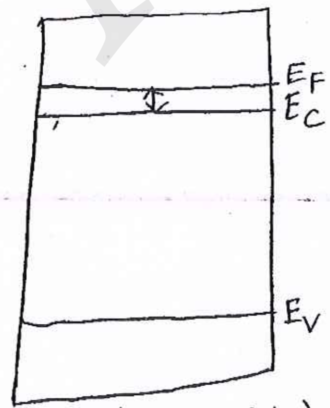
$$E_0 = KT\ln\left(\frac{N_A N_D}{n_i^2}\right)\ eV$$

$$V_0 = KT\ln\left(\frac{N_A N_D}{n_i^2}\right)\ V.$$

Tunnel diode is made up of degenerative semiconductors.

Doping : 1 in $10^3$ Si & Ge atoms.

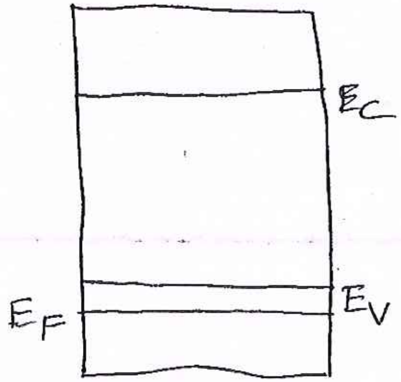
n-Type




→ $N_D > N_C$

→ $E_C - E_F = KT\ln\left(\frac{N_C}{N_n}\right)$

p-type




→ $N_A > N_V$

→ $E_F - E_V = KT\ln\left(\frac{N_V}{N_A}\right)$

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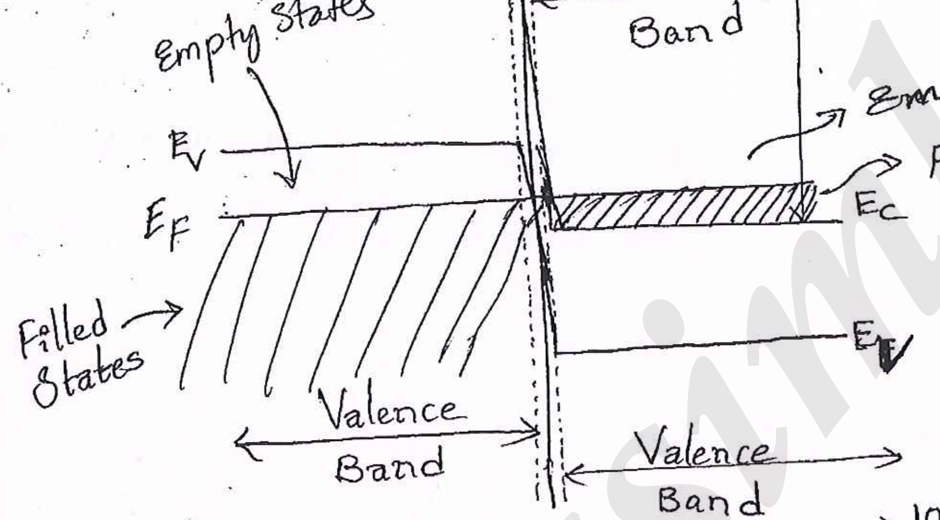
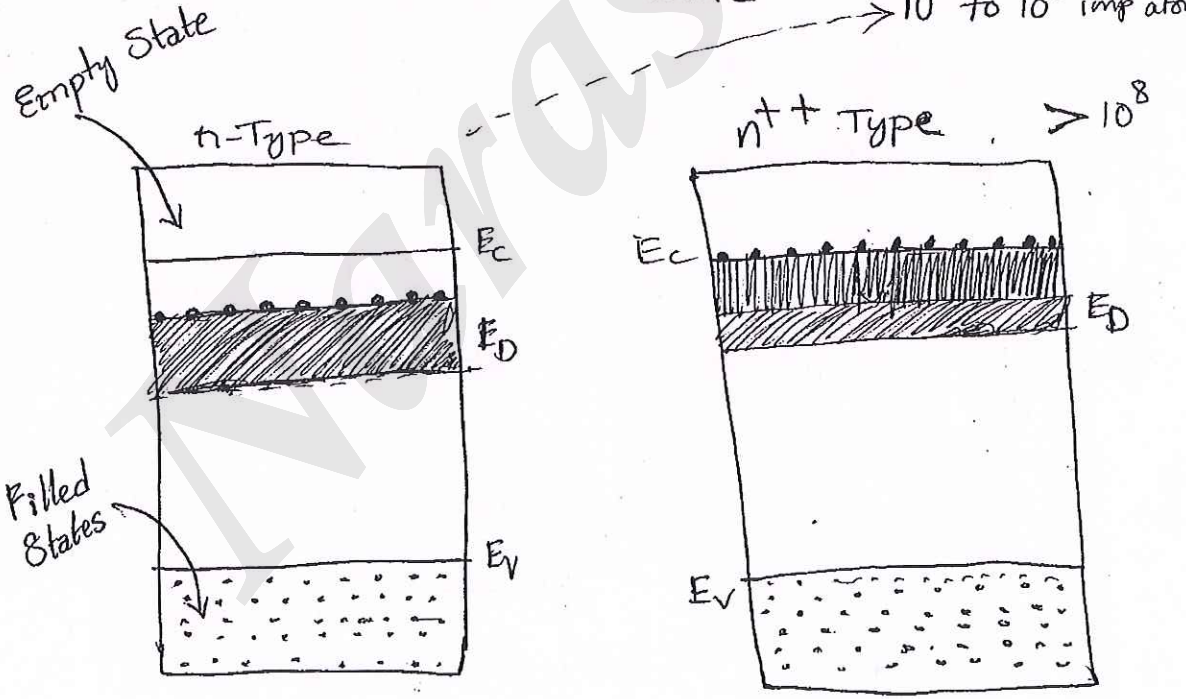



When open Circuited

$\rightarrow 10^{13}$ to $10^{8}$ imp atoms/$cm^3$




OK

$E_D$: Donor atom energy states having $e^-$

$\rightarrow W = 100\,\text{Å}$

$\text{Å} = 10^{-10}\,m$

$\Rightarrow W \simeq 0.01\,\mu m$

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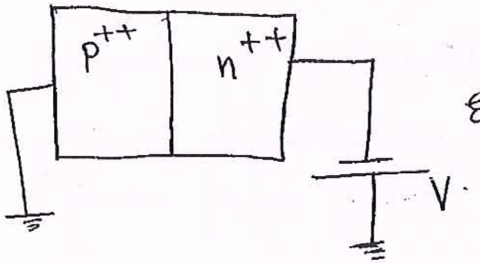
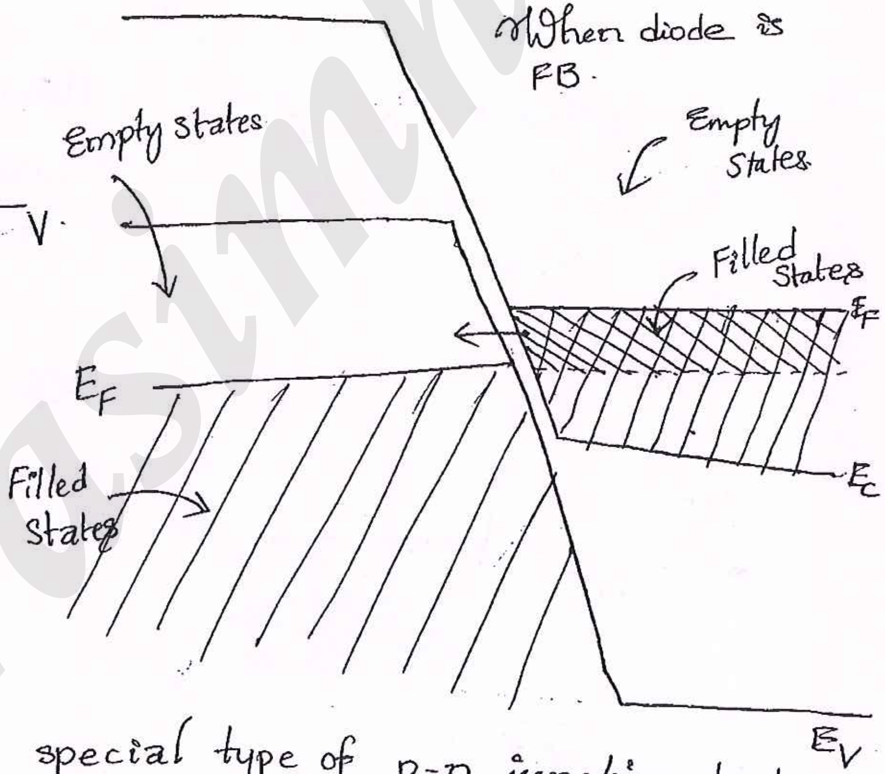
less than $E_0$ is applied. This is called tunneling. (ESAKI in 1958)




Tunnel diode is a special type of p-n junction diode and also it is made up of degenerative semiconductors. The doping concentration in Tunnel diode is 1 in $10^3$ Si or Ge & GaAs atoms. The width of the depletion region in tunnel diode is around 100 Å.

Tunnel diode works based on tunnelling phenomenon. It was invented by ESAKI in 1958.

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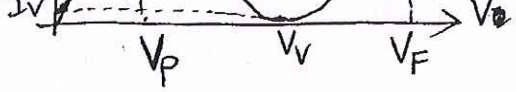
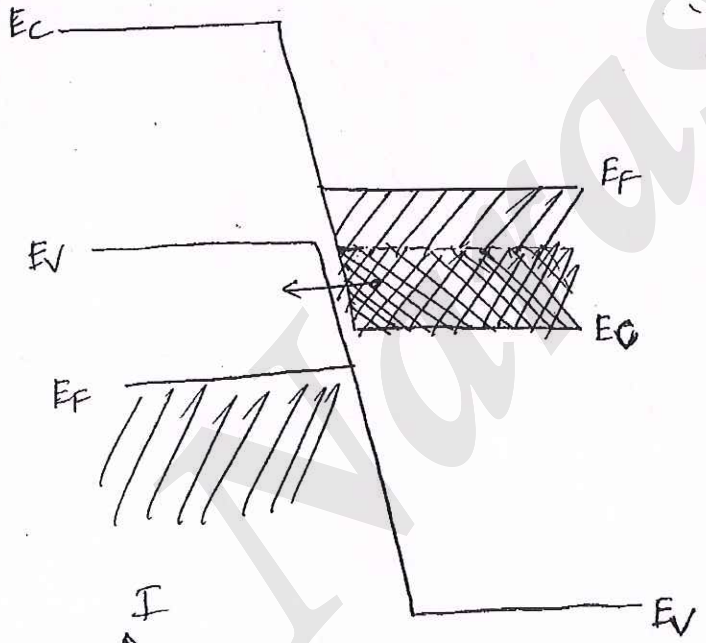




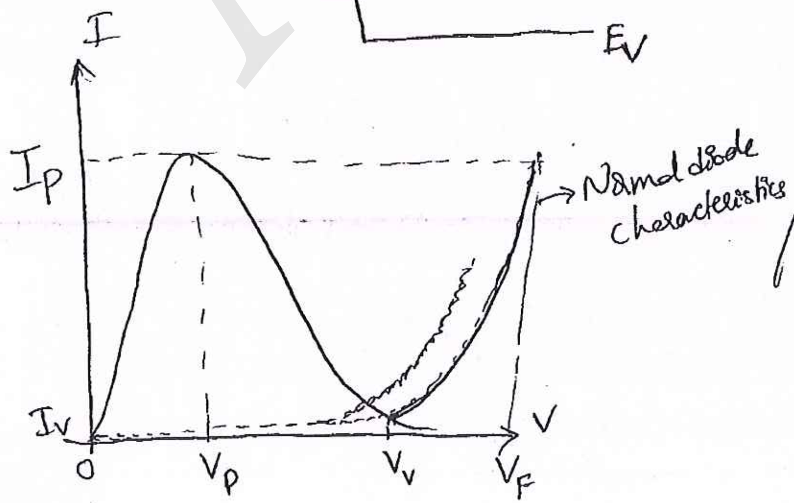
①

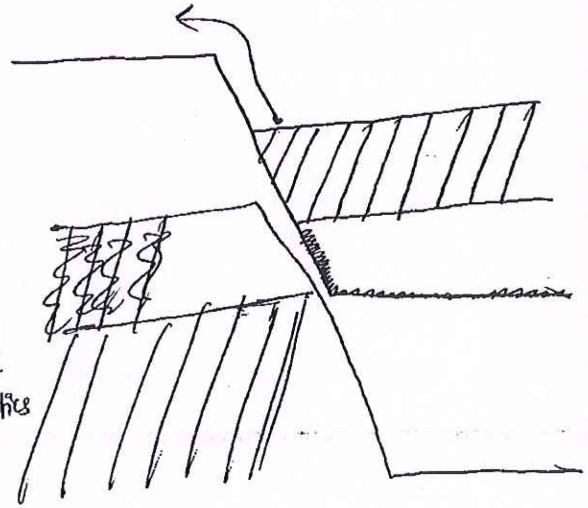
Maximum Tunneling occurs here ∵ filled states are exactly opposite to the empty states

② As the voltage is further increased, $E_F$ moves further up on n-side.




③ As the voltage, further increased, empty states of pside and filled states of n-side will not be opposite to each other



i.e, it acts like a normal p-n junction diode again

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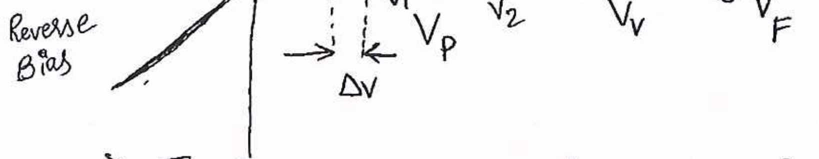



the resistance is infinite ($\because$ slope = 0)
i.e Conductance is 0.

→ $I_p$ & $V_p$ : 10 % variation −50°C to 150°C

$I_p$ : +ve & −ve temperature coefficient.

$V_p$ : −ve temperature coefficient

$V_V$: Valley voltage
$I_V$ : Valley Current.

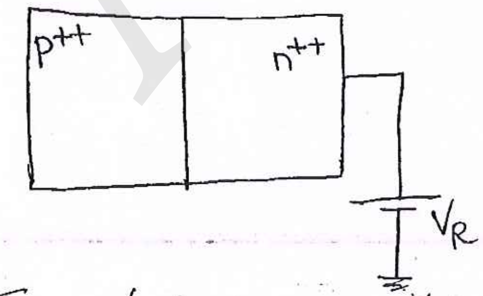
→ $I_V$ : +ve temperature coefficient.

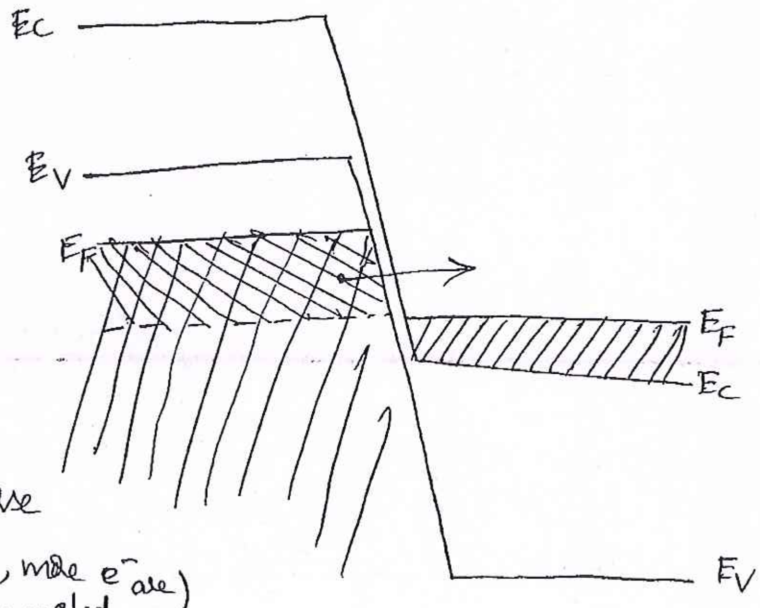
: Two & three times : −50°C to 150°C.

$V_V$ : decreasses by 1mV/°C.

In tunnel diode a single current value (ex: 6mA) corresponds to multiple voltages (i.e, 3 voltage values from graph)

Reverse Bias:




* Tunnel diode acts like a conductor when it is reverse biased (As $V_R\uparrow$, $E_F\downarrow$ on n-side, more $e^-$ are tunneled)

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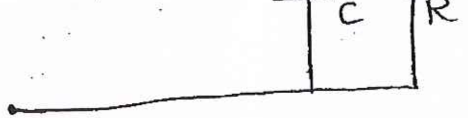


## Advantages:

- Low Cost
- Simple to fabricate
- Low Noise
- High Speed
- Environmental immunity
- Low Power

## Applications:

- Microwave Oscillator
- High Speed Switch (i.e, MW switch)

## Disadvantages:

- Low output swing
- Two terminal device
  (∵ Amplifier should have atleast three terminals)

* Performance of tunnel diode is expressed in terms of the ratio of peak current to valley current.

$$\frac{I_P}{I_V} = 3.5 \text{ for Si}$$

$$= 8 \text{ for Ge}$$

$$= 15 \text{ for GaAs}$$

Hence GaAs is preferred for tunnel diode.

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Sol: $N_D = N_A$. $\quad E_0 = KT\ln\left(\frac{N_A N_D}{n_i^2}\right)$. $\quad 4.4\times10^{22}$ — ?

$n_{i(Ge)} = 4.4\times10^{22}/cm^3$.

$$= 0.2586 \ln\left(\frac{N_A^2}{(4.4\times10^{22})^2}\right)$$

$$W \propto \sqrt{\frac{1}{N_A} + \frac{1}{N_D}} \qquad = 0.2586 \ln\left(\frac{(4.4\times10^{19})^2}{(4.4\times10^{22})^2}\right).$$

$$\times \quad = 0.99\,eV \times$$

i) $V_o = KT\ln\left(\frac{N_A N_D}{n_i^2}\right)$

$N_D$ = Atomic Conc × No: of Donor impurities.

$= 4.4\times10^{22}\times 1/10^3$

$= 4.4\times10^{19}/cm^3 = N_A$.

$$V_o = 0.02586 \ln\left(\frac{(4.4\times10^{19})^2}{(2.5\times10^{13})^2}\right)$$

$= 0.74V$

ii) $$\omega = \sqrt{\frac{2\varepsilon V_{bi}}{q}\left(\frac{1}{N_A}+\frac{1}{N_D}\right)}$$

$V_o = 0.7V$

$\varepsilon = \varepsilon_0\varepsilon_r = 8.854\times10^{-12}_{\ F/m}\times16$

$= 8.854\times10^{-14}_{\ F/cm}\times16$

$= 1.41664\times10^{-12}$

$q = 1.6\times10^{-19}$

$$= \sqrt{\frac{2\varepsilon V_o}{q}\left(\frac{2}{N_A}\right)}$$

$$= \sqrt{\frac{2\times1.41664\times10^{-12}\times0.74\times2}{1.6\times10^{-19}\times4.4\times10^{19}}}$$

$= 77.17\times10^{-8}$ cm

$= 77.17\ A^\circ$

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$$W = \sqrt{\frac{2\varepsilon V_0}{q}\left(\frac{1}{N_A}+\frac{1}{N_D}\right)}.$$

$\varepsilon_r = 11.7 \simeq 12$

$$= \sqrt{\frac{2\times 8.854\times10^{-14}\times 1.13\times 11.7}{1.6\times10^{-19}}\left(\frac{2}{5\times10^{19}}\right)}.$$

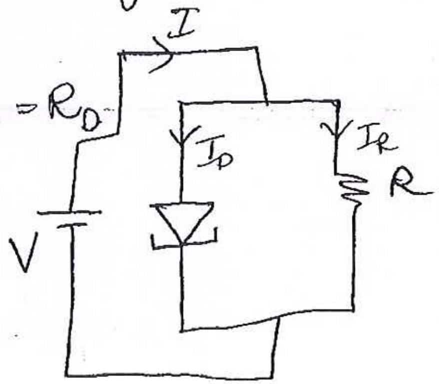
$$= 76.5 A^\circ = 76.5\times10^{-8}\ cm$$

$$= 76.5 A^\circ.$$

For same doping concentration, Si has less $w$ because its atomic concentration is more.

Q) A resistor R is placed in parallel with GaAs tunnel diode which has $\left|\frac{dI_D}{dV}\right|_{max} = \frac{1}{10}\mho$. Find the value of R such that the combination does not give -ve region in V-I characteristics.

Sol: $\left|\frac{dI_D}{dv}\right|_{max} = \frac{1}{10}\mho \Rightarrow \frac{dV}{dI_D} = 10\,\Omega = R_D$




$$\frac{dI}{dV} \geq 0 \qquad I = I_D + I_R$$

$$\Rightarrow R \le \left|\frac{dV}{dI_D}\right|$$

$$\Rightarrow \boxed{R \le 10\Omega}$$

## Optical Sources:

1. Wide band Continuous spectra : Ex: Incandescent lamp.
2. Monochromatic incoherent : Ex: LED
3. Monochromatic coherent : Ex: LASER

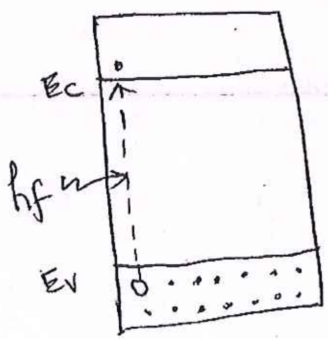
26/9/13 **Light Emitting Diode:**

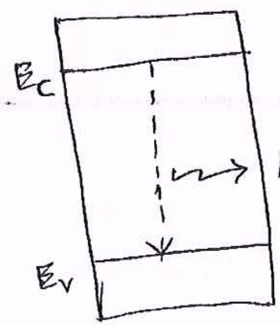
→ LED is also like a normal p-n junction dode but its doping concentration is slightly greater than the normal p-n junction diode.

→ LED operates with forward bias condition

→ LED works based on Stimulated absorption and spontaneous emission.

→ LED is a monochromatic incoherent light source




$$E_G = E_C - E_V = hf$$

$$\lambda = \frac{1.24}{E_G}\ \mu m$$

$$= \frac{12400}{E_g}\ \text{Å}$$

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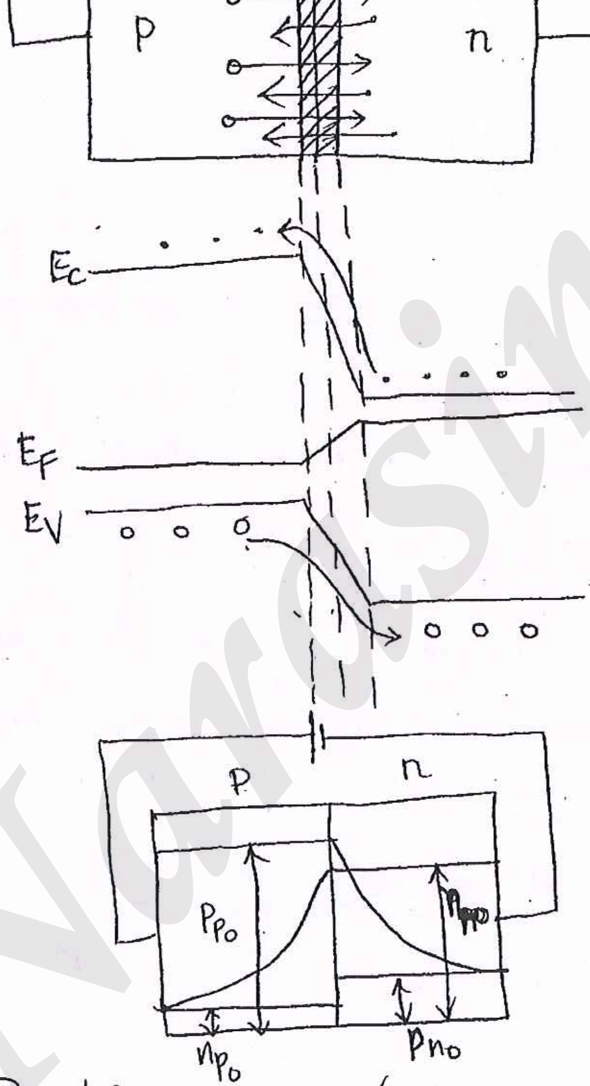
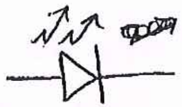



Schematic Symbol for LED and LASER is



## Direct Band Gap Semiconductor:

When the maximum energy of the valency band and minimum energy of the conduction band comes at the same point, those are called direct band gap semiconductors.

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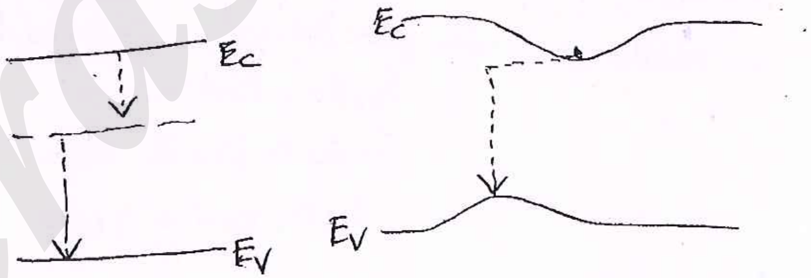
band and valence ... semiconductors.

Ex: GaAs, GaAsP, GaP

## Indirect Bandgap Semiconductors:

When the maximum energy of the valency band and minimum energy of the conduction band are not at the same point, those are called indirect bandgap semiconductors.




→ If the momentum of the $e^-$ is not same in the conduction band and valency band, those are called indirect band gap semiconductors.

Ex: Si, Ge

LED and LASERS are made up of direct band gap semiconductors

i) Stimulated absorption

ii) Spontaneous Emission

Electrons donot return to $E_V$ in only a single path, it will return in different paths. Hence beamwidth is more and directivity is less in LED. It is an incoherent light source.

i) Visible LED

→ Used in optical signals.

→ GaAsP, GaP

→ made of homojunctions

GaAs : Red

GaAsP : Red & Yellow

GaP : Red & Green

ii) InfraRed LED

→ Used in communications

→ GaAs

→ made of double heterojunctions

Homo junction:

P-type and n-type are made of same type of semiconductor

Internal efficiency : <50%

| P | n |
|---|---|
| GaAs | GaAs |

Hetero junction:

P-type is made of GaAs and n-type is made of AlGaAs

| P | n |
|---|---|
| GaAs | AlGaAs |

Double heterojunction:

P-type made of GaAs is sandwiched between P-type AlGaAs and AlGaAs

Internal Efficiency: 60 to 80%

| P | P | n |
|---|---|---|
| AlGaAs | GaAs | AlGaAs |

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$\tau_r$ : radiative recombination carrier life time

$\tau_{nr}$ : Non-radiative recombination carrier life time.

$\tau$ : Total recombination carrier life time.

$$\boxed{\frac{1}{\tau} = \frac{1}{\tau_r} + \frac{1}{\tau_{nr}}} \qquad \boxed{\tau = \frac{\tau_r \cdot \tau_{nr}}{\tau_r + \tau_{nr}}}$$

Internal efficiency ($\eta_{int}$):

$$\eta_{int} = \frac{\tau}{\tau_r}$$

Internal Power ($P_{int}$):

$$P_{int} = \eta_{int} \frac{hcI}{\lambda e}$$

h : Planck's constant = $6.625 \times 10^{-34}$ J.sec

c : Velocity of light = $3 \times 10^{8}$ m/sec.

I : Current through LED

$\lambda$ : Wavelength of radiation

e : Charge of the $e^-$ = $1.6 \times 10^{-19}$ C

Emitting Power ($P_e$):

$$P_e = \frac{P_{int} \cdot F \cdot \eta^2}{4\eta_x^2}$$

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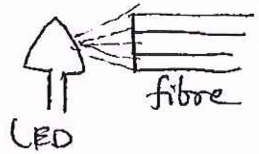
$$\eta_{ep} = \frac{P_e}{P} \times 100$$

P : Input power

$P_e$ : External power

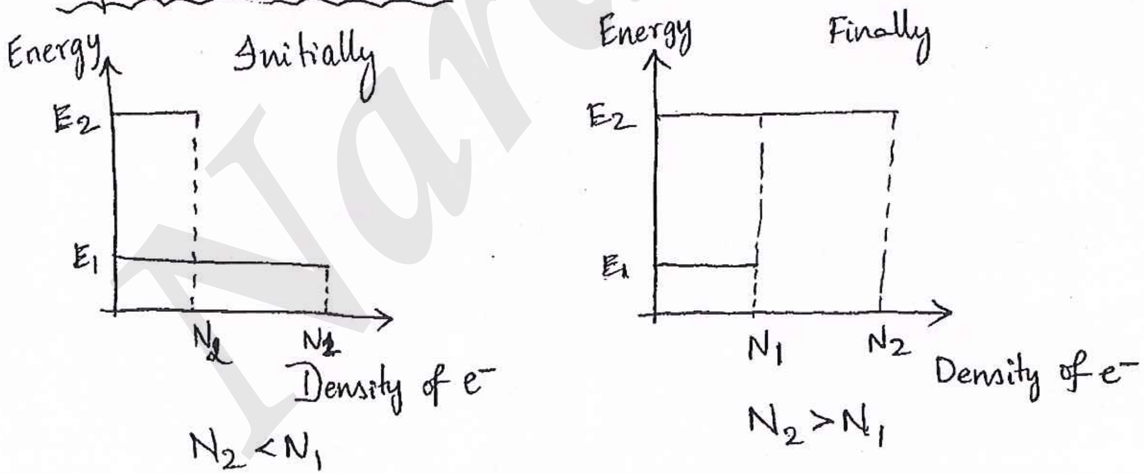
**Power Conversion (or) Coupling Power Efficiency ($\eta_{CP}$):**

$$\eta_{CP} = \frac{P_c}{P} \times 100 = \frac{P_c}{VI} \times 100$$

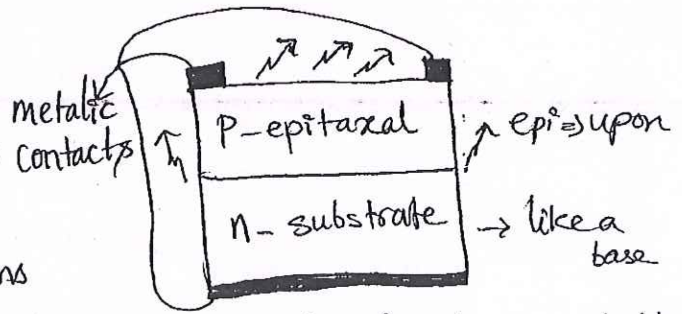



$P_c$ : Coupling Power

**Population Inversion:**




1) **Planar LED:**




→ It has less external efficiency, directivity and radiance

→ Because of the structure, it has more internal reflections and entire power is not radiated.

→ mostly found in embedded boards

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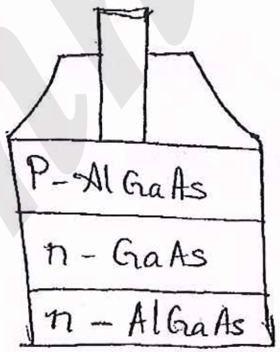
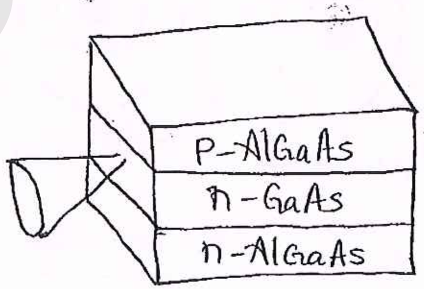
Hence, we go for double heterogeneous junctions.

1) Surface Emitting LED:




2) Edge Emitting LED:




## Advantages of LED:

→ Simple to fabricate

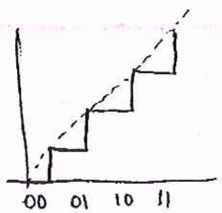
→ Low Cost

→ Reliability

→ Low temperature dependence

→ requires Simple drive circuit

→ Linearity (Linear Conversion)




(A to D; D to A converters)

## Drawbacks of LED:

1. More beamwidth
2. Low directivity
3. Harmonic distortion
4. Low coupling power efficiency

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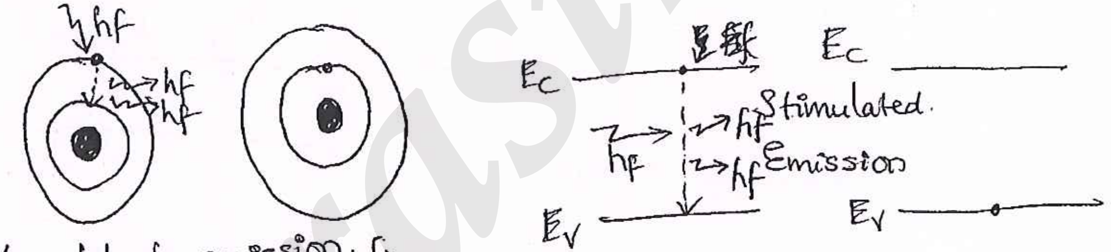
light source

→ LASER works based on stimulated absorption, spontaneous emission and stimulated emission.

→ Beamwidth in LED is 30 to 40nm

" " LASER is 0.1nm




Stimulated emission. figure 1(c)

LASER also works on the population inversion.

$$\boxed{\frac{N_1}{N_2} = e^{+\frac{[E_2-E_1]}{KT}} = e^{+\frac{hf}{KT}}}$$ Boltzman's relation

$$\frac{\text{Stimulated emission rate}}{\text{Spontaneous emission rate}} = \frac{B_{21}\rho_f}{A_{21}} = \frac{1}{[e^{hf/KT} - 1]}$$

$B_{21}$: Einstein coefficient of stimulated emission rate

$A_{21}$: Einstein coefficient of Spontaneous emission rate

$\rho_f$: Spectral density

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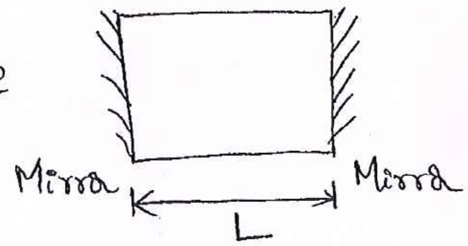
$$\boxed{\frac{A_{21}}{B_{21}} = \frac{8\pi h f^3}{c^3}}$$

In LASER, along with conversion of electrical energy into light energy, light amplification also takes place.

→ Mirrors are used for amplification which produce oscillations because of reflections.




→ No: of longitudinal modes $= \frac{2\eta L}{c}$

→ Frequency of Seperation $= \frac{c}{2\eta L}$

L : Optical distance
C : Velocity of light
$\eta$ : Refractive index

→ Drawbacks of LEDs are advantages of LASER and Advantages of LEDs are drawbacks of LASER.

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resulting in a diode

photons and a light output.

→ This inversion mechanism is called injection electroluminisence.

→ This device is known as Light-Emitting Diode.

→ The spectral output of an LED may have a relatively wide wavelength bandwidth b/n 30 to 40nm

→ Photons may be emitted if an $e^-$ and hole recombine by a direct band to band recombination process in a direct band gap material.

→ The emission wavelength is $\lambda = \frac{hf}{E_G}$ & $\frac{1.24}{E_G}$ μm & $\frac{12400}{E_G}$ Å

where $E_G$ is the bandgap energy measured in eV.

→ When voltage is applied across a p-n junction, $e^-$ and holes are injected across the space charge region where they become excess minority carriers.

→ This excess minority carriers diffuse into the neutral semiconductor regions where they recombine with majority carriers.

→ If this recombination process is a direct band to band

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→ The photon ... giving up energy as it make a transition from the conduction band to the valency band.

→ The LED photon emission is spontaneous, in that, each band to band transition is an independent event.

→ This spontaneous emission process gives a spectral output of the LED with a wide bandwidth.

→ If the structure and operating condition of LED are modified, the device can operate in a new mode producing a coherent spectral output with a bandwidth of wavelength less than 0.1 nm.

→ This new device is a LASER diode.

→ figure 1(a) shows the case, when an incident photon is absorbed, and an $e^-$ is elevated from an energy state $E_1$ to an energy state $E_2$. This process is known as stimulated or induced absorption.

→ If the $e^-$ spontaneously makes the transition back to the lower energy level with a photon being emitted, we have a spontaneous emission process as indicated in fig 1(b).

the process is called stimulated & induced emission.

→ This stimulated emission process produced two photons. Therefore we can have optical gain(or) amplification.

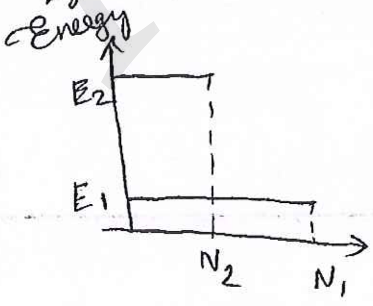
→ Emitted two photons are in phase so that the spectral output will be coherent.

→ In thermal equilibrium, the $e^-$ distribution in a semiconductor is determined by the fermi dirac statistics.

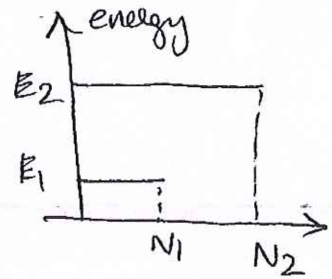
→ If the Boltzman's approximation applies, then we can write

$$\frac{N_1}{N_2} = e^{\left(\frac{E_2 - E_1}{KT}\right)} = e^{\frac{hf}{KT}}$$

where $N_1$ and $N_2$ are the ~~energy~~ $e^-$ concentrations in the energy levels $E_1$ and $E_2$. where $E_2 > E_1$



$e^-$ density



$e^-$ density

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where $A_{12}$ is Einstein coefficient of ~~stimulated~~ spontaneous emission

$$R_{21} = N_2 A_{21} + N_2 \rho_f B_{21}$$

$$R_{12} = R_{21} \Rightarrow A_{12} N_1 \rho_f = N_2 A_{21} + N_2 B_{21} \rho_f$$

($\because$ Generation = Recombination)

$$\rho_f (A_{12} N_1 - B_{21} N_2) = N_2 A_{21}$$

$$\rho_f = \frac{N_2 A_{21}}{A_{12} N_1 - B_{21} N_2} = \frac{\frac{A_{21}}{B_{21}}}{\frac{A_{12} N_1}{B_{21} N_2} - 1}$$

From this, $\rho_f = \frac{A_{21}}{B_{21}} \left[ \frac{1}{e^{hf/KT} - 1} \right]$

→ The no: of photons absorbed is proportional to $N_1$ and the no: of additional photons emitted is proportional to $N_2$. In order to achieve optical amplification (or) lasing action, we must have $N_2 > N_1$. This is called Population inversion

Q) A planar LED is fabricated from GaAs which has a refractive index of 3.6.

a) Calculate optical power emitted into the air as a percentage of the internal optical power for the device

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$$4\eta_x^2$$

$$= P_{int} \cdot \frac{0.68 \times 1^2}{4 \times 3.6^2}$$

$$P_e = P_{int} \cdot (0.013)$$

$$P_e = 0.013\, P_{int}$$

$\Rightarrow P_e$ is 1.3% of $P_{int}$

$P_e = 1.3\%$ of $P_{int}$

b) Given $P_{int} = \frac{P}{2}$

$$\eta_e = \frac{P_e}{P} \times 100$$

$$P_e = \frac{P_{int} \cdot F \cdot \eta^2}{4\eta_x^2}$$

$$P_e = 0.013 \times \frac{P}{2}$$

$$P_e = (6.559 \times 10^{-3}) P$$

$$= \frac{6.559 \times 10^{-3} \times \cancel{P}}{\cancel{P}} \times 100$$

$$= 6.559 \times 10^{-1}$$

$$= 0.6559\%$$

Q) The radiative and non radiative recombination life times of the minority carriers in the active region of a double heterojunction LED are 60ns and 100 ns. Determine total carrier recombination life time and the power internally generated within the device when the peak emission

$$= 0.625 \times \frac{6.625\times10^{-34} \times 3\times10^{8} \times 40\times10^{-3}}{0.87\times10^{-6} \times 1.6\times10^{-19}}$$

$$\cong \cancel{3.567\times10^{-20}\,W} = 35.69\,mW$$

Q) Calculate the ratio of Stimulated emission rate to the spontaneous emission rate for an incandescent lamp operating at a temperature of 1000K. It may be assumed that average operating wavelength is $0.5\,\mu m$.

$$f = \frac{c}{\lambda} = \frac{3\times10^{8}}{5\times10^{-7}} = \frac{3}{5}\times10^{15}\,Hz$$

$$\frac{1}{\left[e^{hf/KT}-1\right]} = \frac{1}{\left[e^{\frac{6.625\times10^{-34}\times 3/5\times10^{15}}{1.38\times10^{-23}\times1000}}-1\right]}$$

$$= 3.13\times10^{-13}$$

Q) A LASER contains a crystal length 4 cm with a refractive index of 1.78. The peak emission wavelength from the device is $0.55\,\mu m$. Determine no: of longitudinal modes, frequency of seperation

No: of longitudinal modes $= \frac{2\times1.78\times4\times10^{-2}}{3\times10^{8}} = 4.75\times10^{-10}$

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$$\eta_{cp} = \frac{P_c}{P} \times 100 = \frac{P_c}{VI} \times 100$$

$$= \frac{190 \times 10^{-6}}{1.5 \times 25 \times 10^{-3}} \times 100$$

$$= 0.507$$

27/9/13

## Photo Diode:

→ It always operates in reverse bias condition.

→ The doping concentration should be less than normal p-n junction diode because in reverse bias condition, current is due to minority carriers. Hence we require more minority carriers ~~to~~ which implies that doping concentration should be less. Also the light falls on the junction of the diode. Hence to absorb more light, the junction area should be more.

* Photo diode is also like a normal p-n junction diode. But its doping concentration is less than the normal p-n junction diode.

* Photo diode always operates in reverse bias

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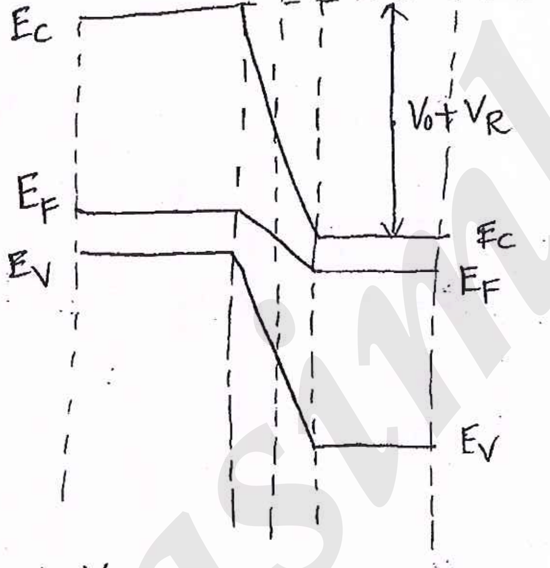
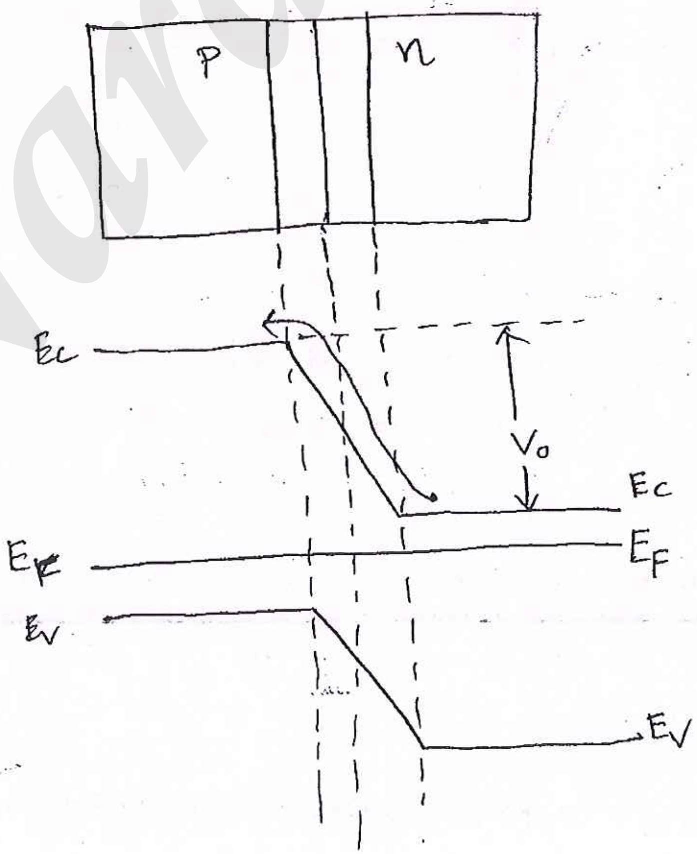



Open Circuit: $V_j = V_o$

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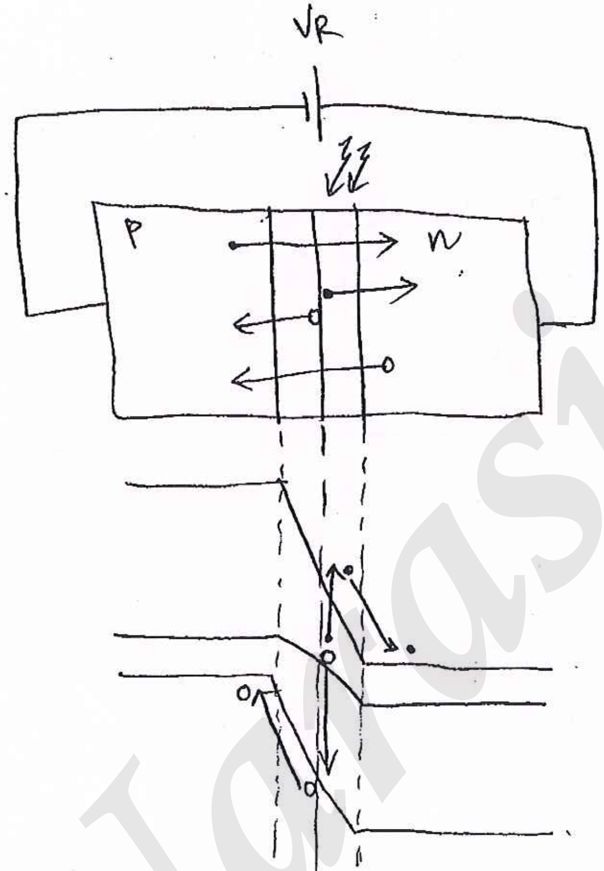
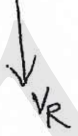
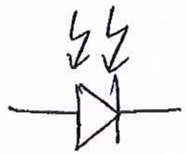



Schematic Symbol:



for photodiode

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Characteristics of a photodiode:

1) High Sensitivity (It should be able to detect small light signals, and produce the corresponding electrical signals)
2) High Fidelity (Faithful reproduction of signals at Rx)
3) Large Electrical Signals for the received optical light
4) Short response time.
5) Minimum noise
6) Stability of the performance characteristics.
7) Small size

$Q_e$ & $\eta = \dfrac{\text{no: of } \ldots}{\text{no: of incident photons}} \ldots \dfrac{\ldots}{\gamma_p}$

**Responsivity (R):**

It is the ratio of photodiode output current to the incident optical power.

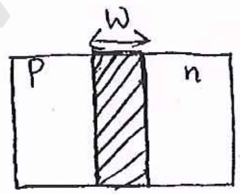
$$R = \frac{I_p}{P_o} \; (A/W)$$

$$R = \frac{\eta e}{hf} = \frac{\eta e \lambda}{hc} \qquad \left(\because f = \frac{c}{\lambda}\right)$$

**Response time:**

1. Transit time
2. RC time constant

Transit time is the time taken by the carriers to move from one side of the depletion region to other side.




p and n regions act like the plates of a capacitor

$$C_{T_0} = \frac{\varepsilon A}{W}$$

$$C_T = \frac{C_{T_0}}{\left[1 + \frac{V_R}{V_0}\right]^{1/n}}$$

$n = 3$ for linear junction

$n = 2$ for abrupt junction

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$P\pi n \rightarrow$ i is p-type

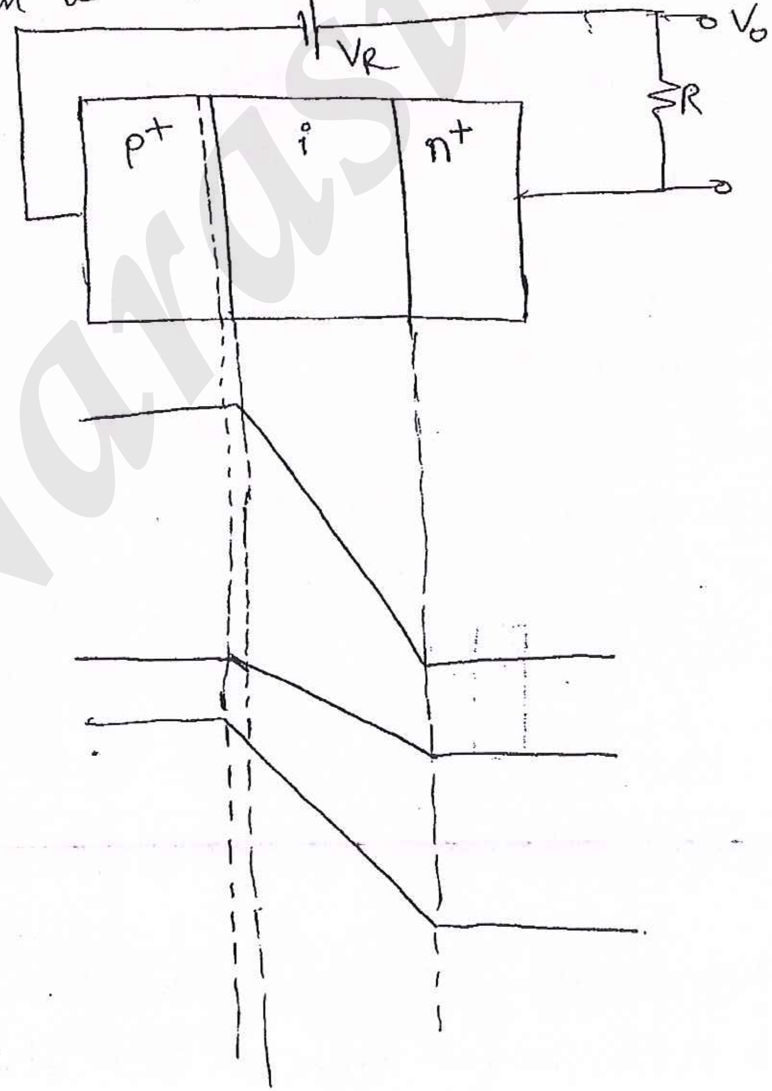
→ $P\nu n \rightarrow$ i is n-type

→ It gives faster response time..

→ PIN diode can also be operated in forward bias.

* → As the forward bias ↑ resistance of 'i' ↓ and viceversa.

Hence it can be used as a variable ~~resista~~ resista.

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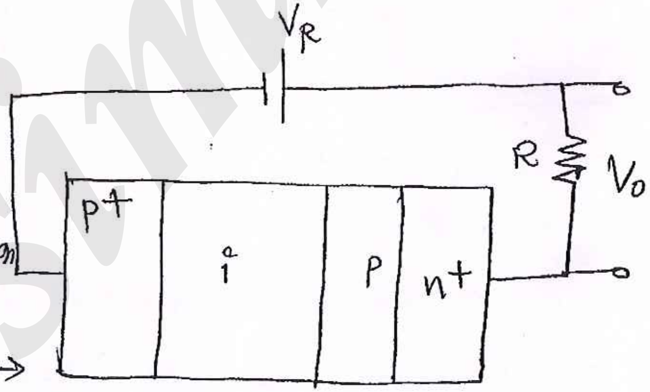
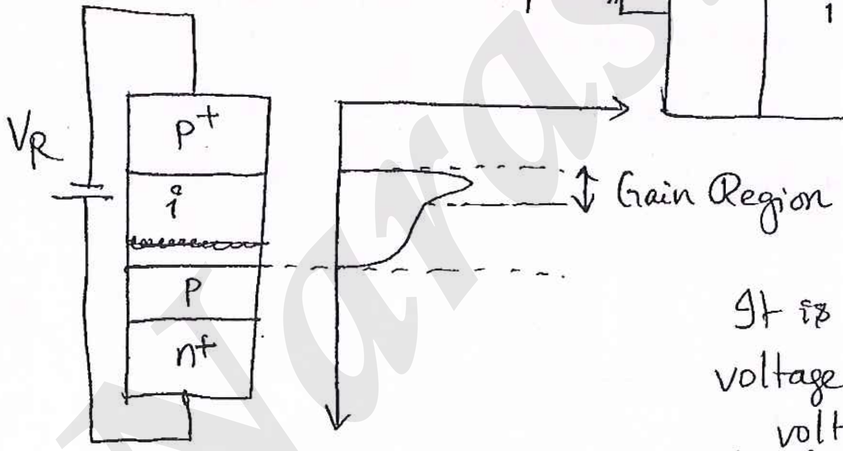
signals whereas APD
converts and amplifies
the signals.


## Avalanche Photodiode: (APD)

Response time:
depends on 1) Transit time
2) Time taken for Avalanche multiplication




It is always operated at a voltage less than the breakdown voltage.
Amplification occurs through Avalanche multiplication phenomenon

Multiplication factor (M)

$$M = \frac{I}{I_p}$$

$I$ is the o/p current after avalanche multiplication

$I_p$ is the o/p current before avalanche multiplication.

$M \rightarrow$ upto $10^4$

The drawback with APD is it requires large reverse bias voltages like 100V to 400V. It is similar to phototransistor.

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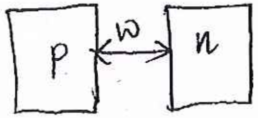
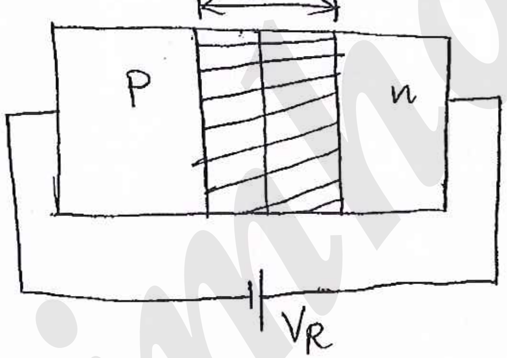



$$C_{T_0} = \frac{\varepsilon A}{W}$$



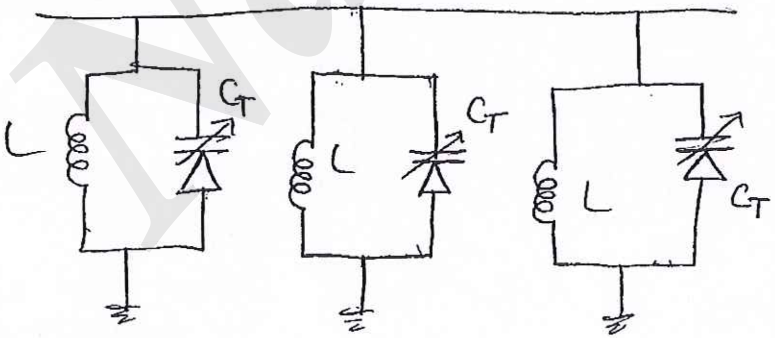

$$C_T = \frac{C_{T_0}}{\left[1 + \frac{V_R}{V_0}\right]^{1/n}}$$

$n = 2$ for non-linear junction
$n = 3$ for linear junction

**Applications:**

1. Tuned circuits
2. FM modulators
3. Automatic frequency control circuits
4. Adjustable band pass filters
5. Parametric amplifiers.

**Tuned Circuits:**




$$f_0 = \frac{1}{2\pi\sqrt{LC_T}}$$

**FM Modulator**

VCO is used in direct method of FM modulation.

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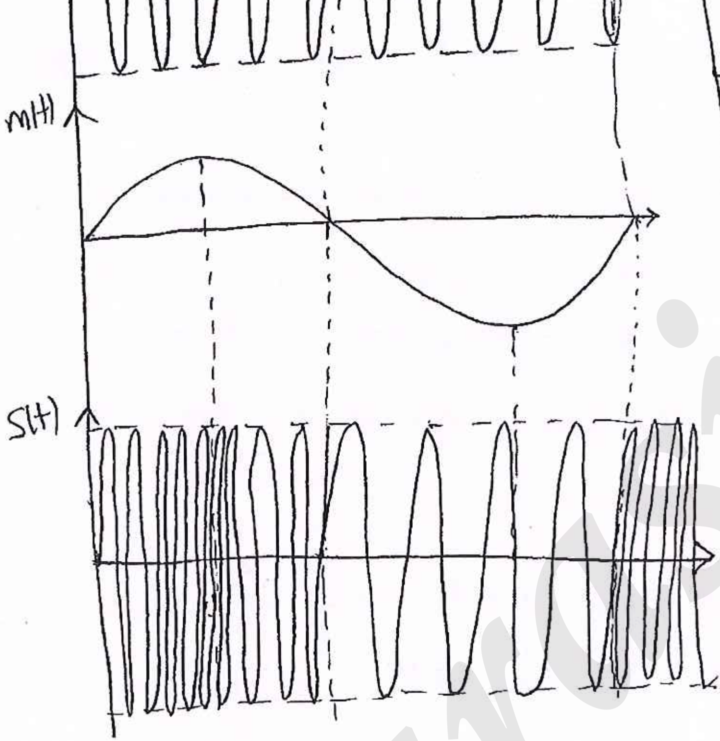
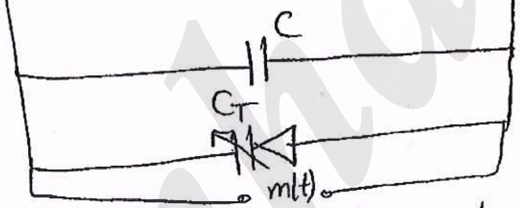


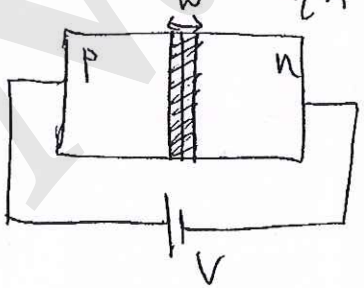

Choose the component values such that it generates frequency of 100kHz.

$$C_T = \frac{C_{T_0}}{\left[1 + \frac{V_R}{V_0}\right]^{1/n}}$$ (applicable only for reverse bias case)

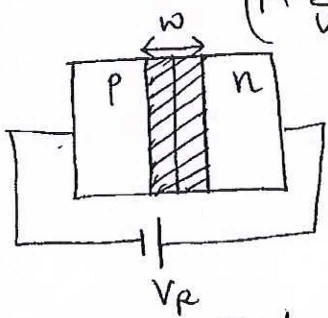
$V_R \uparrow \Rightarrow C_T \downarrow \Rightarrow C' \downarrow \Rightarrow f \uparrow$

## Schottky Diode:

$C_D = \tau g = \frac{\tau I}{\eta V_T}$

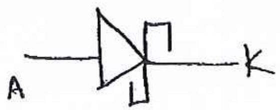



$C_T = \frac{C_{T_0}}{\left(1 + \frac{V_R}{V_0}\right)^{1/n}}$




These capacitances effect increases at higher frequencies which is not required.

Schematic Symbol of Schottky diode (In this 0 $C_d$ and very small $C_T$)



* Schottky is a diode which is formed with metal and semiconductor junction.

→ In schottky diodes, diffusion capacitance is almost all zero and it offers very small transition capacitance.

∴ It can be used as a highspeed switch

→ The switching speed of the diode depends on transition and diffusion capacitors.

→ In schottky diode, current is due to only majority carriers. Therefore, schottky diode is also called majority carrier diode or hot carrier diode.

→ Generally used metals in Schottky diode are Molybdenum, Platinum and Tungsten.

→ To form a schottky diode between metal and n-type semiconductor, the work function of the metal should be greater than the semiconductor.

→ Schottky diodes also forming b/n metal and p-type semiconductors where the work function of the semiconductor should be greater than the metals.

$$Q_e = \frac{\text{no: of } e^- \text{ collected}}{\text{no: of photons incident}}$$

$$\eta \text{ or } Q_e = \frac{1.2\times10^{11}}{3\times10^{11}} = \frac{1.2}{3} = 0.4 \Rightarrow 40\%$$

$$R = \frac{\eta e}{hf} = \frac{\eta e \lambda}{hc} = \frac{0.4\times1.6\times10^{-19}\times0.85\times10^{-6}}{6.625\times10^{-34}\times3\times10^{8}}$$

$$= 0.027\times10 = 0.27\ A/W$$

Q) A photodiode has a $Q_e$ of 65% when photons of energy $1.5\times10^{-19}$ J are incident upon it.

a) At what wavelength, is the photodiode operating

b) Calculate the incident optical power required to obtain a photo current of 2.5 μA

Given $\eta = 0.65$

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

$$\Rightarrow R = \frac{0.65\times1.6\times\cancel{10^{-19}}}{1.5\times\cancel{10^{-19}}}$$

$$= 0.693$$

$$\frac{\eta e\lambda}{hc} = R$$

$$\Rightarrow \lambda = \frac{R\times h\times c}{\eta e}$$

$$E = hf = \frac{hc}{\lambda} \Rightarrow \lambda = \frac{hc}{E}$$

$$= \frac{6.625\times10^{-34}\times3\times10^{8}}{1.5\times10^{-19}}$$

$$\Rightarrow \lambda = 1.325\ \mu m$$

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detection of radiation at a wavelength of 0.9 μm. When the incident optical power is 0.5 μW, and the output current from the device after Avalanche gain is 11 μA. Determine the Multiplication factor of the photodiode under this conditions.

$$Q_e = \eta = 0.8$$

$$R = \frac{\eta e}{hf} = \frac{\eta e \lambda}{hc} = \frac{0.8 \times 1.6 \times 10^{-19} \times 0.9 \times 10^{-6}}{6.625 \times 10^{-34} \times 3 \times 10^{8}}$$

$$= 0.5796 \text{ A/W}$$

$$R = \frac{I_p}{P}$$

$$\Rightarrow I_p = R \times P = 0.5796 \times 0.5 \times 10^{-6}$$

$$= 0.2898 \, \mu A.$$

$$M = \frac{I}{I_p} = \frac{11}{0.2898} = 37.956$$

Q) Determine the $C_T$ of a abrupt junction varactor diode at a reverse bias voltage of 4.2V given $C_{T0} = 80pF$ and $V_0 = 0.7V$.

$$C_T = \frac{C_{T0}}{\left(1 + \frac{V_R}{V_0}\right)^{1/n}} = \frac{80p}{\left(1 + \frac{4.2}{0.7}\right)^{1/2}} = 30.237 \text{ pF}$$

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$= 5.16\ pF$

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