Model Answer M.Sc. I semester (2013)

Paper Code - 'AS-2117

(Basics of Electronics Devices)

Section-A

1 (i) (a)

(ii) (b)

(iii) (b)

(iv) (a)

(V) (a)

(vi) (c)

(vii) (b)

(viii) (b)

(ix) (d)

(X) (c)

Section-B

Answer-2

Total Number of Ge atom in Sample $= 4.4 \times 10^{28} \, m^{-3}$

0.01 Boron (B) atom is doped $= 10^6$ Ge atom

So,

$$1 \text{ B atom} = \frac{10^6}{0.01} = 10^8 \text{ Ge atom}$$

Boron is trivalent impurity and if it is doped in Ge, it will behave like Acceptor impurity.

Therefore,

$$\text{Acceptor density } (N_A) = \frac{4.4 \times 10^{28}}{10^8} \, m^{-3}$$

$$N_A = 4.4 \times 10^{20} \, m^{-3}$$

If all the doped atoms are ionized at 300 K. then The acceptor density is equal to number majority carrier density i.e. holes.

$$\boxed{p = N_A = 4.4 \times 10^{20} \, m^{-3}}$$

From Law of mass action

$$n \cdot p = n_i^2$$

Given that $n_i = 2.5 \times 10^{19} \, m^{-2}$

$$p = 4.4 \times 10^{20} \, m^{-3}$$

Therefore,

$$n = \frac{n_i^2}{p} = \frac{(2.5 \times 10^{19} \, m^{-3})^2}{4.4 \times 10^{20} \, m^{-3}}$$

$$n = \frac{6.25 \times 10^{38}\ m^{-6}}{4.4 \times 10^{20}\ m^{-3}}$$

$$\boxed{n = 1.4204 \times 10^{18}\ m^{-3}}$$

Density of holes $(p) = 4.4 \times 10^{20}\ m^{-3}$

Density of electrons $(n) = 1.4204 \times 10^{18}\ m^{-3}$

Fermi level measured from the Intrinsic fermi level (E_i).

$$n = n_i\, e^{(E_F - E_i)/KT}$$

$$p = n_i\, e^{(E_i - E_F)/KT}$$

or

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

$$E_i - E_F = KT \ln\left(\frac{p}{n_i}\right)$$

In the present case, doped semiconductor is p-type. so fermi level will be just above the valence band, Therefore,

$$E_i - E_F = KT \ln\left(\frac{p}{n_i}\right)$$

$$E_i - E_F = (25.86 \times 10^{-3}\ eV) \cdot \ln\left(\frac{4.4 \times 10^{20}\ m^{-3}}{2.5 \times 10^{19}\ m^{-3}}\right)$$

$$E_i - E_F = (25.86 \times 10^{-3}\ eV) \ln(1.76 \times 10^{1})$$

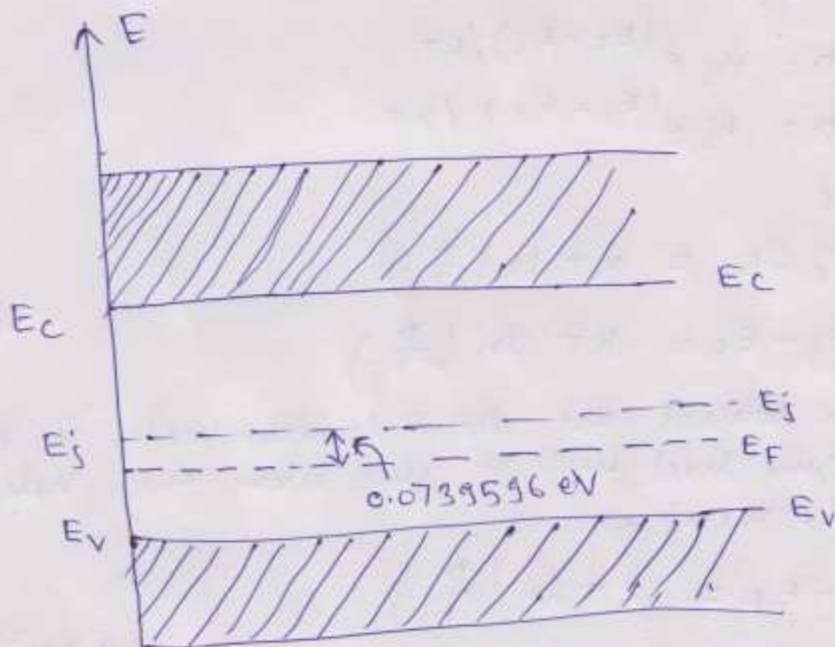
$$E_i - E_F = (25.86 \times 10^{-3}\ eV) \ln(17.6)$$

$$E_j - E_F = (25.86 \times 10^{-3}\ eV) \times (2.86)$$

$$E_j - E_F = 73.9596 \times 10^{-3}\ eV$$

$$E_j - E_F = 0.0739596\ eV$$

$$\boxed{E_F = E_j - 0.0739596\ eV}$$



Answer - 3

Drift Phenomena

In presence of an External Electric field, the random motion of Electron or holes will be directed in electric field direction. This directed motion of charge carriers is known as drift motion of charge carrier and due to the directed motion of charge carriers (electron or hole) is called drift current. This phenomenon is known as Drift Phenon

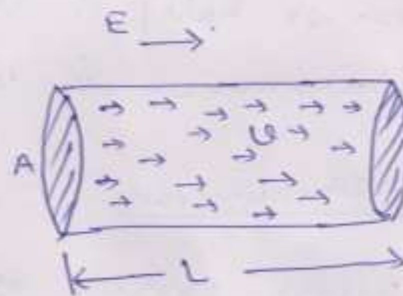
Deffusion Phenomenon

When Excess carrier are created ~~~~ non-Uniformly in a Semiconductor, the electron and hole concentration vary with position. Any such variation of carrier concentration (gradient) in Electron and hole call for a net motion of the carrier from the region of higher Concentration to the region of low concentration.
This type of motion is called diffusion phenomenon in Semiconductor.

This movement of charge carriers produce a current known as diffusion current.

Expression for Electron drift current density:

Let us consider a peice of semiconductor of length L and cross-sectional area A.
The concentration majority charge carrier is n electron/cm³.



An electric field is applied along x-direction. Due to this applied electric field, the electrons started moving in the field direction. The velocity of electrons is known as drift velocity.
Let the drift velocity of electrons are v_n.
Let I_n is the current due to electron drift motion then.

$$I_n = \sum_{i=1}^{n} (-q) \cdot A \cdot (-v_n)$$

Where
$-q$ = charge of electrons

$$I_n = \sum_{j=1}^{n} q A . u_n$$

$$I_n = n . q\, u_n . A$$

current density $(J_n) = \frac{I_n}{A}$

$$\boxed{J_n = nq u_n}$$

drift current density due to Electron.

Let, define mobility: mobility is the motion of electrons per unit electric field.

i.e. $\mu_e = \frac{u_n}{\vec{E}}$

or

$$u_n = \mu_n E$$

Therefore, electron drift current density.

$$\boxed{J_n = nq\mu \vec{E}}$$

Expression for diffusion current density due to electron

The rate of diffusion per unit area is proportion to the magnitude of concentration gradient. Let ϕ_n is the rate of diffusion then

$$\phi_n \propto \left(-\frac{dn}{dx}\right)$$

If this rate is multiplied by charge of the carriers (i.e. electron) gives the diffusion current density.

$$J_n \text{ diffusion} \propto (-q)\,\phi_n$$

$$J_n \text{ diff} \propto (-q)\left(-\frac{dn}{dx}\right)$$

$$J_n \text{ diff} \propto q\,\frac{dn}{dx}$$

$$\boxed{J_n \text{ diff} = D_n \cdot q\,\frac{dn}{dx}}$$

where D_n = Diffusion constant of electron.

Since, the electric field is present, in addition to the carrier gradient. Therefore, the total ~~due to electron~~ current density due to electrons will be the sum of electron drif current density and electron diffusion

current density.

i.e.

$$J_n = J_{n\,drift} + J_{n\,diffusion}$$

$$J_n = nq\mu_n \bar{E} + D_n q \frac{dn}{dx}$$

$$\boxed{J_n = q\left(n\mu_n \bar{E} + D_n \frac{dn}{dx}\right)}$$

Answer- 4

In any Semiconductor, the process of thermal generation of new electron-hole pair and recombination of Existing Electron and hole takes place Continuously.

Rate of Generation (g) :- The Number of electron-hole pair created per Unit volume per second. This rate of generation is function energy band gap of the Semiconductor and the temperature.

i.e.

$$\boxed{g = f(E_g, T)}$$

Recombination rate (r) :- The rate at which electron and holes Collide (or recombine) with each other.

The rate (r) is directly proportional to the numbers density n and p of electron and holes in Semiconductor.

$$r \propto n \cdot p$$

$$\boxed{r = \alpha_r n \cdot p}$$

where α_r is the proportionality Constant which depends on the particular mechanism by which recombination takes place.

In any Semiconductor, if rate of recombination becomes equals to the rate of

generation then this condition is known as thermal Equilibrium i.e.

$$r = g \Rightarrow r - g = 0$$

or

$$n \cdot p = n_i^2$$

$$\boxed{n \cdot p - n_i^2 = 0}$$

Most Semiconductor devices operated by the creation of the charge carrier in Excess from the thermal Equilibrium value.

Introduction of Excess electron-hole pair in a Semiconductor is known as Injection of Excess carriers.

The carrier Injection level is determined by the Concentration of Excess Carriers.

When the excess carrier concentration is small compared to the Equilibrium majority carrier concentration. Then it is said to be low level injection.

If this concentration becomes comparable to or Exceeds the Equilibrium majority carrier concentration, this injection is called as high-level Injection.

Let the Semiconductor be n-type with equilibrium Electron and hole concentration given by n_{no} and p_{no}, respectively.

Let the electron and hole is changed to new values n_n and p_n. we define the Excess Electron and hole concentration by relation.

$$n_e = (n_n - n_{no})$$

$$p_e = (p_n - p_{no})$$

In this case, the Electron and holes are generated in pairs, So

$$\boxed{n_e = p_e}$$

Let us now consider a silicon sample doped with 10^{15} donor cm^{-3} at 300 K. So, we have $n_{no} = 10^{15}\ cm^{-3}$ and $p_{no} = 2{\cdot}25 \times 10^5\ cm^{-3}$. Let $p_e = n_e = 10^{12}\ cm^{-3}$ excess carrier are created.

$$n_n = n_{no} + n_e = 10^{15} + 10^{12} \cong 10^{15}\ cm^{-3}$$

$$p_n = p_{no} + p_e = 10^5 + 10^{12} \cong 10^{12}\ cm^{-3}$$

Low level Injection:

$$n_e \lll n_{no}$$

$$10^{12}\ cm^{-3} \lll 10^{15}\ cm^{-3}$$

low level Injection is Essentially a minority carrier injection because the concentration of majority carrier remains unchanged.

High level Injection

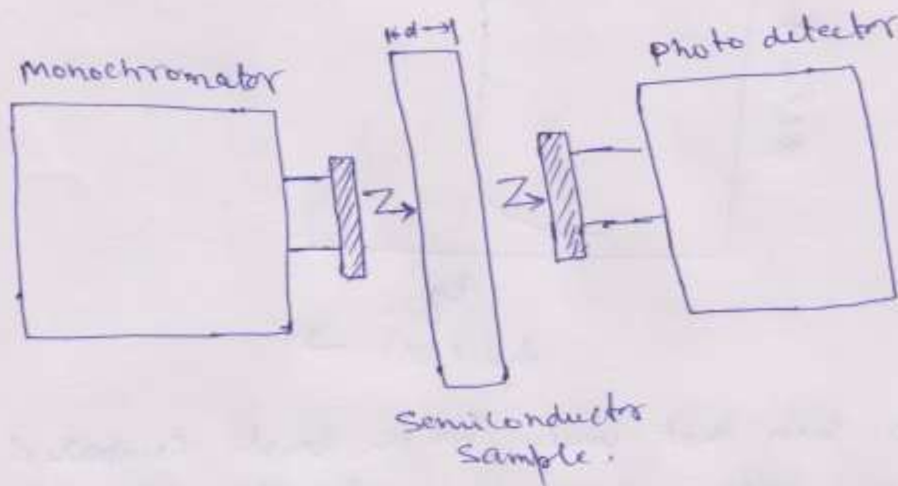
If $n_e = p_e = 10^{17}\ cm^{-3}$

$n_e >> n_{no}$
$n_e \cong n_{no}$ } high level Injection

$$10^{17}\ cm^{-3} >> 10^{15}\ cm^{-3}$$

Carrier Injection by optical Excitation:

As an Illustration of an Injection of Excess carriers, we consider the process of optical absorption in Semiconductor.



Schematic of carrier Injection by optical Excitation

A monochromatic beam of light of energy $h\nu$ is allowed to fall on the semiconductor of thickness d. A photodetector is placed behind the crystal, which measure the Intensity of the transmitted beam.

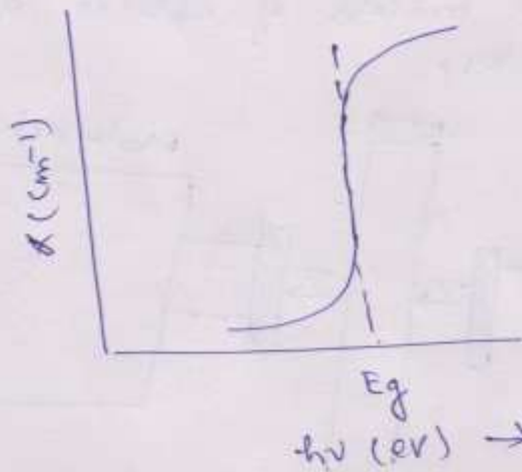
$I(0)$ = Intensity of the Incident beam

$I(d)$ = Intensity of transmitted beam.

$$I(d) = I(0)\exp(-\alpha d)$$

α = absorption coefficient. has unit cm^{-1}
If d is measured in cm.

The typical variation of α with photon energy in a semiconductor is shown below.



It is seen that when $h\nu$ is small compared to Eg, the coefficient α is negligible, and most of the light is transmitted through the semi-conductor crystal, making it transparent to radiation at these frequencies. The small absorption observed in this region is caused by free electron that are excited from lower energy states to higher energy states in given band. This free carrier absorption obviously does not create excess electron-hole pair.

As the photon Energy Increases, α begins to rise rapidly when $h\nu$ approaches E_g. A photon with Energy $h\nu \geq E_g$ is absorbed in the semiconductor because it has enough Energy to break the ~~covent~~ covalent bond and creat an electron-hole pairs. For these frequencies, the crystal becomes opaque to the Incident radiation. If a photon has energy considerably in excess of E_g, then an electron excited from the valence band to the conduction band will have energy in excess of the average thermal Energy. The process of creating excess carriers by shining light is known as photo-generation.

Answer 5

(a) The position of Fermi level at p-side can be calculated by.

$$p = n_i e^{(E_i - E_F)/KT}$$

If all the acceptors are ionized at 300 K then $N_A = p = 1 \times 10^{18}\ cm^{-3}$

For silicon semiconductor Intrinsic charge carrier density

$$n_i = 1.5 \times 10^{10}\ cm^{-3}$$

Now

$$p = n_i e^{(E_i - E_F)/KT}$$

$$N_A = n_i e^{(E_i - E_F)/KT}$$

$$\frac{N_A}{n_i} = e^{(E_i - E_F)/KT}$$

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

$$E_i - E_F = (0.0259\ eV) \ln\left(\frac{1 \times 10^{18}\ cm^{-3}}{n_i}\right)$$

$$E_i - E_F = (0.0259\ eV) \ln\left(\frac{1 \times 10^{18}\ cm^{-3}}{1.5 \times 10^{10}\ cm^{-3}}\right)$$

$$E_i - E_F = (0.0259\ eV) \times \ln\left(\frac{10}{15} \times 10^{8}\right)$$

$$\boxed{E_i - E_F = 0.467\ eV}$$

n-side

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

$$E_F - E_i = KT \ln\left(\frac{5.0 \times 10^{15}\ cm^{-3}}{n_i}\right)$$

$$E_F - E_i = KT \ln\left(\frac{5.0 \times 10^{15}\ cm^{-3}}{1.5 \times 10^{10}\ cm^{-3}}\right)$$

$$E_F - E_i = KT \ln\left(\frac{50}{15} \times 10^{5}\right)$$

$$E_F - E_i = (0.0259\ eV) \times \ln\left(\frac{50}{15} \times 10^{5}\right)$$

$$\boxed{E_F - E_i = 0.329\ eV}$$ on n-side

(b) $$V_{bi} = \frac{KT}{q} \ln\left(\frac{N_A \cdot N_D}{n_i^2}\right)$$

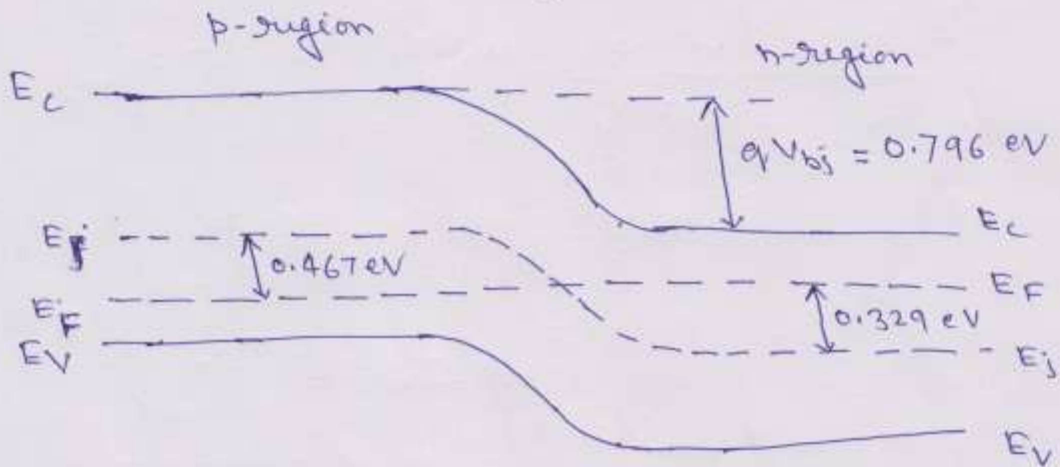
$$qV_{bi} = KT \ln\left(\frac{N_A \cdot N_D}{n_i^2}\right)$$

$$qV_{bi} = (0.0259\ eV) \ln\left(\frac{1 \times 10^{18} \times 5 \times 10^{15}\ cm^{-6}}{(1.5 \times 10^{10}\ cm^{-3})^2}\right)$$

$$qV_{bi} = (0.0259\ eV) \times \ln\left(\frac{5 \times 10^{33}}{2.25 \times 10^{20}}\right)$$

$$qV_{bi} = 0.796 \text{ eV}$$

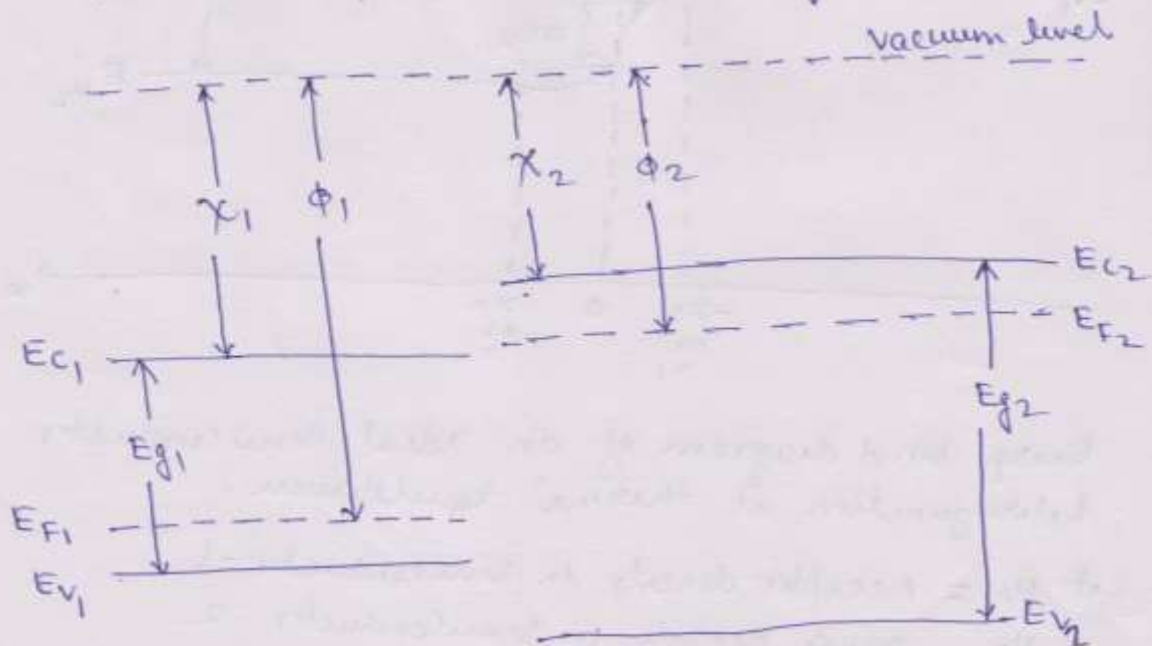
(c) Energy band diagram



Answer- 6

The term heterojunction is applicable to different kind of interface structures realized by bringing two dissimilar materials in contact so that the same crystal structure is retained.
In semiconductor physics, the term means a junction between two different semiconductor.

When semiconductor of different energy gaps and work functions are brought together to form a heterojunction, we expect energy band discontinuities at the interface as the Fermi-level line up at the thermal equilibrium.

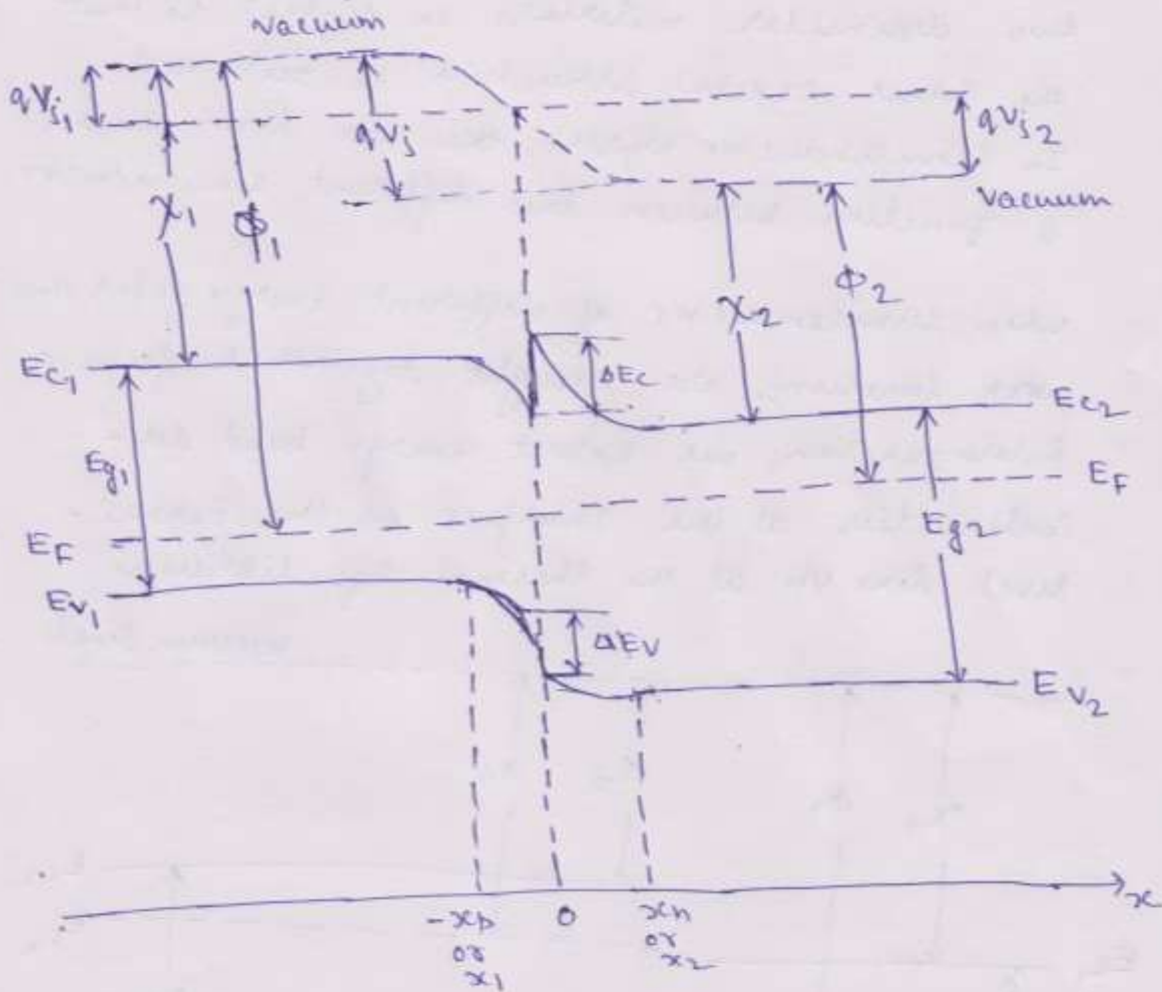


Energy band diagram of the two separate semiconductor.

where, χ_1 and χ_2 = Electron affinity of Semiconductor 1 & 2

ϕ_1 and ϕ_2 = work function of " " " " "

E_{g1} and E_{g2} = Energy bandgap " " "



Energy band diagram of an Ideal Semiconductor heterojunction at thermal Equilibrium.

Let N_{A1} = Acceptor density in Semiconductor - 1

N_{D2} = Donor density in Semiconductor - 2

ϵ_1 = permittivity of semiconductor - 1

ϵ_2 = permittivity of Semiconductor - 2

To derive expressions for various Junction parameters we write the one-dimensional poisson's Equation on the both side of the Junction.

$$\frac{d^2\psi_1}{dx^2} = \frac{-\rho}{\epsilon_1} = -\left(\frac{-qN_{A1}}{\epsilon_1}\right) = \frac{qN_{A1}}{\epsilon_1} \quad \text{for } x_1 \le x \le 0$$

$$\frac{d^2\psi_1}{dx^2} = \frac{qN_{A1}}{\epsilon_1} \quad x_1 \le x \le 0 \quad \text{— (1) Semiconductor-1}$$

Similarly

$$\frac{d^2\psi_2}{dx^2} = \frac{-qN_{D2}}{\epsilon_2} \quad 0 \le x \le x_2 \quad \text{— (2) Semiconductor-2}$$

Integrating Equation (1) with respect to x.

$$\int \frac{d^2\psi_1}{dx^2}\,dx = \frac{qN_{A1}}{\epsilon_1}\int dx$$

$$\frac{d\psi_1}{dx} = \frac{qN_{A1}}{\epsilon_1}x + C$$

$$E_1(x) = -\frac{d\psi_1}{dx} = -\frac{qN_{A1}}{\epsilon_1} + C$$

Boundary Condition $E_1(x) = 0$ at $x = -x_1$

$E_1(x) = E_{M1}$ at $x = 0$

$$E_1(x) = -\frac{qN_{A1}}{\epsilon_1}\left[x_1 + x\right] = E_{M1}\left(1 + \frac{x}{x_1}\right)$$

where $E_{M1} = -\frac{qN_{A1}}{\epsilon_1}x_1$

Similarly for Semiconductor-2

$$E_2(x) = E_{M2}\left(1 - \frac{x}{x_2}\right) = -\frac{qN_{D2}}{\epsilon_2}\left[x_2 - x\right]$$

where, $E_{M2} = -\frac{qN_{D2}}{\epsilon_2}x_2$

Now, Electrostatic Potential on both Semiconductor

$$\psi_1(x) = -\int E_1(x)\,dx$$

$$\psi_2(x) = -\int E_2(x)\,dx$$

$$\psi_1(x) = \frac{q N_{A1}}{\epsilon_1}\left[x_1 \int dx + \int x\,dx\right] + A_1$$

$$\psi_1(x) = \frac{q N_{A1}}{\epsilon_1}\left[x_1 x + \frac{x^2}{2}\right] + A_1$$

Boundary condition,

$\psi_1(x) = 0 \qquad x = 0$

$\psi_1(x) = V_1 \qquad x = -x_1$

$$\boxed{\psi_1(x_1) = V_1 = -\frac{q N_{A1} x_1^2}{2\epsilon_1}}$$

Similarily, for Semiconductor-2

$$\psi_2(x) = -\int E_2(x)\,dx$$

$$\psi_2(x) = +\frac{q N_{D2}}{\epsilon_2}\left[x_2 \int dx - \int x\,dx\right] + A_2$$

$$\psi_2(x) = +\frac{q N_{D2}}{\epsilon_2}\left[x_2 x - \frac{x^2}{2}\right] + A_2$$

$\psi_2(x) = 0 \quad$ at $x = 0$

$\psi_2(x) = V_2 \quad$ at $x = x_2$

$$\psi_2(x_2) = V_2 = \frac{qN_{D2}}{\epsilon_2}\left[x_2^2 - \frac{x_2^2}{2}\right]$$

$$\boxed{V_2 = \frac{qN_{D2}}{2\epsilon_2} x_2^2}$$

Electric Displacement must be continuous at $x=0$

i.e. $\epsilon_1 E_1 = \epsilon_2 E_2$

$$\Rightarrow \boxed{N_{A1} x_1 = N_{D2} x_2}$$

$$V_j = |V_2 - V_1|$$

$$V_j = \frac{qN_{D2}}{2\epsilon_2} x_2^2 + \frac{qN_{A1}}{2\epsilon_1} x_1^2$$

$$V_j = \frac{q}{2}\left[\frac{N_{D2}}{\epsilon_2} x_2^2 + \frac{N_{A1}}{\epsilon_1} x_1^2\right]$$

$$x_2 = \frac{N_{A1}}{N_{D2}} x_1$$

$$V_j = \frac{q}{2}\left[\frac{N_{D2}}{\epsilon_2} \cdot \frac{N_{A1}^2}{N_{D2}^2} x_1^2 + \frac{N_{A1}}{\epsilon_1} x_1^2\right]$$

$$V_j = \frac{q}{2}\left[\frac{N_{A1}^2}{\epsilon_2 N_{D2}} + \frac{N_{A1}}{\epsilon_1}\right] x_1^2$$

$$V_j = \frac{q}{2}\left[\frac{\epsilon_1 N_{A1}^2 + \epsilon_2 N_{D2} N_{A1}}{\epsilon_1 \epsilon_2 N_{D2}}\right] x_1^2$$

$$V_j = \frac{q}{2}\left[\frac{\epsilon_1 N_{A_1} + \epsilon_2 N_{D_2}}{\epsilon_1 \epsilon_2 N_{D_2}}\right] N_{A_1} x_1^2$$

$$V_j = \left[\frac{\epsilon_1 N_{A_1} + \epsilon_2 N_{D_2}}{2 \epsilon_1 \epsilon_2 N_{D_2}}\right] q \cdot N_{A_1} x_1^2$$

$$x_1^2 = \frac{2 \epsilon_1 \epsilon_2 N_{D_2} V_j}{q N_{A_1} (\epsilon_1 N_{A_1} + \epsilon_2 N_{D_2})}$$

$$\boxed{x_1 = \left[\frac{2 \epsilon_1 \epsilon_2 N_{D_2} V_j}{q N_{A_1} (\epsilon_1 N_{A_1} + \epsilon_2 N_{D_2})}\right]^{1/2}}$$

Similarly,

$$\boxed{x_2 = \left[\frac{2 \epsilon_1 \epsilon_2 N_{A_1} V_j}{q N_{D_2} (\epsilon_1 N_{A_1} + \epsilon_2 N_{D_2})}\right]^{1/2}}$$

Total width of Depletion layer.

$$W = x_1 + x_2$$

$$W = \left[\frac{2 \epsilon_1 \epsilon_2 (N_{D_2} + N_{A_1}) V_j}{q (\epsilon_1 N_{A_1} + \epsilon_2 N_{D_2})} \cdot \left(\frac{1}{N_{A_1}} + \frac{1}{N_{D_2}}\right)\right]^{1/2}$$

$$\boxed{W = \left[\frac{2 \epsilon_1 \epsilon_2 (N_{A_1} + N_{D_2}) V_j}{q N_I^{+} (\epsilon_1 N_{A_1} + \epsilon_2 N_{D_2})}\right]^{1/2}}$$

Junction capacitance: (C_j)

$$C_j = \frac{dQ}{dV_j}$$

and

$$dQ = q N_{D_2} dx_2$$

$$\frac{dx_2}{dV_j} = \frac{x_2}{2V_j}$$

Therefore,

$$C_j = \frac{q N_{D_2}}{2V_j}\left[\frac{2\epsilon_1 \epsilon_2 N_{A_1} V_j}{q N_{D_2}(\epsilon_1 N_{A_1} + \epsilon_2 N_{D_2})}\right]^{1/2}$$

$$\boxed{C_j = \left[\frac{q \epsilon_1 \epsilon_2 N_{A_1} N_{D_2}}{2V_j(\epsilon_1 N_{A_1} + \epsilon_2 N_{D_2})}\right]^{1/2}}$$

Answer. 7

A tunnel diode consists of a simple p-n junction in which both p and n side are degenerate i.e. very heavily doped with impurities.
Energy level diagram of a tunnel diode in thermal equilibrium is shown in figure-1.

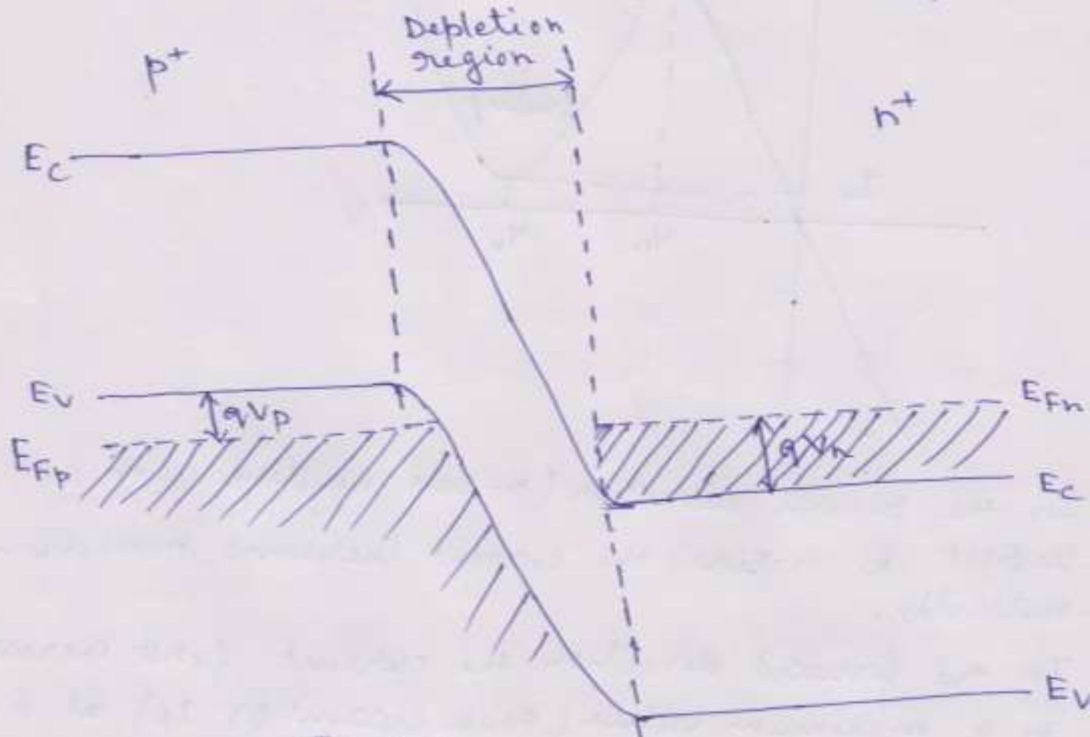
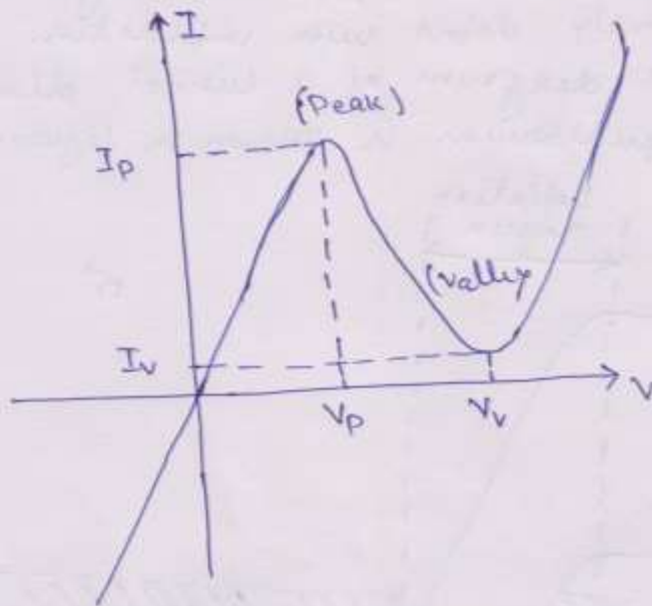


Figure-1

Because of the high doping the Fermi level is located within the allowed bands themselves. The amount of degeneracy, V_p and V_n, is typically a few KT and the depletion layer width is of the order of 100 Å or less, which considerably narrower than the conventional p-n junction.

current-voltage characteristics of a tunnel diode is shown in figure-2.



In the reverse direction (p-side negative with respect to n-side) the current increases monochro-
-matically.

In the forward direction the current first increases to a maximum value (Peak current or I_p) at a voltage V_p. For the voltage larger than V_p, the current then decreases to a minimum value I_v at a voltage V_v. A voltage larger than V_v, the current Increases Exponentially with the voltage.

The static I-V ~~charactistics~~ characteristics is the result of three current components:

(i) Band to band tunneling current
(ii) Excess current
(iii) Thermal current.

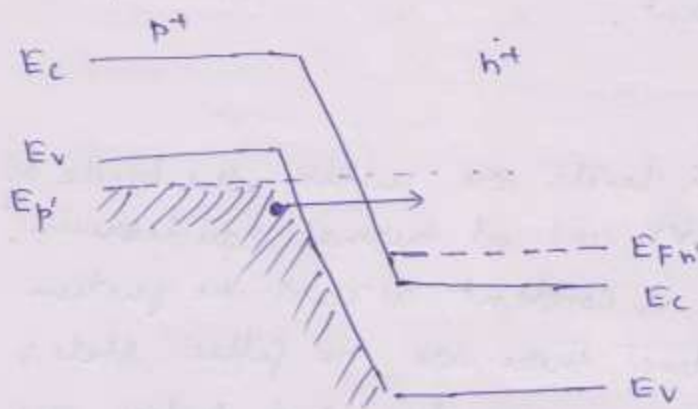
Note that the fermi levels are within the bands of of the Semiconductor, and at thermal equilibrium, the fermi level is constant across the juction. Above the fermi level there are no filled states on either side of the Junction, and below the fermi level, there are no Empty states available on either side of the junction. Hence tunneling current cannot flow at zero applied voltage.

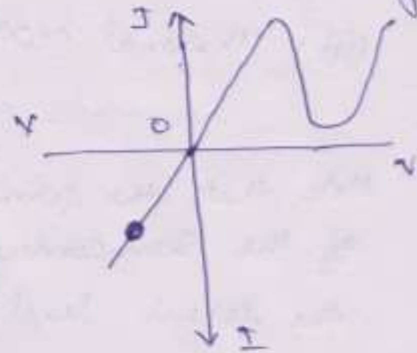
When a bias voltage is applied, the electrons may tunnel from the valence band to the conduction band, or vice versa.

The necessary condition for tunneling are:

1. occupied Energy states exist on the side from which the electron tunnels.
2. Unoccupied Energy state exist at the same Energy level as in (1) on the side to which the electron can tunnel.
3. The tunneling potential barrier height is low and the barrier width is small enough that there is a finite tunneling probability.

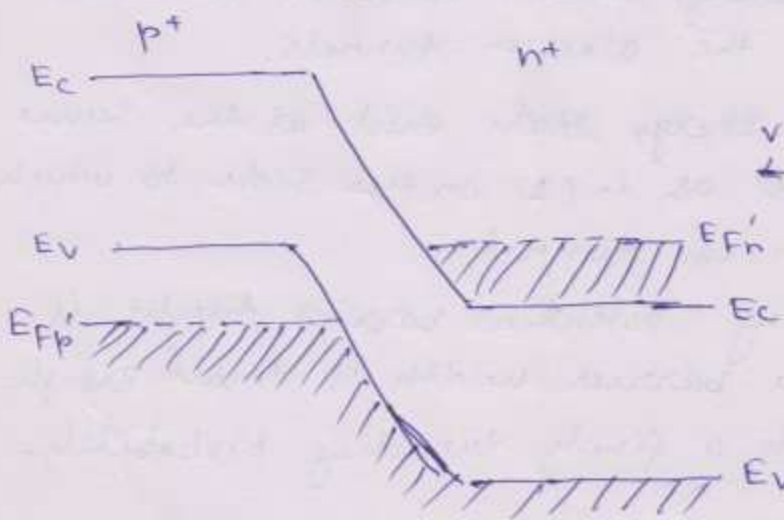
4. The momentum is conserved in the tunneling process.

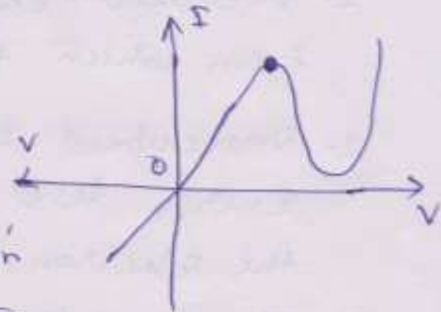




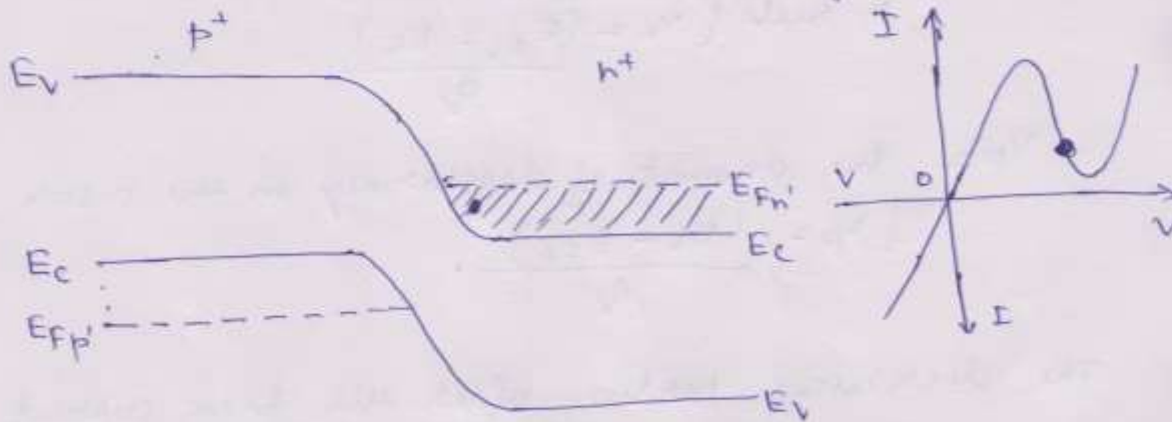
Electron tunneling from the valence band into the conduction band when a reversed biased is applied. The corresponding current is also designated by the dot on the I-V curve.

When a forward bias is applied, a band of energies exist for which there are feild states on the n-side corresponding to state which are available and unoccupied on the p-side. The electron can thus tunnel from n-side to the p-side.

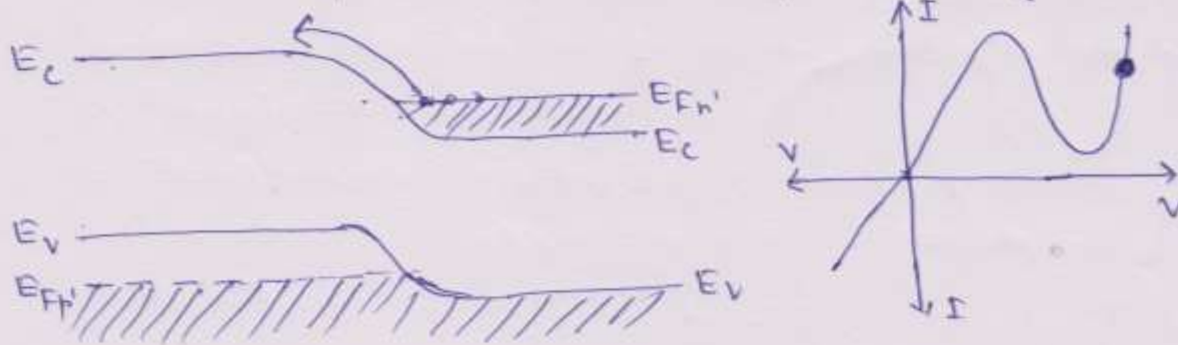




When the Forward bias is further increased, there are fewer available unoccupied state on the p-side. If forward voltage is applied such that the band is "uncrossed", that is the edge of the conduction band is exactly opposite the top of the valence band, there are no available states opposite to the filled states.



Thus at this point the tunneling current no longer flow. With still further increase of the voltage the normal thermal current will flow, and will increase exponentially with applied voltage.



One thus expects that as the forward voltage Increases, the tunneling current Increases from zero to a maximum current I_p and then decreases to zero when $V = V_n + V_p$, where V is the applied forward voltage.

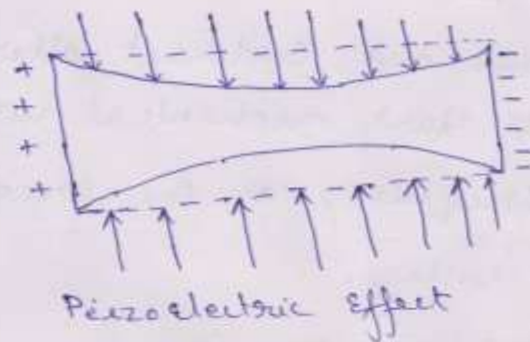
V_n = the amount of degeneracy on the n-side $\left[V_n = \frac{(E_{Fn} - E_C)}{q} \right.$

V_p = the amount of degeneracy on the p-side. $\left[V_p = \frac{(E_V - E_{FP})}{q} \right.$.

The decreasing portion after the peak current give rise to the negative resistance region.

Answer - 8

Certain crystal possess the special property that if a mechanical pressure is applied to them, an electrical voltage is developed between opposite faces of the crystal as shown in figure. This is true for compression as well as for expansion of the crystal.



Piezoelectric Effect

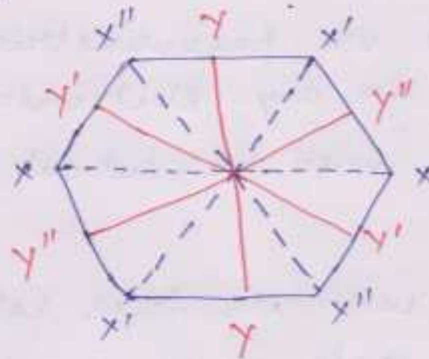
The polarity of the voltage which developed due to compression or expansion is reverse in the two cases and the magnitude of the voltage depends in each case on the magnitude of compression or expansion. This is known as Peezo electric effect and the crystal is known as a Peizoelectric crystal.

The Inverse of this effect is also true for such crystals: if an electrical valtage is applied between opposite faces of the

The crystal, it expands or contracts depending on the polarity of the voltage and the magnitude of expansion or contraction. depends on the magnitude of the voltage.
This implies that if an alternating voltage is applied to a piezoelectric crystal, it will expand and contract alternately, i.e. it will start mechanical vibration with the same frequency as the frequency of alternating voltage.
These vibrations are forced vibrations and have sufficient amplitude only if the frequency of applied voltage equals the natural frequency of vibrations of the crystal.

A number of crystal are known to be piezoelectric. out of these, quartz crystals are almost always employed in crystal controlled oscillator.

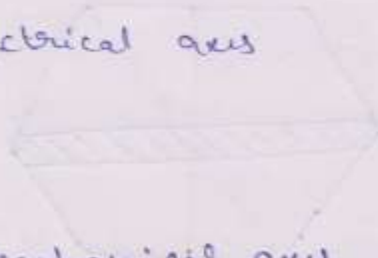
They have a hexagonal cross-section as shown in figure given below.



Electrical and mechanical axis of quartz. crystal.

The three axis passing through opposite corners of the hexagon are known as the Electrical axis while other three axis perpendicular to these axis (i.e. Electrical axis) are known as the mechanical axis.
i.e.

$$\left.\begin{matrix} XX \\ X'X' \\ X''X'' \end{matrix}\right\} = \text{Electrical axis}$$



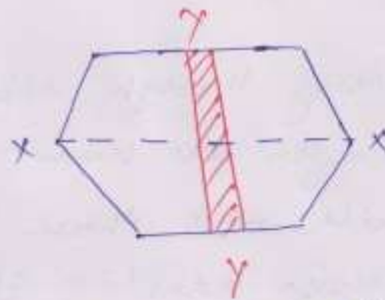
$$\left.\begin{matrix} YY \\ Y'Y' \\ Y''Y'' \end{matrix}\right\} = \text{Mechanical axis}$$

An alternating voltage can be applied along any of the Electrical axis and vibrations

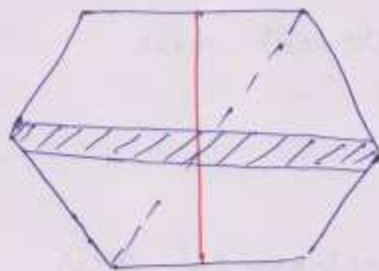
along corresponding mechanical axis can be observed.

In order to make use piezoelectric property of quartz crystal in any electronic circuit, a suitable piece must be cut out from the quartz crystal.

A piece cut out with its faces perpendicular to an electrical axis is known as an x-cut crystal, while that with its faces



An x-cut crystal



A y-cut crystal.

perpendicular to a mechanical axis is known as a y-cut crystal.

Both kinds of crystals vibrate if an alternating voltage is applied between opposite faces. The natural frequency of vibration depends on the elastic properties of the material of the crystal, the type of cut and on its thickness d (mm)

for quartz crystal, vibration frequency can be given as

$$\nu = \frac{2.85 \times 10^6}{d} \text{ Hz} \quad \text{for x-cut crystal}$$

$$\nu = \frac{1.96 \times 10^6}{d} \text{ Hz} \quad \text{for y-cut crystal}$$

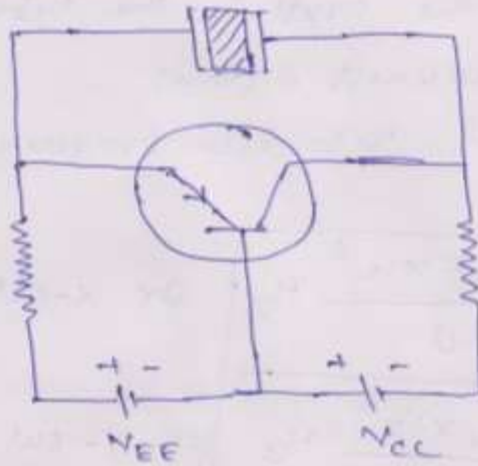
This frequency shows very little dependence on temperature as well.

Application of piezoelectric crystal

Crystal oscillator:

A quartz crystal behaves as a resonant circuit with a very sharp resonance at natural frequency of vibration. It can, therefore, be used in place of the tuned circuit in an oscillator.

Thus various circuits are possible for a crystal controlled oscillator. One simple oscillator circuit (known as peirce oscillator) is shown in figure below.



A crystal controlled oscillator