DEPARTMENT OF ELECTRNICS & COMMUNICATION ENGINEERING, KITSW

COURSE: **U14EI 205 - BASIC ELECTRONICS ENGINEERING**	**ECE-I, Semester-II, 2015-16**

ASSIGNMENT-2 HINTS &SOLUTIONS

1 Show that the Fermi level is at the center of forbidden gap in an intrinsic semiconductor. State what happens to the Fermi level of N-type and P-type semiconductors by referring to expressions concerned.

(First define Fermi level)

- Fermi level is the measure of the energy of least tightly held electrons
- Fermi level also indicates the probability of occupancy of a given energy level by an electron
- The probability that the charged particle will have an energy E is given by Fermi-Dirac distribution or Fermi function $f(E) = \frac{1}{1+e^{\left(\frac{E-E_F}{kT}\right)}}$

  Where E_F = Fermi energy or Fermi level (eV)

  k = Boltzman's constant ($1.38 x 10^{-24}$ J/K or $8.62 x 10^{-5}$ eV/K), T= temperature (K)

  kT= 0.026 eV at room temp (300 K)

  - **If $E=E_F$, then $f(E)$ = 0.5**

- **So, Fermi level is defined as the energy point where the probability of occupancy by an electron is exactly 50% , or 0.5**

Expression for Fermi level in an intrinsic semiconductor:

- **Derivation of Fermi level in an intrinsic semiconductor** (E_F^i) :

  Refer to your class notes for derivation of E_F^i

- The Fermi level of intrinsic semiconductor is given by

$$E_F^i = \left(\frac{E_C + E_V}{2}\right) + \frac{kT}{2}\ln\left(\frac{N_V}{N_C}\right)$$

E_C = Conduction band bottom edge energy level (eV)

E_V = Valence band top edge energy level (eV)

N_C = Effective density of energy states in conduction band

N_V = Effective density of energy states in valence band

k = Boltzman's constant ($1.38 x 10^{-24}$ J/K or $8.62 x 10^{-5}$ eV/K), T= temperature (K)

kT= 0.026 eV at room temp (300 K)

- The second term contributes very little, hence the intrinsic Fermi level is

$$E_F^i = \left(\frac{E_C + E_V}{2}\right)$$

The Fermi level in case of intrinsic semiconductor (E_F^i) lies in the middle of bandgap

Extrinsic semiconductor:

- **N-type semiconductor:** The Fermi level of N-type semiconductor (E_F^N) is given by

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

Where, E_C = Conduction band bottom edge energy level (eV)
N_C = Effective density of energy states in conduction band
N_D = Donor impurity concentration (atoms/cm³)
k = Boltzman's constant ($1.38 x 10^{-24}$ J/K *or* $8.62 x 10^{-5}$ eV/K), T= temperature (K)
kT= 0.026 eV at room temp (300 K)

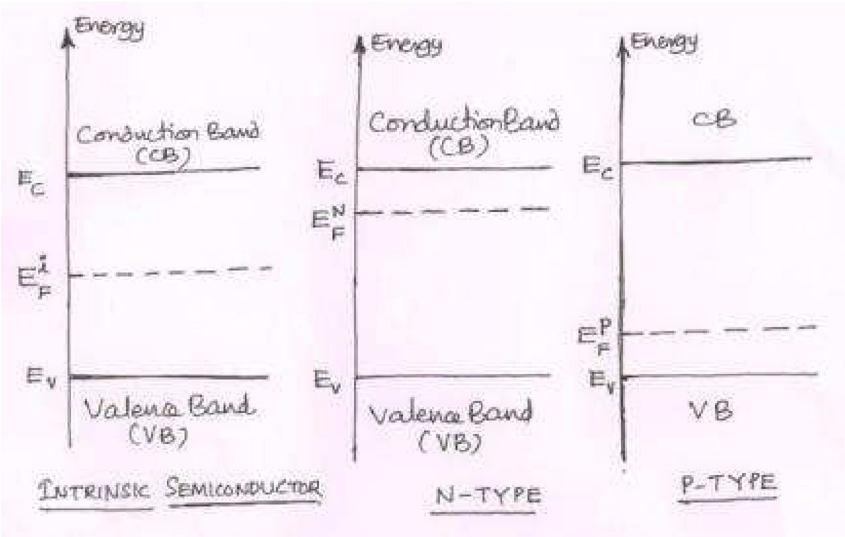
  - In **N-type SC, the Fermi level (E_F^N) is higher than intrinsic Fermi level (E_F^i) and close to the conduction band** (just below the CB).

- **P-type semiconductor:** The Fermi level of N-type semiconductor (E_F^P) is given by

$$E_F^P = E_V + kT \ln\left(\frac{N_V}{N_A}\right)$$

Where, E_V = Valence band top edge energy level (eV)
N_V = Effective density of energy states in valence band
N_A = Acceptor impurity concentration (atoms/cm³)
k = Boltzman's constant ($1.38 x 10^{-24}$ J/K *or* $8.62 x 10^{-5}$ eV/K), T= temperature (K)
kT= 0.026 eV at room temp (300 K)

  - In **P-type SC, the Fermi level (E_F^P) is lower than intrinsic Fermi level (E_F^i) and close to the valence band** (just above the VB).



2 Explain Drift and diffusion currents with reference to a semiconductor.

- The two mechanisms of flow of current in a semiconductor are:
  - (i) Drift Current (J_{drift}),
  - (ii) Diffusion current (J_{diff})
- Net current in a semiconductor (J) is sum of drift current and diffusion current

$$J = J_{drift} + J_{diff} \qquad \ldots\ldots\ldots (1)$$

Here J is current density given by $J = \sigma E$

Where, σ = conductivity $(\Omega - m)^{-1}$ of the material,

E = electric field (V/m) applied across the semiconductor

Drift current (J_{drift})

- The charged particles move or drift under the influence of the applied electric field E
- The ordered movement of charge carriers due to applied electric field is called *drift and the resulting current is called drift current*
- The drift current due to applied electric field E (V/m) is

$$J = \sigma E \qquad \ldots\ldots (2)$$

Where, σ is conductivity $(\Omega - m)^{-1}$ of the material, given by

$$\sigma = n\mu q,$$

Where, μ is mobility (m^2/V-s) ← ((m/s)/(V/m))

n = electron concentration (number of electrons/unit volume)

q = charge on electron (- 1.6x 10^{-19} C)

- As current in a semiconductor is due to both electrons (n) and holes (p)

$$J_{drift} = J_{n-drift} + J_{p-drift}$$

$$J_{drift} = (n\mu_n q)E + (p\mu_p q)E$$

$$J_{drift} = (n\mu_n + p\mu_p) qE \qquad \ldots\ldots\ldots (3)$$

Where, μ_n =mobility of electrons (cm^2/V-s) , n= concentration of electrons (atoms/cm^3)

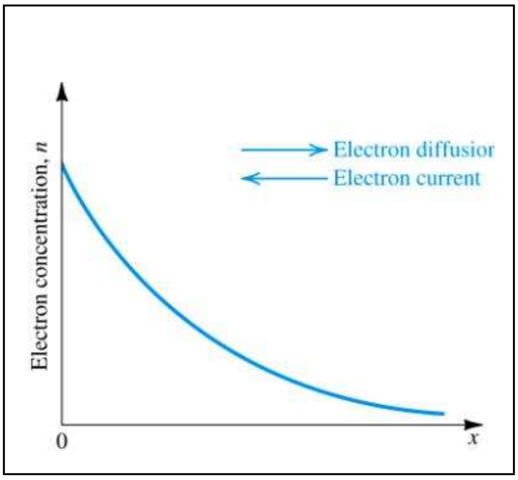
μ_p = mobility of holes (cm^2/V-s); p = concentration of electrons (atoms/cm^3)

Diffusion current (J_{diff})

(It is possible for electric current to flow in a semiconductor, even in the absence of applied voltage. ……. Diffusion current)

- Carrier concentration gradient: The charge carriers have a natural tendency to diffuse (move) from a region of higher concentration to the region of lower concentration
- The uncoordinated random movement of charge carriers due to charge gradient is called diffusion and *the current associated with diffusion process is called Diffusion current*.
- Diffusion current density is directly proportional to concentration gradient
- Diffusion current density $\propto$ The rate of change of concentration per unit length of SC

Diffusion current for electrons:



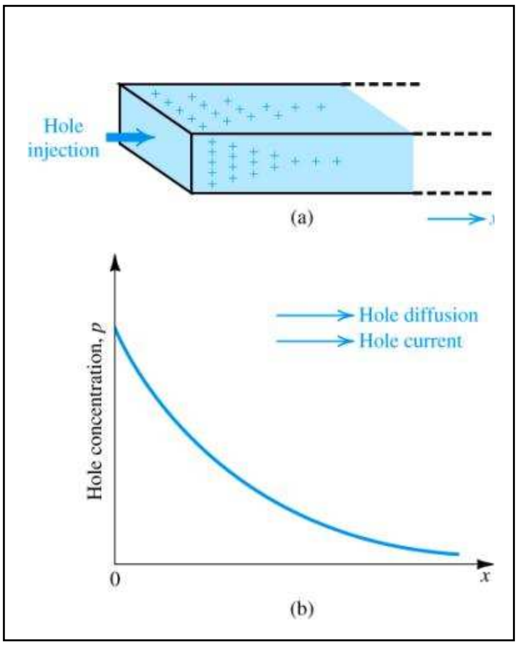
- Carriers move toward regions of lower concentration, so diffusion current densities are proportional to the negative of the carrier gradient.
- As shown in figure, the **electrons** diffusing in the x direction, giving rise to an electron-diffusion current in the negative -x direction

$$J_{n-diff} \propto (-q)(-\frac{\partial n}{\partial x})$$

$$J_{n-diff} = D_n \; q \frac{\partial n}{\partial x} \quad \text{......} \; (4)$$

Where, D_n is electron diffusion coefficient (cm²/s)

Diffusion current for holes:



- The holes diffuse in the positive direction of x and give rise to a hole-diffusion current in the same direction

$$J_{p-diff} \propto (q)(-\frac{\partial n}{\partial x})$$

$$J_{p-diff} = -D_p \; q \frac{\partial p}{\partial x} \quad \text{......} \; (4)$$

Where, D_p is called hole diffusion coefficient (cm²/s)

Total current:

Total current is the sum of drift and diffusion current

$$J = J_{drift} + J_{diff}$$

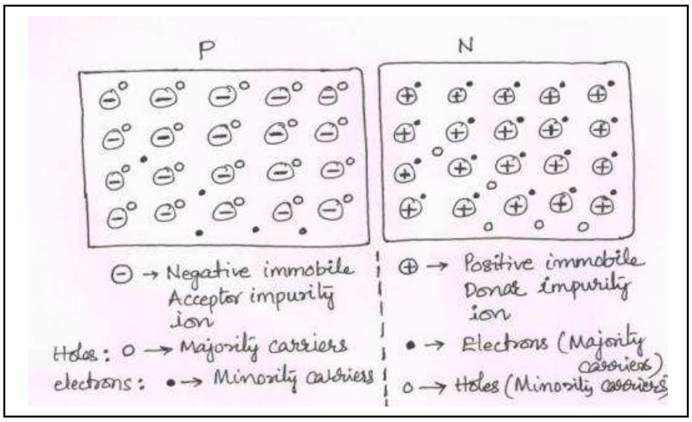
$$J = (J_{n-drift} + J_{p-drift}) + (J_{n-diff} + J_{p-diff})$$

$$J = (J_{n-drift} + J_{n-diff}) + (J_{p-drift} + J_{p-diff})$$

$$J = (q\mu_n nE + qD_n \frac{\partial n}{\partial x}) + (q\mu_p pE - qD_p \frac{\partial p}{\partial x})$$

$$J = J_n + J_p$$

3. Explain how the depletion region is formed at a P-N junction.

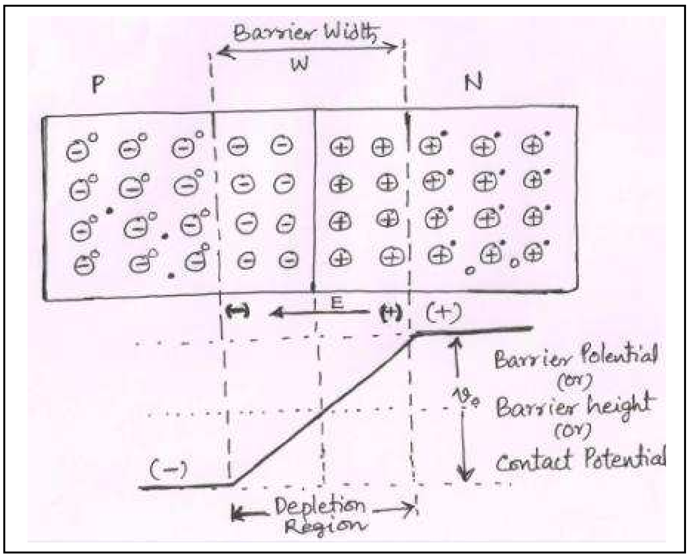


P-type semiconductor has :

- Mobile charge carriers:
  (i) Holes as majority carriers,
  (ii) Electrons as minority carriers
- Immobile ions: Negatively charged impurity ions

N-type semiconductor has :

- Mobile charge carriers: (i) Electrons as majority carriers, (ii) Holes as minority carriers
- Immobile ions: Positively charged impurity ions
- By themselves, P-type and N-type semiconductors are of very limited use
- If a junction is made by joining P-type material to N-type material, a useful device is produced called P-N junction diode



As soon as the P-N junction is formed, the following processes are initiated:

- **Charge gradient across the junction:** Excess of holes in P-type and excess of electrons in N-type materials.
- **Diffusion of charge carriers:** Due to charge gradient,
  - majority holes from P region diffuse into the N region ; and
  - majority electrons from N region diffuse into P region diffuse into P region

This diffusion of majority carriers establishes diffusion current (I_{diff}) in the diode

- **Electron-hole recombination:** As the charge carriers diffuse across the junction, holes will recombine with free electrons and (vice-versa) electrons will recombine with holes.
- **Depletion region or space-charge region:**
  - The process of electron-hole recombination will uncover the bound charges and leave behind a region of immobile ions at the immediate vicinity of the junction.
  - This region where there will be no mobile charges is called a depletion region or it is also called space charge region. This region is devoid of the free carriers.
  - **Depletion region** acts like a barrier that opposes the flow of electrons from n-side and holes from p-side.
  - The physical width of depletion region is called barrier width (W). It is of order of Angstrom (10^{-10} m)
  - The barrier width is given by $w=\sqrt{\frac{2\varepsilon_o\varepsilon_r v_o}{q}\left(\frac{N_D+N_A}{N_D N_A}\right)}$

    N_D = Donor impurity concentration, N_A = Acceptor impurity concentration , n_i = intrinsic concentration, ε_r = relative permittivity, v_o = barrier potential (V), q = charge on electron (C)

Barrier potential(v_o)

- The depletion region consists of *uncovered negative charge* on the P side and *uncovered positive charge* on the N side.
- That means a potential is developed across the junction and that potential is positive on the N side and negative on the P side.
- This potential will be now preventing further diffusion of charge (majority) carriers across the junction.
- This is called barrier potential (v_o) because of the fact that it is a barrier to further movement of carriers.
- Barrier potential is also referred to as height of the barrier or built-in potential or contact potential
- The expression for barrier potential (v_o) is given by

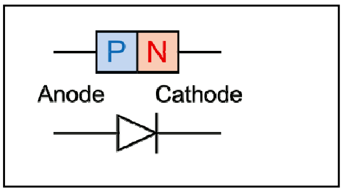
$$v_o = \frac{kT}{q}\ln\left(\frac{N_D N_A}{n_i^2}\right)$$

Where, N_D = Donor impurity concentration N_A = Acceptor impurity concentration,

k = Boltzman's constant (eV/K), T= temp (K); kT= 0.026 eV at room temp (300 K),
n_i = intrinsic concentration, q = charge on electron (C)

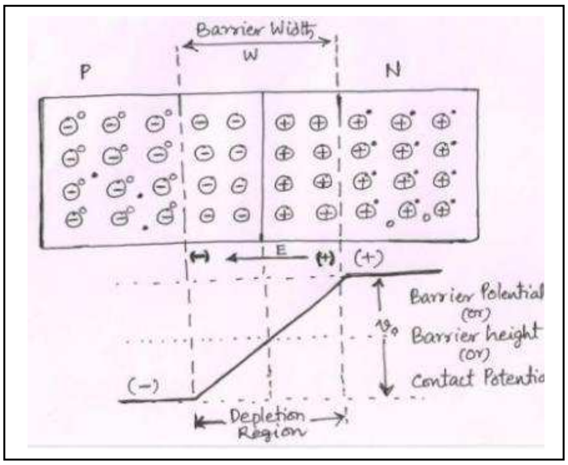
- The Barrier potential or built-in potential $(v_o) = \begin{cases} 0.3\,V, & for\ Ge\ diodes \\ 0.7V, & for\ Si\ diodes \end{cases}$
- Due to barrier potential, an electric field (E) will be set up, which is directed from N side to P side
- On one side the barrier potential discourages the diffusion of majority carriers across the junction. At the same time the barrier potential helps the minority carriers ***to drift*** across the junction resulting in drift current (I_{drift})
- Under steady state or at equilibrium, $I_{diff} = I_{drift}$

  So *net current in the diode under open circuit is zero*.



- The circuit symbol of P-N junction diode is shown. This diode has immense applications in electronics starting from rectification

4. Explain the operation of the p-n diode in forward and reverse bias modes. Also plot the V-I characteristic curve for Si and Ge diodes.



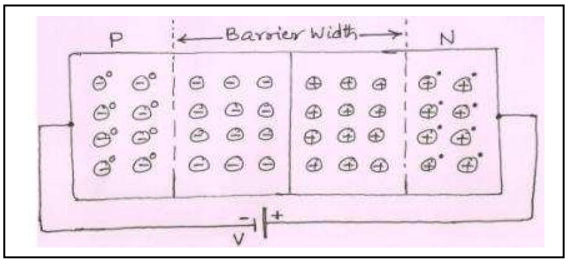
Open circuited diode

- When no external voltage is applied across the P-N junction diode, it is said to be open circuited.
- The figure shows the P-N junction under open circuit. It depicts a space-charge region or depletion region in the vicinity of the junction

Biased diode: When some external voltage is applied across the diode, it is said to be biased.

Reverse bias: Figure shows a reverse biased P-N junction.

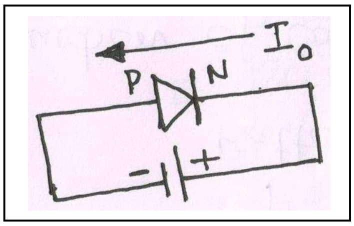
  - Positive terminal of the external battery is connected to the N side
  - Negative terminal of the battery is connected to the P side



- The majority carriers are drawn away from the junction due to external battery polarity.
- This act widens the depletion region and increases the barrier potential.
- However, the barrier potential drifts the minority carriers to cross the junction.
- As the minority carriers are small in number in number, the diode current in reverse bias is very small. It is also called *reverse leakage current.*

- Reverse saturation current (I_o): At a given temperature, the minority carriers are fixed in number. Hence the diode reverse current will remain constant, even if the applied reverse bias voltage is increased. For this reason, the diode reverse current is also called *reverse saturation current (I_o)*

$$I_o = \begin{cases} few\ \mu A, & for\ \ Ge\ diodes \\ few\ nA, & for\ \ Si\ \ diodes \end{cases}$$



- Breakdown voltage (V_{BD}) : If the reverse voltage is increased beyond a particular value, called breakdown voltage (V_{BD}), there will be a sudden rise in the I_o .
- V_{BD} is normally very high and practical rectifier diodes are not operated in breakdown condition.
- Breakdown voltage in conventional diodes: $V_{BD} = \begin{cases} 50-70V & , for\ \ Ge\ \ diodes \\ around\ 100V, & for\ \ Si\ \ diodes \end{cases}$

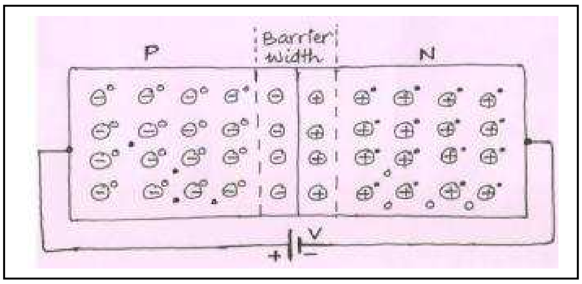
(Note: Breakdown region of operation is useful in "Voltage Regulator" applications. Those diodes are called Zener diodes, which are deliberately operated in breakdown region)

- The I_o *is* a temperature dependent parameter
- When temperature increases, more covalent bonds will be broken. Majority carriers will be drawn away from junction by applied reverse bias, whereas the barrier potential will help the minority carriers drift across the junction. This increases the reverse saturation current.
- *Reverse saturation current doubles for every 10 °C rise in temperature*

$$I_{02} = I_{01}\left(2^{\left(\frac{\Delta T}{10}\right)}\right); \quad \text{Where,} \quad I_{01} = \text{Reverse saturation current at temp } T_1 \ {}^0C$$

I_{02} = Reverse saturation current at temp $T_2 \ {}^0C$, $\Delta T = (T_2 - T_1)\,{}^oC$

Forward bias: Figure shows a forward biased P-N junction

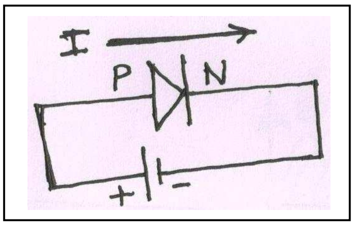


- Positive terminal of the external battery is connected to the P side
- Negative terminal of the battery is connected to the N side

- Majority holes in P side are repelled from positive terminal of the battery and are forced to cross the junction, by penetrating the depletion region.
- Majority electrons in N side are repelled from negative terminal of the battery and are forced to cross the junction, by penetrating the depletion region.
- This act reduces the depletion region and the barrier potential.
- The diode does not conduct well until the applied voltage (V) overcomes the barrier potential (v_o)

- The Barrier potential or built-in potential (v_o) = $\begin{cases} 0.3\,V, & for\ Ge\ diodes \\ 0.7\,V, & for\ Si\ diodes \end{cases}$
- When applied voltage (v) approaches 0.7 V for Si, large number of electrons and hole are drifted to cross the junction
- When $v > v_o$, even a small increase in the v produces a sharp increase in the current
- <u>Cut-in voltage or knee voltage</u> (v_0): The voltage at which the diode current starts to increase rapidly is called *cut-in voltage or knee voltage*
- <u>Diode current equation</u> : For the applied external voltage (v), the forward current through diode (I) is given by

$$I = I_0\, e^{\left(\frac{v}{\eta V_T}\right)};$$



Where, I = forward current through the diode (Amp)

I_0 = Reverse saturation current through the diode (A)

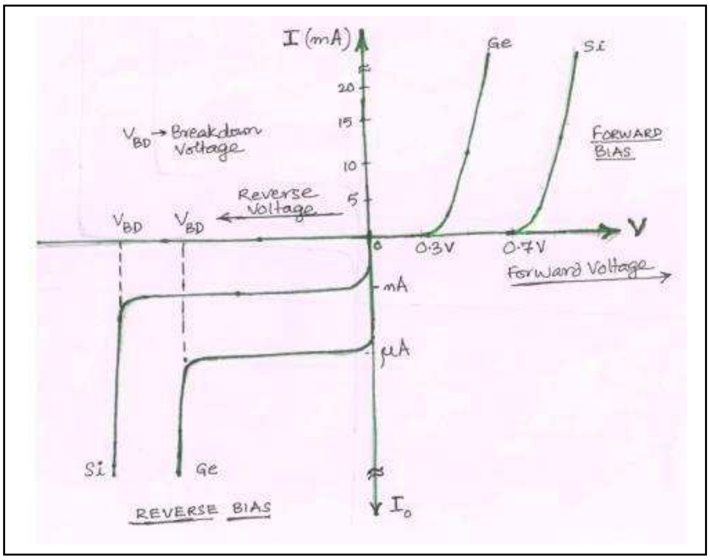
v = forward voltage applied across the diode (V)

$$\eta = \begin{cases} 1;\ for\ Ge \\ 2;\ for\ Si \end{cases}$$

V_T = Volt equivalent of temperature (Volts) = $\dfrac{T}{11{,}600}$ Volts, T in Kelvin

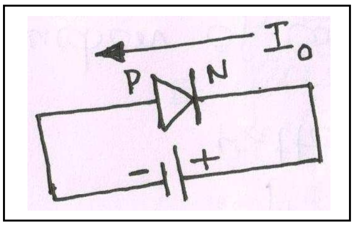
At room temperature (27 ^0C = 300 K), V_T = 300/11,600= 0.025862 V ≈ 26mV

- The diode <u>forward current increases exponentially</u> with the applied voltage across the diode
- The following figure shows the V-I characteristics of Ge and Si P-N junction diodes



(Though figures are very essential in presentation, You should not take much time in drawing figures. You should be able to draw each figure within a minute or two. It requires prior practice. Otherwise you will end up finding no time to attempt all questions. Do practice, drawing all figures!)

5. What is reverse saturation current (I_o)? Mention approximate order of I_o for Ge and Si diodes. Discuss the effect of temperature on I_o by writing necessary expression.



- When a diode is reversed biased, the current in the diode is due to minority carries
- As the minority carriers are small in number in number, the diode current in reverse bias is very small. It is also called *reverse leakage current.*
- Reverse saturation current (I_0): At a given temperature, the minority carriers are fixed in number. Hence the diode reverse current will remain constant, even if the applied reverse bias voltage is increased. For this reason, the diode reverse current is also called *reverse saturation current (I_0)*

$$I_o = \begin{cases} few\ \mu A, & for\ \ Ge\ diodes \\ few\ nA, & for\ \ Si\ \ diodes \end{cases}$$

- The I_o *is* a temperature dependent parameter
- When temperature increases, more covalent bonds will be broken. Majority carriers will be drawn away from junction by applied reverse bias, whereas the barrier potential will help the minority carriers drift across the junction. This increases the reverse saturation current.
- *Reverse saturation current doubles for every 10 °C rise in temperature*

$$I_{02} = I_{01}\left(2^{\left(\frac{\Delta T}{10}\right)}\right);$$ Where, I_{01} = Reverse saturation current at temp $T_1\ ^0C$

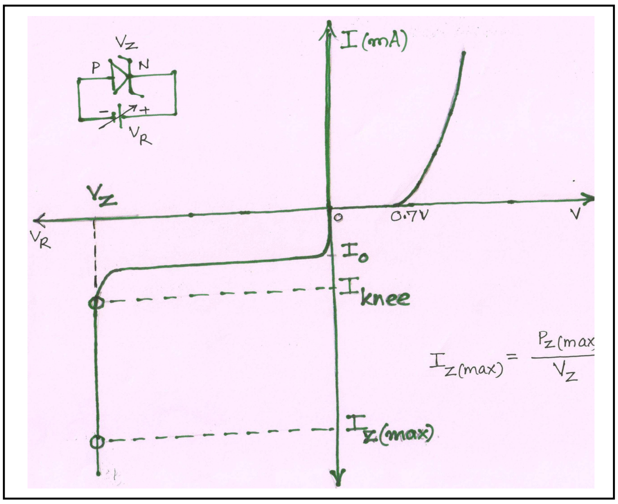
I_{02} = Reverse saturation current at temp $T_2\ ^0C$, $\Delta T = (T_2 - T_1)\ ^oC$

6. Explain breakdown mechanisms that occur in a p-n junction diode.

Refer to class notes …

Points to be covered:

Breakdown:



- Some diodes are specially manufactured to breakdown when they are operated in reverse bias.
- When the applied reverse bias voltage exceeds the specified voltage, called breakdown voltage, the diode enters into breakdown mode.
- The figure shows typical V-I characteristic curves of a breakdown diode.

- In the breakdown mode, the voltage across the diode remains constant even if, the reverse current in the diode varies over fairly wide range.
- The manufacture specifies the following details:
  - (i) Breakdown voltage of the diode (V_z)
  - (ii) Maximum power that the diode can dissipate ($P_{z(\max)}$), and
  - (iii) The minimum current to be maintained through the diode (I_{knee})

Breakdown mechanisms: **(i)** Zener mechanism, (ii) Avalanche mechanism

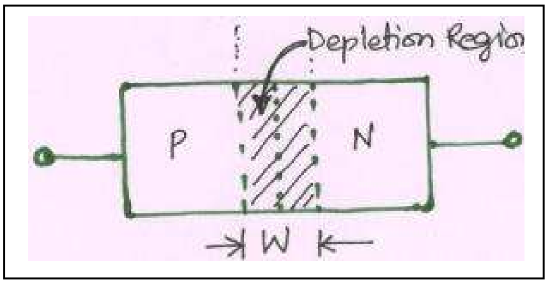
- Elaborate on Zener mechanism
- Elaborate on avalanche mechanism
- Draw neat diagrams showing the Zener and avalanche breakdown voltages
- Mention application:
  - Used in voltage regulators.
  - Draw the circuit schematic of Zener voltage regulator

7. How many types of capacitances are associated with pn-junction? Explain which type of capacitance is important for forward and reverse bias modes of operation.

Refer to class notes…

Important Points…

Capacitance in P-N junction diode:



- The P and N regions are essentially low resistance areas due to high concentration of majority carriers.
- The depletion region, which is depleted of charge carriers, serves as an effective insulation.
- Hence, a diode has a very high resistance depletion region (Insulator) sandwiched between low resistive P and N regions
- The P and N regions acts as plates of capacitor , while the depletion region acts as the insulating dielectric
- Thus a P-N junction diode can be compared to a charged capacitor and the capacitances associated with the P-N junction are : *(i) Transition capacitance, (ii) Diffusion capacitance*

Transition Capacitance (C_T) :

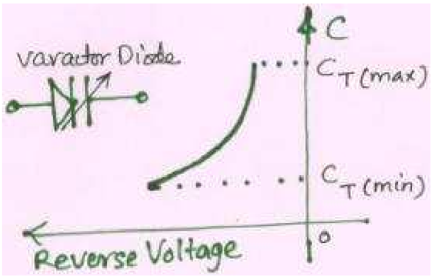
- This is the capacitance of a reverse biased diode.
- It is also known as Space-charge capacitance or junction capacitance

- C_T is given by $C_T = \frac{\varepsilon A}{W}$

  Where ε = the permittivity of semiconductor material

  A = Cross-sectional area of junction

  W = width of depletion region
- The C_T can be controlled by varying the width of depletion region (W). The W can be varied with the applied reverse bias voltage.
- As the reverse bias voltage increases, the W increases and hence C_T decreases and vice-versa.



Varactor Diodes or Vari-caps:

- The Si diodes designed for getting variable capacitance effects under reverse bias are called Varactor diodes. They are also called voltage variable capacitance diodes.
- The typical variation in capacitance that can be obtained is 2-12 μF and 20-28 μF .

Diffusion Capacitance (C_D) :

- This is the capacitance of a forward biased diode.
- During forward bias, the barrier width of the diode decreases.
- C_D is given by $C_D = \frac{\tau I}{\eta V_T}$

  Where τ = mean life time the charge carrier

  I = forward current through the diode (Amp)

  $$\eta = \begin{cases} 1\,; \text{ for Ge} \\ 2; \text{ for Si} \end{cases}$$

  V_T = Volt equivalent of temperature (Volts) = $\frac{T}{11,600}$ Volts, T in Kelvin

  At room temperature (27 ^0C = 300 K), V_T = 300/11,600= 0.025862 V ≈ 26mV
- C_D of a forward biased diode $\propto$ Diode forward current (I)
- C_D ranges from 10 to 1000 pF
- C_D of a forward biased diode>> C_T of a reverse biased diode

8. Explain the phenomenon of Hall Effect. Mention its applications.

Refer to class notes

Hints:

Hall effect: statement

When a current carrying conductor is placed in a transverse magnetic field ($\vec{\mathbf{B}}$) , an electric filed ($\vec{E}$) is induced perpendicular to $\vec{I}$ and $\vec{\mathbf{B}}$

Derivation for Hall coefficient: *Refer to class notes….*

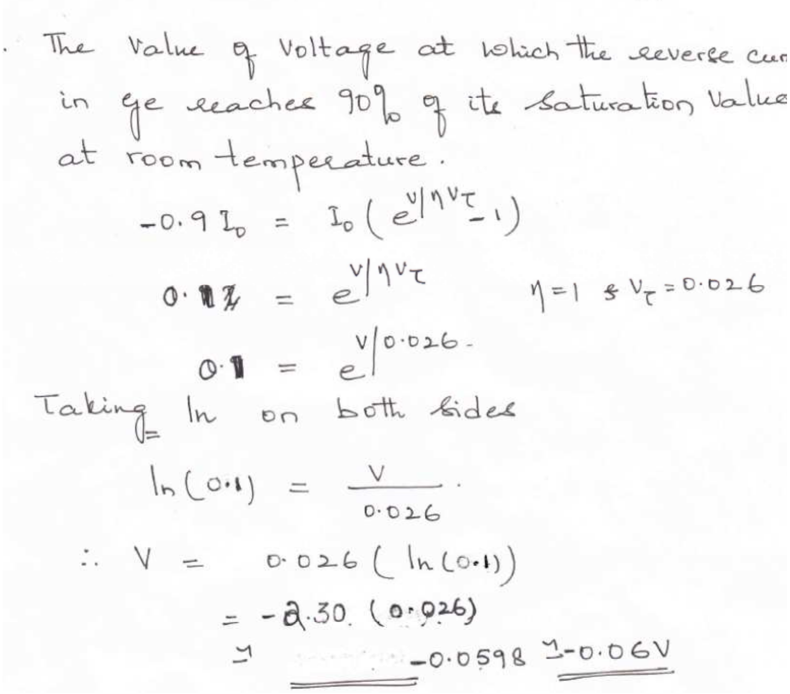
$$R_H = \frac{V_H\, W}{B\, I}$$

Applications of Hall effect: *Hall efect finds very useful applications in electronics*

- Identification semiconductor as P-type or N-type
- Measurement of carrier concentrations in a semiconductor
- Measurement of mobility of electrons and holes in a semiconductor
- Magnetic field meter
- Hall effect Multiplier

Refer to class notes for details on above listed applications

9. For what value of voltage will the reverse current (I_o) in a p-n junction Ge diode reach 90% of its saturation value at room temperature?



The value of Voltage at which the reverse cur
in Ge reaches 90% of its saturation value
at room temperature.

$$-0.9\, I_o = I_o\left(e^{V/\eta V_T} - 1\right)$$

$$0.1 = e^{V/\eta V_T} \qquad \eta = 1 \;\&\; V_T = 0.026$$

$$0.1 = e^{V/0.026}$$

Taking ln on both sides

$$\ln(0.1) = \frac{V}{0.026}$$

$$\therefore\ V = 0.026\left(\ln(0.1)\right)$$

$$= -2.30\,(0.026)$$

$$\simeq \underline{\underline{-0.0598}} \simeq \underline{\underline{-0.06\,V}}$$

10. A Si diode operates at a forward voltage of 0.6V. Calculate the factor by which the current will be multiplied when the temperature changes from 25^oC to 150^oC.

Factor by which the current gets multiplied in a Si diode when temp. changes from 25°C to 150°C. [i.e I_{25} / I_{150}]
(298°K) (423°K)

$V_f = 0.4$ V. $I = I_o(e^{V/\eta V_T} - 1)$

when temperature changes, I_o changes & V_T changes.

$$I_{o(150)} = I_{o(25)}\left(2^{\frac{(T_2-T_1)}{10}}\right)$$

$$= I_{o(25)}\left(2^{12.5}\right)$$

$$= 5792.6\,(I_{o25})$$

$$V_T \text{ at } 423^\circ k = \frac{T}{11{,}600} = \frac{423}{11600} = 0.0365\text{V}$$

$$V_T \text{ at } 298^\circ k = \frac{T}{11{,}600} = \frac{298}{11600} = \cancel{0.0259\text{V}}$$
$$= 0.0257\text{V}$$

$$\frac{I_{25}}{I_{150}} = \frac{I_{o(25)}\left(e^{V/\eta V_T} - 1\right)}{I_{o(150)}\left(e^{V/\eta V_T} - 1\right)}$$

$$= \frac{\cancel{I_{o(25)}}\left(e^{0.4/2(0.0257)} - 1\right)}{5792.6\,(\cancel{I_{o25}})\left(e^{0.4/2(0.0365)} - 1\right)}$$

$$= \frac{2396.3}{(5792.6)(238.7)} = 1.73\times10^{-3}$$