IMPORTANT FORMULAS TO REMEMBER

1. Types of materials:

a. Insulators

• At room temperature, an insulator does not conduct. However, it may conduct if its temperature is very high or if a high voltage is applied across it. This phenomenon is termed the **breakdown of the insulator.**

• **Example:** diamond.

b. Semiconductors

• At 0°K, semiconductor materials have the same structure as insulators except for the difference in the size of the bandgap E_G, which is much smaller in semiconductors ($E_G \simeq 1$ eV) than in insulators.

• **Example:** Ge and Si.

c. Metals

• Without supplying any additional energy such as heat or light, a metal already contains many free electrons, which is why it works as a good conductor.

• **Example:** Al. Cu etc.

2. Thermal Voltage V_T OR V_{TH}

"Volt-equivalent of temperature"

$$\boxed{V_T = \frac{\bar{k}T}{q}}$$

or $\boxed{V_T = \frac{T}{11600} \text{ volts}}$

where T = Temperature in kelvin

$\boxed{V_T \simeq 26 \text{ mV}}$

1.For silicon, $E_G(T) = 1.21 - 3.60 \times 10^{-4}\, T$

and at room temperature (300°K), $E_G = 1.1$ eV

2.Similarly, for germanium, $E_G(T) = 0.785 - 2.23 \times 10^{-4}\, T$

and at room temperature, $E_G = 0.72$ eV

• Free electrons and holes are always get generated in pairs. Therefore, the concentration of free electrons and holes will always be equal in an intrinsic semiconductor

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

Where η_i is called the intrinsic concentration.

4. Effect of Temperature on Conductivity of Intrinsic Semiconductor

$$n_i^2 = A_0 T^3 e^{-\left(\frac{E_{G0}}{kT}\right)}$$

Where E_{G0}: Energy gap at 0K in eVs

k: Boltzmann's constant in eV/K

A_0: Material constant independent of temperature

5. The Mass-Action Law

The law of mass action states that the product of the number of electrons in the conduction band and the number of holes in the valence band is constant at a fixed temperature and is independent of the amount of donor and acceptor impurity added.

$$np = \eta_i^2$$

For a p-type semiconductor,

$$n_p = \frac{\eta_i^2}{p_p}$$

For an n-type semiconductor,

$$p_n = \frac{\eta_i^2}{n_n}$$

6. Transport Phenomena In Semiconductors:

6.1 Mobility:

$$V = \mu E$$

$$\Rightarrow V = \left(\frac{qt}{m}\right)E$$

$$\therefore \mu = \frac{qt}{m}$$

$$\mu = \frac{\text{drift velocity}}{\text{field intencity}}$$

$$\mu = \frac{V_d}{E} \rightarrow \text{unit } \frac{m^2}{V-s} \text{ or } \frac{cm^2}{V-s}$$

- In a semiconductor, mobility of charge carriers depends on:

i. Temperature

ii. Doping concentration

$\mu \, \alpha \, T^{-m} \leftarrow$ decrease as a non-linear variation.

Where m= material constant

6.2. Mobility versus E graph:

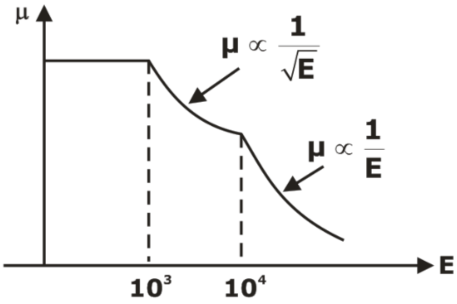


Figure: Mobility versus E graph

$\mu \propto T^{-m}$

Where, for Ge: m =1.66 for e and 2.33 for hole

for Si: m = 2.5 for e^- and 2.7 for hole

Table 2:

Parameter	Ge	Si	GaAs
Electron mobility (μ_n)	3800 cm^2/V-s	1300 cm^2/V-s	5800 cm^2/V-s
Hole mobility (μ_p)	1800 cm^2/V-s	500 cm^2/V-s	400 cm^2/V-s
Ratio $\left(\frac{\mu_n}{\mu_p}\right)$	2.1: 1	2.6: 1	14.5: 1

- If μ_n/μ_p is greater then, the material will offer minimum switching time.
- In a semiconductor, the mobility of charge carriers depends on various types of SCATTERING such as:

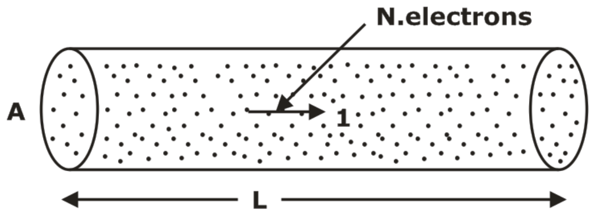
1. LATTICE scattering
2. IMPURITY scattering
3. SURFACE scattering

- Due to this, the resultant mobility of charge carriers is given by μ, and the mathematical formula is given by:

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

Taken one at a time, keeping others as constant.

7. Current Density



Therefore,

$I = \frac{Nq}{T} = \frac{Nqv}{L}$ $\left[\because \quad v = \frac{L}{T}\right]$

$\therefore$ Current density $= \frac{I}{A} = \frac{Nqv}{LA}$

$\Rightarrow J = qv\left(\frac{N}{LA}\right)$ [Unit of J = amp/m^2]

since, $\frac{N}{LA}$ = n(electron concentration in electrons per cubic meter).

$\therefore \boxed{J = nqv = \rho v}$

8. Conductivity

From the above discussion

$\boxed{J = nqv = nq\mu E = \sigma E}$

i. For semiconductors conductivity

$$\boxed{\sigma = nq\mu_n + pq\mu_p}$$

ii. For intrinsic semiconductor

$$\boxed{\sigma_i = \eta_i\left(\mu_n + \mu_p\right)q}$$

iii. For n-type semiconductor

n >> p

$\therefore \sigma_n \simeq n\, q\, \mu_n$

but, $n \simeq N_D$

so, $\boxed{\sigma_n \simeq N_D q \mu_n}$

iv. For p-type semiconductor

p >> n

$\sigma_p \simeq pq\, \mu_p$

but, $p \simeq N_A$

so, $\boxed{\sigma_p \simeq N_A q \mu_p}$

8.1 Conductivity Vs Temperature

- As we know that in metals, the resistivity of metal increases with an increase in temperature. So, the conductivity of metals decreases with an increase in temperature.
- In pure semiconductors, conductivity mainly depends upon the number of charge carriers. So, in a semiconductor, conductivity increases with temperature.
- For a 1°C increase in temperature, the conductivity of Ge increases by 6%, while in Si, it increases by 8%.
- The conductivity of extrinsic semiconductors decreases above normal temperature with temperature.

9. Diffusion and Drift of Carriers

$$J_n(x) = q\mu_n n(x)\,E(x) + q\,D_n \frac{dn(x)}{dx}$$

Drift Diffusion

$$J_p(x) = q\mu_p p(x)\,E(x) - qD_p \frac{dp(x)}{dx}$$

The total current density is the sum of the contributions due to electrons holes

$$J(x) = J_n(x) + J_p(x)$$

10. Length of Diffusion

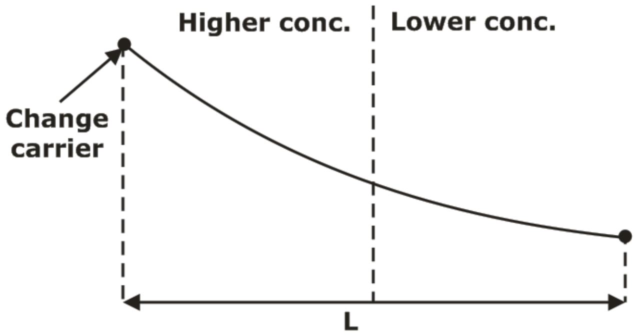


Figure 22

Length of diffusion is given as below,

$$L = \sqrt{D\,\tau}\ \text{cm}$$

D = Diffusion constant for charge carrier (cm^2/s)

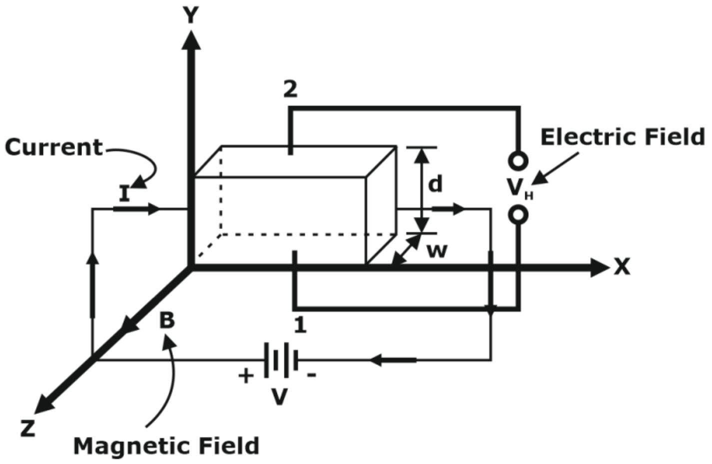
τ = Carrier life-time or mean life time of minority carriers (s).

11. Einstein Relationship:

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

where V_T is the "volt-equivalent of temperature."

12. The Hall Effect:



$$\boxed{qE = Bvq}$$

$$E = \frac{V_H}{d} \text{ and } J = v\rho = \frac{I}{wd}$$

Combining these relationships, we find

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

It is customary to introduce the **Hall coefficient** R_H defined by

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

$$\boxed{R_H = \frac{V_H w}{BI}}$$

⇒ Hall coefficient, $R_H \propto$ Temperature coefficient of resistance of given specimen.

⇒ For metals, σ is larger, V_H is small.

⇒For semiconductors, σ is small, V_H is large.

Applications:

Hall effect is used in many applications as following:

- measurement of magnetic flux density.
- measurement of displacement.
- measurement of current.
- measurement of power in Electro-magnetic waves.
- determination of mobility of semiconductor material.

13. COMPENSATED SEMICONDUCTOR

13.1 N-type compensated semiconductor:

Let $N_D > N_A$

By the law of electrical neutrality:

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

So, $p_n = \frac{n_i^2}{n_n}$ (minority carrier concentration in N-type compensated semiconductor)

13.2 P-type compensated semiconductor:

Let, $N_A > N_D$

By the law of electrical neutrality:

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

14. Minimum Conductivity In Semiconductors

1. $n = n_i\sqrt{\frac{\mu_P}{\mu_n}}$

2. $p = n_i\sqrt{\frac{\mu_n}{\mu_P}}$

3. $\sigma_n = 2n_i q\sqrt{\mu_n \mu_P}$

14.1 Equation for donor concentration for N-type semiconductor when σ is MINIMUM:

$$N_D = n_i\sqrt{\frac{\mu_P}{\mu_n}} - n_i\sqrt{\frac{\mu_n}{\mu_P}}$$

$$N_D = n_i\left[\sqrt{\frac{\mu_P}{\mu_n}} - \sqrt{\frac{\mu_n}{\mu_P}}\right]$$

14.2 Equation for acceptor concentration for P-type semiconductor when σ is MINIMUM:

$$N_A = n_i\sqrt{\frac{\mu_n}{\mu_P}} - n_p\sqrt{\frac{\mu_P}{\mu_n}}$$

$$N_A = n_i\left[\sqrt{\frac{\mu_n}{\mu_P}} - \sqrt{\frac{\mu_P}{\mu_n}}\right]$$

15. The Fermi Level

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

- The function f(E), the Fermi-Dirac distribution function, gives the probability that an electron will occupy an available energy state of E at absolute temperature T. The quantity E_F is called the **Fermi level**.

- If $E = E_F$ then $f(E) = \frac{1}{2}$ = 0.5 or 50%

If $E > E_F$ then $f(E) < ½$

If $E > E_F$ then $f(E) > ½$

•

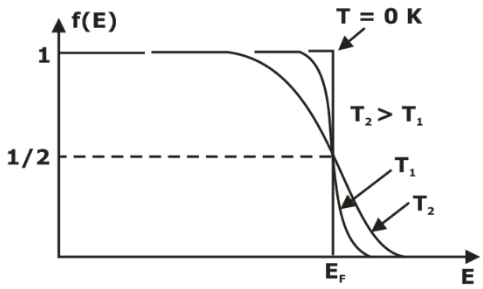


Figure: The Fermi Dirac distribution function

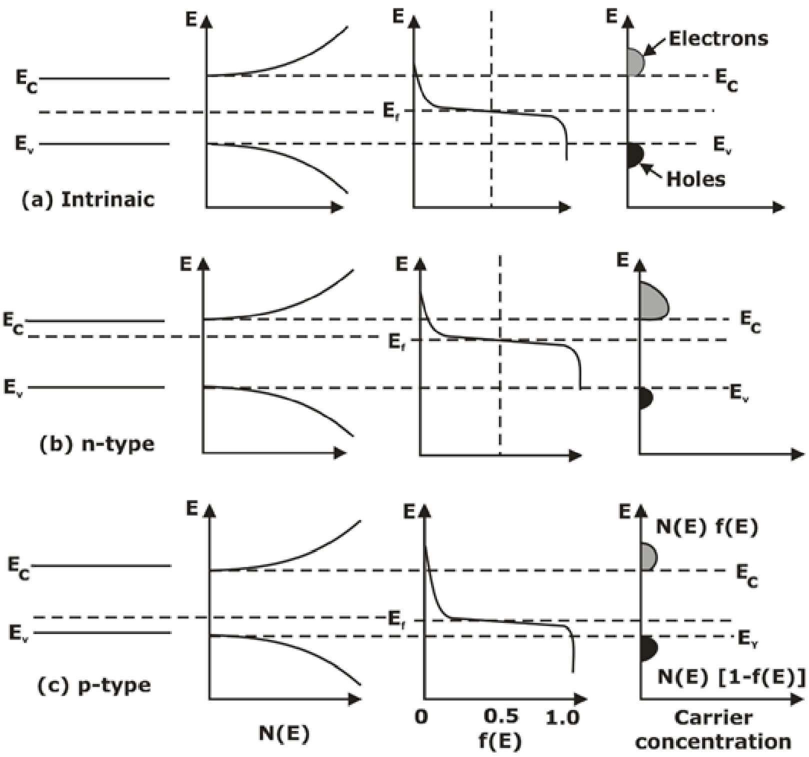


Figure: Schematic band diagram, the density of states, Fermi-Dirac distribution and the carrier concentrations for (a) Intrinsic, (b) n-type and (c) p-type semiconductors at thermal equilibrium

15.1 Fermi Level in Intrinsic Semiconductor

In an intrinsic semiconductor, Fermi level E_F is given by

$$E_F = \frac{E_c + E_v}{2} - \frac{1}{2} kT \ln\left(\frac{N_c}{N_v}\right)$$

Where N_C = density of states in the conduction band

N_V = density of states in the valence band

In pure Semiconductor at T = 0K, Fermi level lies in the middle of the bandgap.

15.2 Fermi Level in the n-type semiconductor

Fermi level in an n-type semiconductor is given by

$$E_F = E_c - kT \ln\left(\frac{N_c}{N_D}\right)$$

Where N_D = doping concentration.

- Fermi level in n-type semiconductors depends on temperature as well as on doping concentration.
- At 0K, the Fermi level coincides with that of the lowest energy level of the conduction band.
- As doping increases, the Fermi level moves towards the conduction band.
- A shift in Fermi level in an n-type semiconductor with respect to the Fermi level of an intrinsic semiconductor is

$$\text{shift} = kT \ln\left(\frac{n}{n_i}\right)$$

$$\text{shift} \cong kT \ln\left(\frac{N_D}{n_i}\right)$$

15.3 Fermi Level in the p-type semiconductor

Fermi level in the p-type semiconductor is given by

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

- In a p-type semiconductor, the Fermi level depends on both temperature and doping concentration N_A.
- As temperature increases, the Fermi level moves away from E_V, i.e. towards the middle of the bandgap.
- As 0K Fermi level coincides with the highest energy level E_V of the valence band.
- As doping concentration increases, Fermi level moves toward E_V or away from the middle of the bandgap
- Shift in Fermi level in a p-type semiconductor with respect to Fermi level of intrinsic semiconductor as

$$\text{shift} = kT \ln\left(\frac{p}{n_i}\right)$$

$$\text{shift} \cong kT \ln\left(\frac{N_A}{n_i}\right)$$

16. Optical Absorption

• A photon with energy less than E_g cannot excite an electron from the valence band to the conduction band. Thus, in a pure semiconductor, there is negligible absorption of photons with $h\nu < E_g$.

• If a beam of photons with $h\nu > E_g$ falls on a semiconductor, there will be some predictable amount of absorption, determined by the properties of the material

16.1 The intensity of light transmitted through the sample thickness *l* is

$$I(x) = I_0 e^{-\alpha x}$$

$$I_t = I_0 e^{-\alpha l}$$

• The coefficient α is called the **absorption coefficient** and has units of cm^{-1}. This coefficient will, of course, vary with the photon wavelength and with the material.

17. Continuity Equations

$$\frac{\partial n}{\partial t} = \frac{1}{q}\Delta \bullet J_N + \frac{\partial n}{\partial t}\bigg|_{\substack{Therman \\ R-G}} + \frac{\partial n}{\partial t}\bigg|_{\substack{Other \\ processes}}$$

$$\frac{\partial p}{\partial t} = -\frac{1}{q}\Delta \bullet J_p + \frac{\partial p}{\partial t}\bigg|_{\substack{Therman \\ R-G}} + \frac{\partial p}{\partial t}\bigg|_{\substack{Other \\ processes}}$$

Also

$$\frac{dp}{dt} = \frac{p - p_o}{\tau_h} + D_h \frac{\partial^2 p}{\partial x^2} - \mu_h \frac{\partial (pE)}{\partial x}$$

$$\frac{dn}{dt} = -\frac{n - n_o}{\tau_e} + D_n \frac{\partial^2 n}{\partial x^2} - \mu_h \frac{\partial (nE)}{\partial x}$$

CHAPTER-2-PN JUNCTION

1. Equation for contact potential:

Let the PN junction is kept either open-circuit condition or unbiased condition.

Mathematically,

1.1. Contact potential :

$V_0 = V_{bi}$

$$V_0 = V_{bi} = V_T \ln\left(\frac{N_A N_D}{n_i^2}\right) \leftarrow \text{Unit in Volts}$$

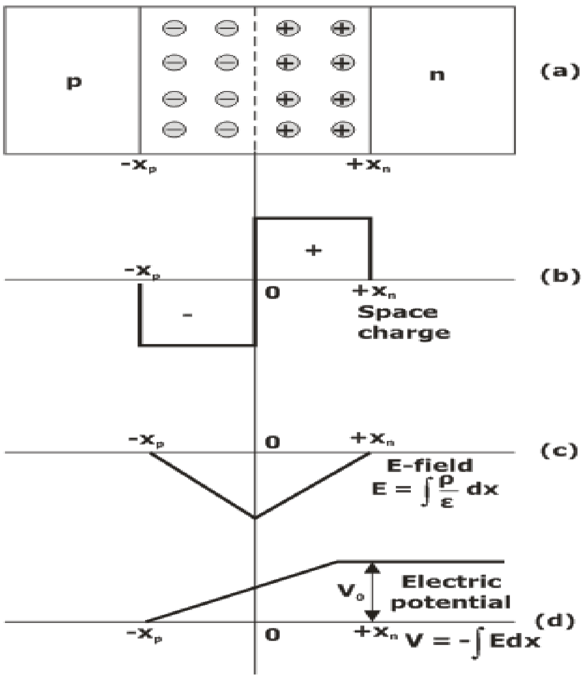
Also with temperature

$$\downarrow V_0 = V_{T\uparrow} \ln\left(\frac{N_A N_D}{n_i^2 \uparrow}\right)$$

NOTE:

- Contact Potential, V_0 is a function of temperature.
- Contact Potential, V_0 decreases with the temperature.
- For 1^0C rise in temperature, V_0 decreases by 2.5 mV.

1.2. Electric Field:



$\rho(x) = -qN_A$; $\quad -x_p < x < 0$

$\rho(x) = qN_D$; $\quad 0 < x < x_n$

Maximum electric field will be at x = 0, we have

$$E_{max} = \frac{-qN_A}{\epsilon} x_p = \frac{-qN_D}{\epsilon} x_n$$

1.3.1 Equation for width of depletion layer W:

$N_A x_p = N_D x_n$

$$x_p = \sqrt{\frac{2\in}{q}\left(\frac{N_D}{N_A}\right)\left(\frac{1}{N_A+N_D}\right)V_0}$$

$$x_n = \sqrt{\frac{2\in}{q}\left(\frac{N_A}{N_D}\right)\left(\frac{1}{N_A+N_D}\right)V_0}$$

$W = x_n + x_p$

Therefore, from the above equations, we get

$$W=\sqrt{\frac{2\varepsilon}{q}\left(\frac{1}{N_A}+\frac{1}{N_D}\right)V_0}$$ (Unit is metres)

Where,

ϵ = Permittivity in F/m

$\epsilon = \epsilon_0 \epsilon_r$

ϵ_0 = Absolute Permittivity of free space = 8.854×10^{-12} F/m = 8.854×10^{-14} F/cm

And,

ϵ_r = Relative permittivity of a medium

The dielectric constant of the material used

ϵ_r = 11.7 (Si)

NOTE:

- The maximum electric field in the junction

$E_{max} = -\frac{2V_0}{W}$, for the case of zero applied voltage

$E_{max} = \frac{-2(V_0 + V_R)}{W}$, for the case of applied reverse-biased voltage V_R

where W is the total width of the depletion region.

1.3.2 Reverse bias configuration:

$$W=\sqrt{\frac{2\in}{q}\left(\frac{1}{N_A}+\frac{1}{N_D}\right)(|V_0|+|V_{RB}|)}$$

$$W=\sqrt{\frac{2\in}{q}\left(\frac{1}{N_A}+\frac{1}{N_D}\right)V_i}$$

$V_i = |V_0| + |V_{RB}|$

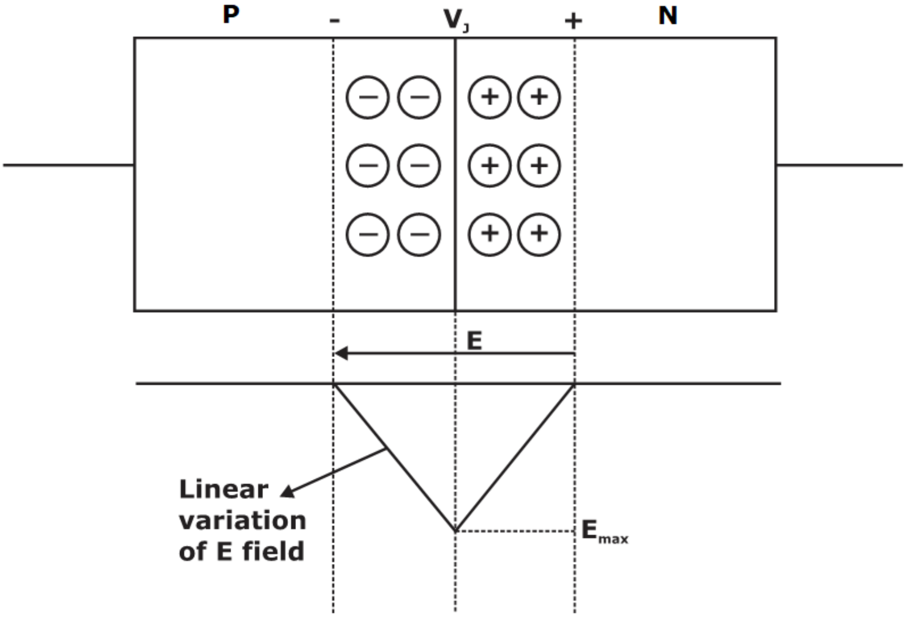


Figure 2

- Cut-in voltage decreases with a rise in temperature. For 1°C rise in temperature, the cut-in voltage decreases by 2.5 mV, i.e. $\frac{dV\gamma}{dT} = -2.5\ \text{mV}/^{\circ}\text{C}$.
- I_0 approximately increases by 7% for every 1°C increase in temperature.
- I_0 doubles for every 10°C rise in temperature.

$$I_{0(T_2)} = I_{0(T_1)} (2)^{\frac{T_2 - T_1}{10}}$$

CHAPTER-3-PN JUNCTION DIODE

1. Forward bias configuration:

$$I_f = \left\{ \frac{AqD_pP_{n0}}{L_P} + \frac{AqD_nn_{p0}}{L_n} \right\} \left\{ e^{\frac{V_D}{n_{V_T}}} - 1 \right\}$$

Also,

$$p_{n0} = \frac{n_i^2}{N_D}$$

$$n_{p0} = \frac{n_i^2}{N_A}$$

$$I_f = \left(\frac{AqD_p}{L_pN_D} + \frac{AqD_n}{N_AL_n} \right) n_i^2 \left(e^{V_D/n_{VT}} - 1 \right)$$

$\frac{AqD_p}{L_pN_D}$ = If due to flow of holes from P side to N side

$\frac{AqD_n}{N_AL_n}$ = If due to flow of electrons from N side to the P side

Also,

$$L_p = \sqrt{D_p\tau_p}$$
$$L_n = \sqrt{D_n\tau_n}$$

Hence,

$$I_f = \left(\frac{Aq}{N_D}\sqrt{\frac{D_p}{\tau_p}} + \frac{Aq}{N_A}\sqrt{\frac{D_n}{\tau_n}} \right) n_i^2 \left(e^{V_D/\eta V_T} - 1 \right)$$

The reverse saturation current in the Forward bias diode is:

$$I_s = \left(\frac{AqD_pP_{n0}}{L_p} + \frac{AqD_nn_{p0}}{L_n} \right)$$

$$I_s = \left(\frac{AqD_p}{L_pN_D} + \frac{AqD_n}{L_nN_A} \right) n_i^2$$

$$I_s = \left(\frac{Aq}{N_D}\sqrt{\frac{D_p}{\tau_p}} + \frac{Aq}{N_A}\sqrt{\frac{D_n}{\tau_n}} \right) n_i^2$$

A = Cross-Sectional Area of Junction

2. Volt-Ampere Characteristics of a p-n Junction Diode

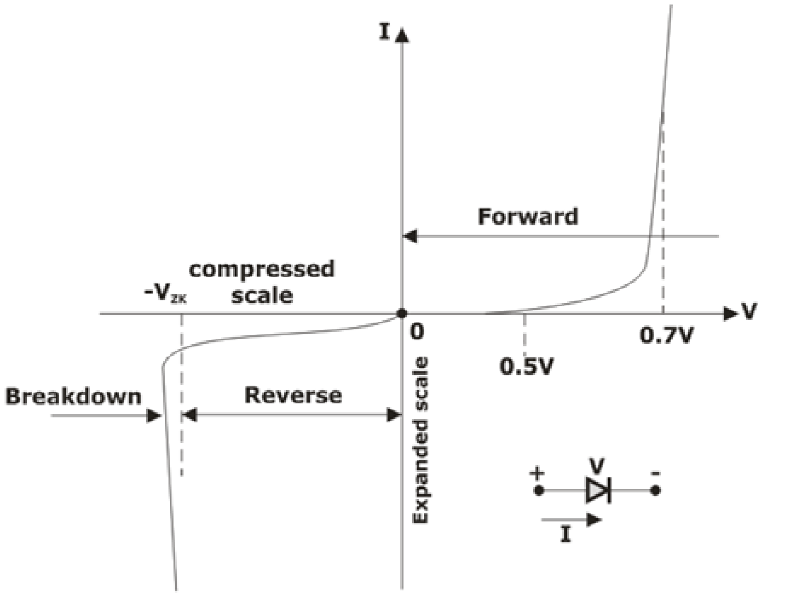
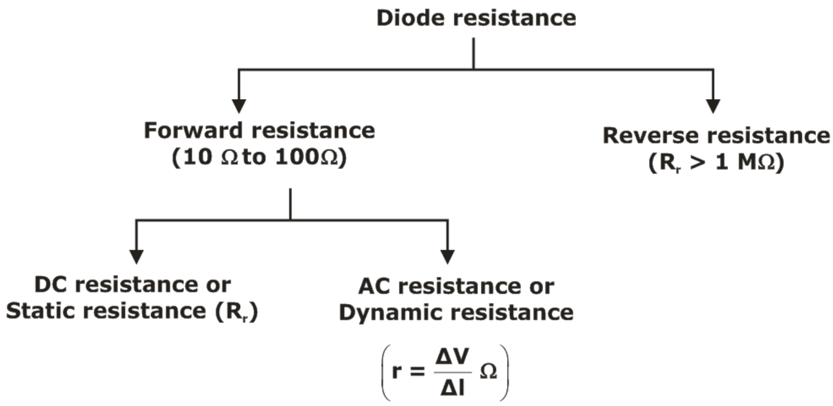


Figure 1: PN Junction Characteristics

3. Diode Resistance



$$r \simeq \frac{\eta V_T}{I}$$

4. Capacitive Effects in the p-n Junction

Transition or depletion layer capacitance:

$C_T = C_J = \frac{\in A}{W}$ = Unit is Farads.

A = Cross Sectional Area Of junction

W = Width of Depletion Region

$C_T \propto A$

$C_T \propto 1/W$

For better performance of diode or BJT, the value of C_T must be as small as possible.

In a reverse-biased PN junction, the transition capacitance, C_T

$C_T \propto V^{-n}$

n = grading coefficient

n = 1/2; for Step graded diode (abrupt PN Junction diode)

= 1/3; for Linear graded diode

5. Diffusion Capacitance

$$C_D = \frac{\tau I}{\eta V_T}$$

Where η is a constant dependent upon semiconductor, V_T is volt equivalent temperature, and τ is the mean lifetime of minority carriers.

NOTE

- For a reverse bias junction, C_D may be neglected compared with C_T (transition capacitance).
- For a forward bias junction, the C_D is usually much larger than C_T
- Diffusion capacitance C_D is proportional to the current I.

6. ZENER DIODES

- Basically, a p-n junction with little increase in doping level ($1:10^5$) aria is fabricated only with Si.
- Generally designed with normal junction and popularly known as constant voltage device.
- It can be used as a reference voltage device.
- Major application is as a voltage regulator circuit and can be used as a clipper.
- Always operated under reverse bias.
- When forward bias, it will be working as a normal diode with cut-in voltage 0.6 V or 0.7 V.
- Zener diode is specified in terms of breakdown voltage and maximum power dissipation.
- Zener diodes are commercially available with breakdown voltages in the range of 2.5 V – 300 V.

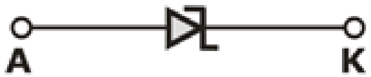


Figure 2: Circuit symbol of Zener diode

6.1Resistance of Zener Diode

$$R_Z = \frac{\Delta V_Z}{\Delta I_Z}\ \Omega$$

For the ideal Zener diode, dynamic resistance is zero.

6.2 Equivalent Circuit of Zener Diode

Case-I: When Zener diode is in forward bias

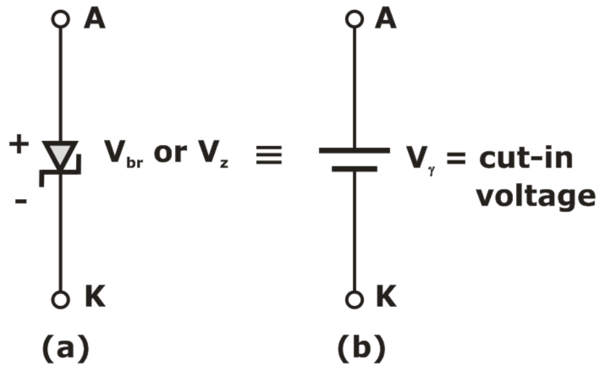


Figure3 : (a) Zener diode in forward bias and (b) Equivalent circuit

Forward bias Zener diode can be replaced by a cut-in voltage

Case-II: When Zener diode is in reverse bias

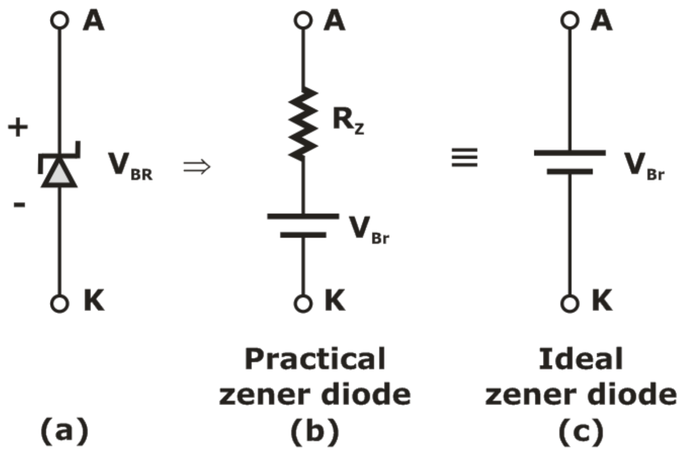


Figure 4 : (a) Zener diode in reverse bias (b) & (c) Equivalent circuit

CHAPTER-4-SPECIAL DIODES

1. **Tunnel Diode**

A tunnel diode is a high conductivity two terminal p-n junction diode doped heavily about 1000 times higher than a conventional junction diode.

1.1Current-Voltage characteristic

Figure 1 shows the current-voltage characteristic of a tunnel diode. If the tunnel diode is reversed biased, then it acts like a good conductor, i.e. the reverse current increases with increasing reverse voltage.

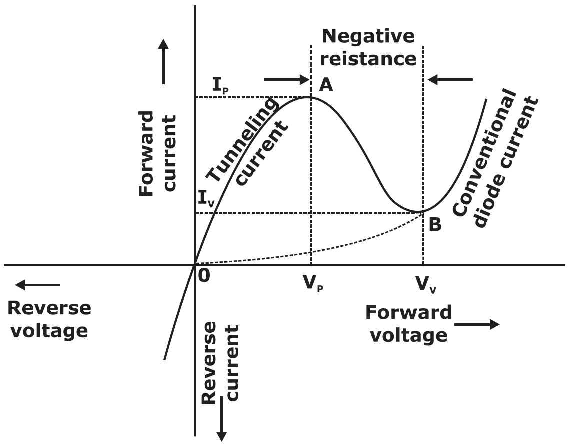


Figure 1: Current-Voltage characteristic of Tunnel Diode

2. PIN Diode

The PIN diode has a fast response time at high frequencies.

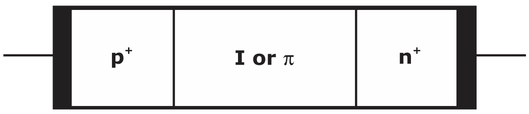


Figure2: Schematic Construction of PIN Diode

2.1. Characteristic of PIN Diode

Some important characteristics of PIN diodes are:

i. When a PIN diode is forward biased, it offers a variable resistance.

ii. When a PIN diode is reversed biased, it offers infinite resistance in the reverse direction.

iii. PIN diode has highly improved switching time in comparison with a PN diode.

2.2. Applications of Pin diodes

Some important applications of PIN diodes are:

i. PIN diodes can be used in the construction of phase modulators and amplitude modulators.

ii. It can be used as an alternator.

iii. It is used as a constant impedance device.

iv. It can be used as a phase shifter.

v. It can be used as a T-R switch in radar applications.

3. Varactor Diode:

A varactor diode is a specially manufactured pn junction with a suitable impurity concentration profile and operated under reverse-biased conditions to yield a variable junction capacitance. The expression approximates the transition capacitance of a varactor diode,

$$C_T = \frac{C_T(0)}{[1+(V/V_k)]^n}$$

where,

V_k is the volt equivalent temperature;

V is the reverse bias applied in volts;

n = 1/2 for alloyed junctions;

n = 1/3 for diffused junctions

3.1 Applications of Varactor Diode

Following are some important applications of varactor diode:

i. Used in a parametric amplifier.

ii. Varactor diode is used in automatic frequency control.

iii. It is used in tuning circuits.

iv. Used in adjustable bandpass filter.

4. Schottky Diode

Schottky diode is an extension of a point-contact diode. It is also known as a hot-carrier diode, a hot electron diode or epitaxial Schottky barrier (ESBAR) diode. It is mainly used as a rectifier at signal frequencies exceeding 300 MHz.

4.1 Current-Voltage Characteristic of Schottky Diode

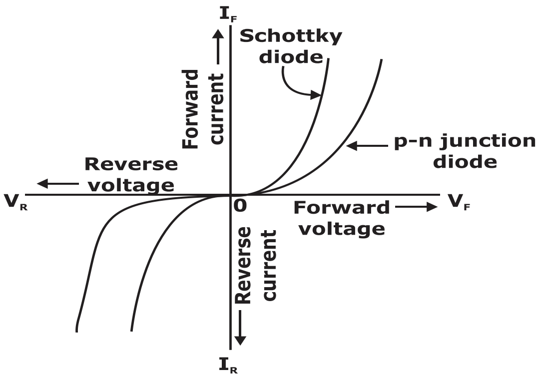


Figure 5: illustrates the current-voltage characteristic of the Schottky diode.

4.2 Advantages of SCHOTTKY Diode

Following are the advantages of varactor diode over an ordinary p-n junction diode:

i. It is a unipolar device because there are no minority carriers in the reverse direction (i.e., no significant current from metal to semiconductor when the diode is reverse-biased). Hence, the delay due to the hole-electron recombination present in junction diodes is absent in varactor diodes.

ii. The junction contact area between semiconductor and metal is larger than in point contact diode, and hence the forward resistance is lower (i.e., noise is comparatively lower).

iii. Since no holes are available in metal, and there is no depletion layer or stored charges to worry about. So, the Schottky diode can switch OFF faster than a bipolar diode.

(NOTE: An ordinary junction diode is a bipolar device because it has electrons and holes as majority carriers.**)**

5. Light-Emitting Diode (LED)

• LED will emit the light when properly forward biased.

• PRINCIPLE: ELECTRO-LUMINESCENCE (conversion of electrical energy into light energy).

• In LED, light is emitted due to a large number of recombination in the depletion region.

• LED, i.e. generally fabricated with Direct bandgap semiconductors(DBGSC).

• A popularly used material is GaAs.

• LED can emit the light either in the VISIBLE SPECTRUM or INVISIBLE SPECTRUM OF LIGHT, depending on DOPENTS.

• In the invisible spectrum of light, LED emits INFRARED LIGHT.

• IR LED is widely used as a remote-control transmitter.

• The colour of light given by LED depends on

i. Wavelength and frequency of emitted light.

ii. Type and concentration of dopants.

• LED fabricated with GaAs emits infrared light.

• LED materials are

i. GaAs

ii. GaAsP

iii. GaP←Highly unstable material (unreliable, unpredictable). Belongs to indirect bandgap semiconductors(IBGSC). Also, since the material is unstable but then also under controlled doping, it is made to work as LED. Material is forced to emit light; under controlled doping.

• Modern LED's are fabricated with some of the DBGSC and also some of the IBGSC under "controlled doping".

• Always operated under forward bias.

• When Reverse Biased, the LED will be working as a normal diode & it cannot emit any light.

• The function of limiting resistance in the LED

i. To limit the forward current.

ii. To limit the light output.

• The efficiency of LED

$$\eta \propto I_f$$

$$\eta \propto \frac{1}{\text{Temp}}$$

$$\eta \propto \frac{1}{\text{Junction Temp}}$$

• Cut in voltage, $V_\gamma = 1.3\,V \text{ to } 1.5\,V$ depending on dopant.

• Power dissipation in mW.

- When compared to LCD, the disadvantage of LED is higher power dissipation.
- LED has longer operating life.
- LED is relatively faster in operation when compared to LCD because of the smaller response time (in μs).

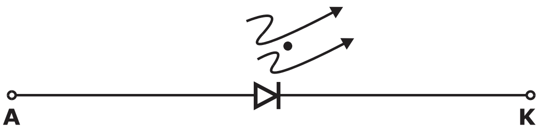


Figure 6: Symbol of LED

5.1 Applications:

i. As Remote-Control Transmitter.

ii. As a display device.

iii. In designing of Opto Couplers.

NOTE

i. GaAs → IR LIGHT

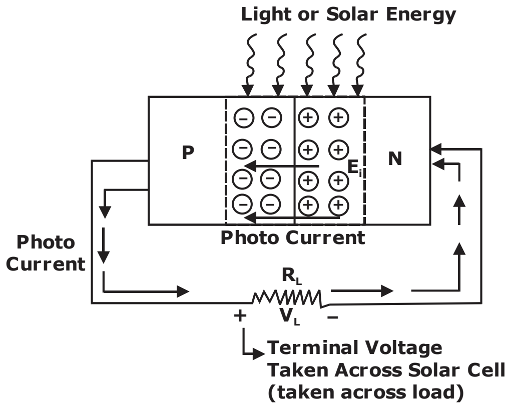
ii. GaAsP → (YELLOW/ORANGE} depending on doping concentration.

iii. GaP → (GREEN/RED)

$$\lambda_C = \frac{1.24}{E_g} \mu m$$

6. Solar Cell:

- When light falls on the space charge Region, electrons and holes are generated. They are quickly separated and swept out of the Depletion layer by the Electric field so that a photocurrent is generated.
- This generated Photocurrent will produce a voltage drop across the load, indicating that the solar cell has delivered the power to the load.



Important point

- Photocurrent is a drift current
- The solar cell is generally fabricated with Si (most popular) or GaAs or the 3^{RD} & 2^{ND} group compound semiconductors.
- The terminal voltage of the solar cell is very small and is in the range of 0.1V to 0.5V.
- The maximum terminal voltage of the solar cell is 0.5V.

- Solar cells are widely used in satellites
- The open-circuit voltage of Solar cells is

$$V_{OC} = V_T \ln\left(1 + \frac{I_L}{I_S}\right)$$

$$V_{OC} = V_T \ln\left(1 + \frac{J_L}{J_S}\right)$$

Where,

I_L = Solar current

J_L = Solar Intensity (light intensity)

I_S = Reverse Saturation current

J_s = reverse saturation current density.

$$V_{OC} = V_T \ln\left(1 + \frac{I_L}{I_S}\right) = V_T \ln\left(1 + \frac{J_L}{J_S}\right)$$

Also,

$$I_S = \left(\frac{AqD_P}{L_P N_D} + \frac{AqD_n}{L_n N_A}\right) n_i^2 \text{ Amp}$$

$$J_S = \left(\frac{qD_P}{L_P N_D} + \frac{qD_n}{L_n N_A}\right) n_i^2 = \frac{I_S}{A} \leftarrow \text{Ampere / cm}^3$$

$$\boxed{\text{Fill Factor} = \frac{\text{Max Power obtained} (\rho_{max})}{V_{OC} . I_{SC}}}$$

Where,

V_{OC} = Open circuit voltage of a solar cell

I_{SC} = short circuit current of a solar cell.

$$\boxed{\text{Efficiency} (\eta) = \frac{\text{Max obtained Power} (\rho_{max})}{G.A}}$$

Where,

G = Input light in watts/m^2

A = surface Area in m^2

$$\textit{Quantum efficiency}(\eta) = \frac{\frac{I_P}{q}}{\frac{P_o}{f}}$$

Where

I_p=Photocurrent

P_o=incident power

f and q have usual meanings

$$\text{Re}\,sponsivity(R) = \frac{\eta q}{hf}$$

Where h=planks constant