Semiconductor Physics

Kumkum Sanyal

Applied Physics Section
Thadomal Shahani Engineering College.
Bandra West, Mumbai - 400050

kasanyanl@gmail.com

April 23, 2021

Unit 03: SEMICONDUCTOR PHYSICS

Prerequisites

(Intrinsic and extrinsic semiconductors, Energy bands in conductors, semiconductors and insulators, Semiconductor diode, I-V characteristics in forward and reverse bias)

Contents:

- Direct and indirect band gap semiconductor
- Fermi-Dirac distribution, Fermi Energy and Fermi level
- Fermi level in intrinsic and extrinsic semiconductors
- Effect of impurity concentration and temperature on Fermi level
- Fermi level diagram for p-n junction (unbiased, forward bias, reverse bias)
- Mobility, Current density, Hall Effect
- Applications of semiconductors: LED, Zener diode, Photovoltaic cell.

Formation of Band

- The electrons of a single isolated atom occupy atomic orbitals, which form a discrete set of energy levels.
- When two atoms are brought together to form a molecule, their valence electron wave-functions overlap.
- This overlapping gives rise to splitting of a single energy state into two different energy states.
- The number of new energy levels equals the number of interacting atoms.
- Thus the large number of atoms present in a solid (e.g. $\sim 10^{23}$per cc. in Cu) produces large number of closely spaced splitted energy levels.
- The levels are so close that they form a virtually continuous spread of permitted energies.
- This spread of energies is known as Bands.

Conduction band and Valence band

- Thus what was discreet $1s$ energy state for an isolated atom will now become $1s$ band in the solid.
- The width of a band depends on the location of the electron inside the atom, e.g. the width is more for outer-shell valence electrons than the inner-shell core electrons.
- The electrons in the solid fill up the bands one after the other in the ascending order of energy.
- The fully occupied highest energy band at absolute zero temperature is called Valence Band.
- The band next to it which can be completely empty or partially filled up is known as Conduction Band.

Concept of Band-Gap

- An electron in a solid can only have energies that fall within its energy bands.
- The two energy bands namely the conduction band and the valence band in some solid may overlap (case of a conductor).
- A continuous distribution of permitted energies is therefore available to the valence electrons.
- In case of a semiconductor or an insulator there is an interval between the conduction and valence bands representing energies the electrons cannot possess.
- A forbidden band thus separates the conduction and the valence bands.
- The energy gap between the bands depends on the internuclear separation, e.g. gap is more in C than in Si.
- The gap energy less than $3eV$ correspond to semiconductor whereas more value of gap energy correspond to insulator.

Fermi-Dirac Probability Function

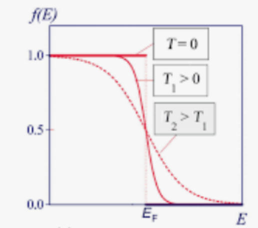
- Fermi-Dirac Probability Function $f(E)$ determines the statistical distribution of electrons among various available energy states.
- Assumptions: Electrons are indistinguishable and Pauli Exclusion Principle is valid.
- $f(E)$ gives the probability that a given quantum energy state E will be occupied by an electron at an absolute temperature TK.
- Another interpretation of $f(E)$ is that it is the ratio of filled to total quantum states at an energy E.
- Fermi-Dirac Probability Function

$$\boxed{f(E) = \frac{1}{1+e^{(E-E_f)/K_B T}}}$$

$E_f \rightarrow$ Fermi Energy, $K_B \rightarrow$Boltzman's constant

Concept of Fermi Energy

- Let $T = 0K$ and consider the cases (i) $E > E_f$ and (ii) $E < E_f$
- Case (i): $E > E_f \rightarrow 1$ can be neglected in comparison to exponential term $(e^{+\infty})$, $f(E) \approx \frac{1}{e^{+\infty}} = 0$
- Case (ii): $E < E_f \rightarrow$ Exponential term$(e^{-\infty})$ being very small can be neglected, $f(E) = 1$
- Let $T \neq 0K$ and $E = E_f \rightarrow f(E) = \frac{1}{2} = 0.5$



- All states above E_f are empty at $0K$.
- All states below E_f are filled up at $0K$.
- All states at E_f has 50% chance of being occupied at any non-zero temperature.
- As the temperature increases but $K_B T$ still smaller than E_f, electrons will leave state below E_f and occupy states above E_f.
- The graph is symmetrical around E_f and all of them pass through the $f(E) = 0.5$ point.

Fermi Energy & Fermi Level

- *Fermi Energy -* It is the highest energy that an electron can possess at absolute zero temperature.
- Fermi energy has a constant value for a specific material.
- The formula for Fermi energy is
$$E_f = (\frac{\hbar^2}{2m})(3\pi^2 n)^{2/3}$$
with $n \rightarrow$ free electron density, $m \rightarrow$ mass of electron and $\hbar = \frac{h}{2\pi}$, h being Planck's constant.
- The Fermi level is any energy level of an electron having the probability of being exactly half-filled at any non-zero temperature.
- The value of Fermi level at absolute zero is the Fermi energy.
- The position of the Fermi level in relation to the band energy levels is a crucial factor in determining electrical and thermal properties.

Effective Mass Approximation

- The movement of an electron in a crystal, in general, will be different from that of a free electron.
- In addition to the external applied force there will be internal forces in the crystal due to the periodic presence of positively charged ions and the negatively charged electrons.
- The parameter m^* *(effective mass)* is the mass that a particle seems to have when responding to external forces while taking into account the effect of internal forces; $F = m^* a$.
- Mathematically $m^* = \frac{\hbar^2}{(d^2E/dk^2)}$; $k = \frac{2\pi}{\lambda} \rightarrow$ the wave number.
- The parameter m^* thus relates quantum mechanical results to classical force equation.

Intrinsic Semiconductor

- An ideal intrinsic semiconductor is a pure semiconductor with no impurity atoms and no lattice defects.
- For an intrinsic semiconductor at $T = 0K$
  All energy states are filled up in the valence band,
  All energy states are empty in the conduction band.
- E_c is the bottom of the conduction band energy,
  E_v is the top of the valence band energy.
- As the temperature rises, electrons and holes are created in pairs by thermal energy.
- For intrinsic semiconductor at thermal equilibrium, concentration of electrons in conduction band (n_0) = concentration of holes in valence band (p_0).
- Fermi level must therefore be somewhere between E_c and E_v.

Electron Concentration in Conduction Band

- The thermal equilibrium concentration of electrons in the conduction band is
  $n_0 = \int_{E_c}^{+\infty} g_c(E) f(E)\, dE$
  $g_c(E) \rightarrow$ density of allowed quantum states (no. of states per unit energy interval) in the conduction band,
  $f(E) \rightarrow$ Fermi probability function.
- The density of states in the conduction band is given by
  $g_c(E) = \frac{4\pi(2m_n^*)^{3/2}}{h^3}\sqrt{E - E_c}$
  $m_n^* \rightarrow$ effective mass of electron.
- Here $E > E_c$ and if $(E_c - E_f) \gg K_B T$, then $(E - E_f) \gg K_B T$.
- Fermi probability function reduces to $f(E) \approx exp\, \frac{-[(E-E_f)]}{K_B T}$.

Electron Concentration contd.

- $n_0 = \int_{E_c}^{+\infty} \frac{4\pi(2m_n^*)^{3/2}}{h^3} \sqrt{E - E_c}\, exp[\frac{-(E-E_f)}{K_B T}]\, dE$
- Consider a variable $x = \frac{E-E_c}{K_B T}$
- $n_0 = \frac{4\pi(2m_n^* K_B T)^{3/2}}{h^3}\, exp[\frac{-(E_c-E_f)}{K_B T}]\, \int_0^{+\infty} x^{1/2}\, exp(-x)\, dx$
- $\int_0^{+\infty} x^{1/2}\, exp(-x)\, dx = \frac{1}{2}\sqrt{\pi}$
- $n_0 = 2(\frac{2\pi m_n^* K_B T}{h^2})^{3/2}\, exp[\frac{-(E_c-E_f)}{K_B T}]$
- $n_0 = N_c\, exp[\frac{-(E_c-E_f)}{K_B T}]$;
  $N_c = 2(\frac{2\pi m_n^* K_B T}{h^2})^{3/2} \rightarrow$ the effective density of states in the conduction band.
- If effective mass (m_n^*)=(m_0) rest mass of the electron, then at $T = 300K$ the value of $N_c = 2.5 \times 10^{19}\, cm^{-3}$ for most of the semiconductors.

Hole Concentration in Valence Band

- The thermal equilibrium concentration of holes in the valence band is
  $p_0 = \int_{-\infty}^{E_v} g_v(E)\,[1 - f(E)]\,dE$
  $g_v(E) \rightarrow$ density of allowed quantum states (no. of states per unit energy interval) in the valence band,
  $[1 - f(E)] \rightarrow$ Fermi probability function for holes.
- The density of states in the valence band is given by

  $g_v(E) = \frac{4\pi(2m_p^*)^{3/2}}{h^3}\sqrt{E_v - E}$
  $m_p^* \rightarrow$ effective mass of hole.
- Here $E < E_v$ and $(E_f - E_v) \gg K_B T$.
- Therefore $[1 - f(E)] \approx exp\,\frac{-[(E_f - E)]}{K_B T}$.

Hole Concentration contd.

- $p_0 = \int_{-\infty}^{E_v} \frac{4\pi(2m_p^*)^{3/2}}{h^3} \sqrt{E_v - E}\, exp\, [\frac{-(E_f - E)}{K_B T}]\, dE$
- $p_0 = 2(\frac{2\pi m_p^* K_B T}{h^2})^{3/2}\, exp\, [\frac{-(E_f - E_v)}{K_B T}]$
- $p_0 = N_v\, exp\, [\frac{-(E_f - E_v)}{K_B T}]$;
  $N_v = 2(\frac{2\pi m_p^* K_B T}{h^2})^{3/2}$ $\rightarrow$ the effective density of states in the valence band.
- The magnitude of N_v is also $\sim 10^{19}$ at $T = 300K$ for most of the semiconductors.
- Since $n_0 = p_0$ in an intrinsic semiconductor, they are referred to as *intrinsic carrier concentration n_i*.
- $n_i^2 = n_0 p_0 = 4[\frac{2\pi K_B T}{h^2}]^3\, (m_n^* m_p^*)^{3/2}\, exp[\frac{(E_v - E_c)}{K_B T}]$

Intrinsic carrier concentration

- The intrinsic carrier concentration n_i is given by
  $n_i = AT^{3/2}\, exp[\frac{-E_g}{2K_BT}]$; E_g $\rightarrow$band gap energy, A $\rightarrow$ constant.
- The intrinsic carrier concentration(n_i) is a very strong function of temperature.
- For a given material at a constant temperature(T), n_i is constant and so also the product (n_0p_0).
- When impurity atoms are added, the concentrations of electrons and holes are no more equal.
- Whatever be the individual carrier concentration in an extrinsic semiconductor, the product of electron-hole concentration(np) will remain same as n_i^2 at thermal equilibrium.
- The mass action law for semiconductors : $np = n_i^2$
  Here (n, p) refer to electron and hole concentration respectively in extrinsic semiconductor.

The Intrinsic Fermi-Level Position

- For an intrinsic semiconductor
  $N_c\, exp[\frac{-(E_c - E_{fi})}{K_B T}] = N_v\, exp\,[\frac{-(E_{fi} - E_v)}{K_B T}]$
  E_{fi} refers to intrinsic Fermi energy level.
- Take natural log of both sides of above equation and solve for E_{fi}
  $E_{fi} = \frac{1}{2}(E_c + E_v) \, + \frac{1}{2} K_B T\, ln(\frac{N_c}{N_v})$
- Substitute the expressions of N_c & N_v,
  $E_{fi} = \frac{1}{2}(E_c + E_v) \, + \frac{3}{4} K_B T\, ln(\frac{m_p^*}{m_n^*})$
- The term $\frac{1}{2}(E_c + E_v)$ is the energy exactly midway between E_c and E_v or $\frac{1}{2}(E_c + E_v) = E_{midgap}$.
- If the effective masses of electron and hole are equal then *Intrinsic Fermi energy E_{fi} is exactly at the center of the band-gap.*

Extrinsic Semiconductor (n-type)

- Intrinsic material, when doped with controlled amount of specific impurity atoms, becomes extrinsic semiconductor.
- n-type semiconductor$\rightarrow$ group V elements are added (majority carrier $\rightarrow$ electrons; minority carrier $\rightarrow$holes).
- Additional energy levels (donor levels E_d) will be created near the conduction band.
- At $T = 0K$, the valence band and the donor levels are filled up, conduction band will be empty of electrons.
- The energy required to raise the electrons from the donor levels to the conduction band is much less than that from the valence band .
- At room temperature ($300k$), all the donor atoms will donate their extra electrons to the conduction band.

Extrinsic Semiconductor (p-type)

- p-type semiconductor$\rightarrow$ group III elements are added (majority carrier $\rightarrow$ holes; minority carrier $\rightarrow$electrons).
- Additional energy levels (acceptor levels E_a) will be created near the valence band.
- At $T = 0K$, the valence band is filled up but the acceptor levels and the conduction band are empty of electrons.
- The energy required to raise the electrons from the valence band to the acceptor levels is much less than it is required for the conduction band.
- At room temperature ($300k$), all the acceptor atoms will receive electrons from the valence band, thereby creating holes in the valence band.

Charge Neutrality

- In thermal equilibrium, the semiconductor crystal is electrically neutral.
- This charge neutrality condition is valid in intrinsic as well as in extrinsic semiconductor.
- In intrinsic semiconductor, at thermal equilibrium electron and hole have the same concentration $n_0 = p_0$.
- Let now add to it the donor impurity concentration N_d and the acceptor impurity concentration N_a.
- At room temperature all the donor atoms have given up their extra fifth electron and the all the acceptor atoms have taken the electrons.
- Total positive charge density = total negative charge density

  $$N_d^+ + p = n + N_a^-$$

  n, p includes all the electrons in the conduction band and holes in the valence band respectively.

n-type Semiconductor :

- $N_a = 0\, and\, n \gg p$ so that $n \approx N_d$
- Therefore the majority carrier (electron) concentration in n-type semiconductor is $n_n = N_d$

  and the minority carrier (hole) concentration is $p_n = \frac{n_i^2}{N_d}$

p-type Semiconductor :

- $N_d = 0\, and\, p \gg n$ so that $p \approx N_a$
- Therefore the majority carrier (hole) concentration in p-type semiconductor is $p_p = N_a$

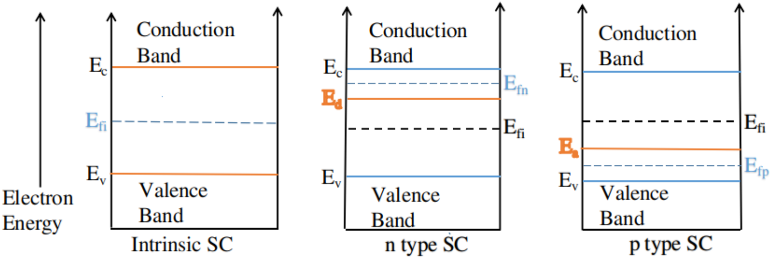
  and the minority carrier (electron) concentration is $n_p = \frac{n_i^2}{N_a}$

Fermi level in Extrinsic Semiconductor

- In extrinsic semiconductor, the number of electrons in the conduction band and the number of holes in the valence band are not equal.
- Consequently the Fermi energy level for the extrinsic semiconductor will also shift from it's mid-gap energy position of intrinsic semiconductor.
- At $T = 0K$, the Fermi level will lie halfway between the donor energy level E_d and the conduction band energy E_c for a n-type semiconductor.
- Similarly for a p-type semiconductor, the Fermi level will be at mid-position of the gap between the valence band energy E_v and the acceptor level E_a at $T = 0K$.

Energy-Band Diagram

- Energy-band diagram is a diagram plotting various key electron energy levels (Fermi level and nearby energy band edges) as a function of some spatial dimension (say x) and often not being drawn to scale.
- Consider absolute zero temperature condition ($T = 0K$).



E_{fi} $\rightarrow$Fermi level for intrinsic semiconductor
E_{fn}, E_{fp} $\rightarrow$Fermi levels for extrinsic semiconductor

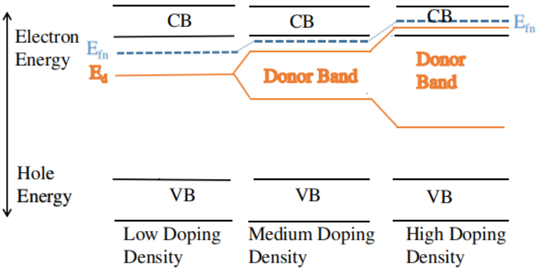
Variation of Fermi Level with Doping Concentration

- Consider first an intrinsic semiconductor at a constant temperature.
- A small amount of (n-type or p-type) impurity is added such that there is no interaction between the impurity atoms.
- Discrete (donor or acceptor) energy states will be created near the bottom of the conduction band or the top of the valence band.
- As the impurity concentration increases, so does the interaction between the impurity atoms.
- Discrete energy states will split to give rise to energy band.
- The impurity concentration keeps on increasing with temperature being maintained constant.
- The band then broadens in width and finally merges either with the conduction band(n-type) or with the valence band(p-type).

Fermi Level contd.

n-type Semiconductor :

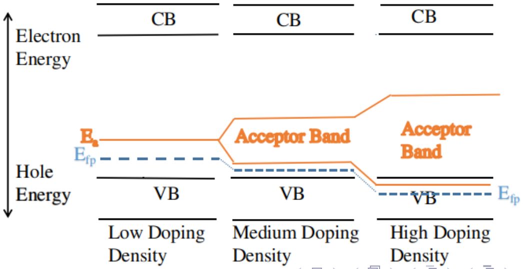
- The Fermi level is located in the energy gap between the donor energy state and the bottom of the conduction band at a constant temperature.
- With the increase in donor impurity density the Fermi level will also go up towards the conduction band.
- Finally at very high impurity concentration the Fermi level will enter the conduction band.



Fermi Level contd.

p-type Semiconductor :

- The Fermi level is located in the energy gap between the acceptor energy state and the top of the valence band at a constant temperature.
- With the increase in acceptor impurity density the Fermi level will go down towards the valence band.
- Finally at very high impurity concentration the Fermi level will enter the valence band.



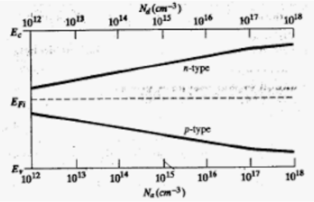
Mathematical Derivation

n-type Semiconductor :

- The free electron density for an intrinsic semiconductor is $n_0 = N_c\, exp[\frac{-(E_c - E_f)}{K_B T}]$
- Solving for $E_c - E_f$ we get $E_c - E_f = K_B T\, ln(\frac{N_c}{n_0})$
- At usual temperature all the donor atoms are ionised.
- Therefore the density of electrons in the conduction band is approximately equal to the density of donor atoms $n_0 \approx N_d$ so that $E_c - E_f = K_B T\, ln(\frac{N_c}{N_d})$.
- As the donor density increases, the Fermi level moves closer to the conduction band.
- It conversely signify the increased density of electrons in the conduction band.

p-type Semiconductor :

- The hole density in an intrinsic semiconductor is $p_0 = N_v\, exp\, [\frac{-(E_f - E_v)}{K_B T}]$
- Solving for $E_f - E_v$ we get $E_f - E_v = K_B T\, ln(\frac{N_v}{p_0})$
- At usual temperature all the acceptor atoms are ionised by accepting electrons from the valence band.
- Thus the density of holes is nearly equal to the density of acceptor atoms $p_0 \approx N_a$ so that $E_f - E_v = K_B T\, ln(\frac{N_v}{N_a})$.
- Here also with increasing acceptor atom density the Fermi level moves towards the valence band.



Position of Fermi level as a function of donor density (n-type) and acceptor density (p-type).

Variation of Fermi Level with Temperature

- Here the impurity concentration in the extrinsic semiconductor is maintained constant.
- In an n-type semiconductor, there are two sources of electrons :
  a) The donor energy levels close to the conduction band with ionization energy $\sim meV$
  b) The valence band with ionization energy $\sim eV$.
- At absolute zero of temperature, the Fermi level is at the middle of the band gap between the donor level and the conduction band.
- As the temperature increases first the donor atoms will get ionised.
- The Fermi level moves up to a point where the majority of the states are contained underneath it (Fermi level between conduction band and donor level).

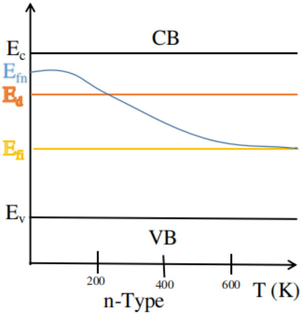
Temperature Variation contd.

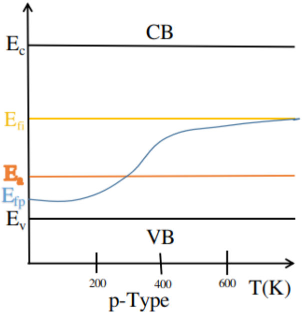
- Once all the donor atoms are ionised, the additional thermal energy will increase the generation of electron-hole pairs with increasing temperature.
- The intrinsic carrier concentration n_i thus becomes a dominant factor.
- The Fermi level starts moving down closer to the middle of the band gap resembling an intrinsic semiconductor.
- Eventually the semiconductor will lose its extrinsic characteristics.
- The Fermi level will then occupy the middle of the forbidden energy gap.

- In a p-type semiconductor, the Fermi level lies in the middle of the gap between the valence band and the acceptor level at absolute zero temperature.
- With the rise in temperature, first the impurity atoms in the acceptor level will be ionized.
- The Fermi level will remain within the gap between the valence band and the acceptor level.
- After complete ionization of acceptor impurity takes place, the intrinsic electron-hole pair concentration (n_i) begins to dominate.
- The Fermi level thus starts moving up towards the middle of the forbidden energy band.
- At very high temperature, when essentially the extrinsic semiconductor becomes an intrinsic one ,the Fermi level will occupy the mid position of the band gap.

Energy Band Diagram

Here the energy band diagram is shown with the variation of Fermi energy level with temperature in extrinsic semiconductor.





p-n Junction

- A p-n junction is formed by bringing into contact a p material and a n material with one another.
- However the entire semiconductor is a single crystal material with p-impurity on one side and n-impurity on the other side.
- Initially the concentration gradient across the junction will activate the diffusion process of the majority carriers.
- This diffusion process will create a space-charge region at the junction whose n side will be positively charged and p side will be negatively charged.
- This space-charge region is depleted of any mobile charge, hence referred to as depletion region.
- An electric field is thus developed in the space-charge region with polarity as p-side negative and n-side positive.

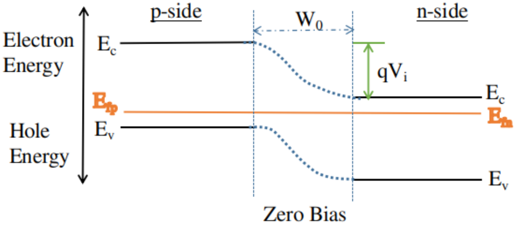
Three Regions of Operation

1. Zero Applied Bias :

- No external voltage is applied across the p-n junction.
- The junction is in then thermal equilibrium.
- The built-in potential barrier V_i in the space-charge region favours the movement of minority carriers while hindering the movement of majority carriers across the junction.
- The potential V_i thus maintains equilibrium between diffusion of majority carriers and drifting of minority carriers.
- There is no net current across the junction.

Fermi Level under Zero Bias

- The Fermi energy level is constant throughout the entire system.
- The relative position of the conduction and valence bands with respect to the Fermi energy changes between p and n regions.
- The conduction and valence band energies bend through the space-charge region.
- The energy band diagram for zero bias is shown here



Second Region of Operation

2. Forward Bias :

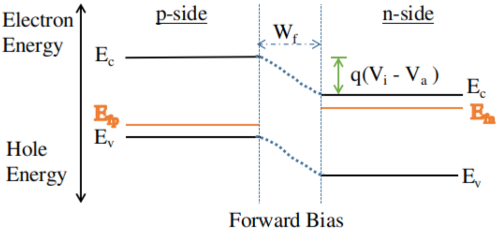
- The external voltage V_a is applied with p end of the junction connected to positive and n end to negative terminal.
- The potential barrier at the junction is thus reduced to give a lower value of the electric field in the depletion region.
- This field reduction results in the diffusion of large number of majority carriers across the junction.
- The flow of majority carriers generates forward current through the junction.
- The drift current is however limited by the small number of minority carriers on either side of the junction.
- The forward current in a forward biased p-n junction is

$$I_f \approx I_o\, e^{(qV_a/K_B T)}$$

I_f →Forward current ; I_o →Reverse saturation current; q →Charge.

Fermi Level under Forward Bias

- When an external voltage is applied ,the equilibrium is disturbed.
- The Fermi energy level will no longer be constant through the system.
- The Fermi level in the p region is now lower than that in the n region.
- The difference between the two is equal to the applied voltage in units of energy(qV_a).



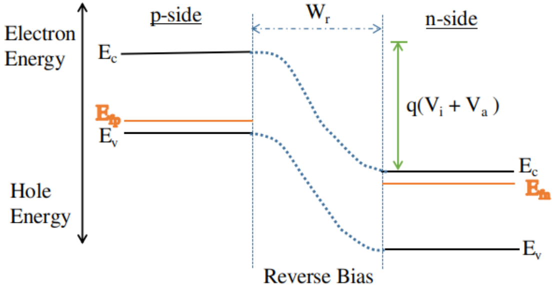
Third Region of Operation

3. Reverse Bias :

- Here the negative end of the external voltage V_a is connected to p side and the positive end to n side of the junction.
- Thus the width of the depletion region increases.
- No majority carrier can diffuse across the junction.
- Only the thermally generated minority carriers can flow across the junction.
- The number of minority carriers is very small and limited at room temperature.
- Therefore a very small current ($nA - \mu A$) will flow in the direction opposite to the conventional current.
- This current is known as reverse saturation current (I_0).

Fermi Level under Reverse Bias

- Here the Fermi energy level in the p region is now higher than that in the n region.
- The barrier height increases by an amount (qV_a).



Current Density, Conductivity, Mobility

- Current density (J): defined as current per unit area, $J = \frac{I}{A}$.
- Conductivity (σ): defined as current density per unit electric field, $\sigma = \frac{J}{E}$.
- Mobility (μ): defined as drift speed of electron per unit electric field, $\mu = \frac{v_d}{E}$.
- Relation between J, σ *and* μ :

$$\boxed{\begin{array}{l} J = \sigma E \quad unit \rightarrow amp/m^2 \\ \sigma = ne\mu \ unit \rightarrow siemens/m \\ \mu = \frac{e\tau}{m} \quad unit \rightarrow m^2/V.s \end{array}}$$

$n \rightarrow$ electron concentration; $m \rightarrow$ electron mass;
$\tau \rightarrow$ relaxation time

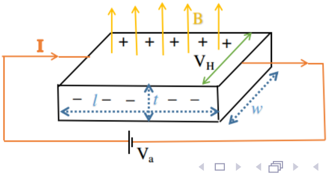
J, σ, μ for Semiconductor

- For both intrinsic and extrinsic semiconductor $J = \sigma E$.
- The electron and hole concentrations are equal to n_i in an intrinsic semiconductor.
- Therefore for an intrinsic semiconductor $\sigma_i = n_i e(\mu_n + \mu_p)$
  $\mu_n \rightarrow$ Electron mobility; $\mu_p \rightarrow$ Hole mobility.
- For an extrinsic semiconductor $\sigma_{ex} = e(n\mu_n + p\mu_p)$
  $n \rightarrow$ Electron concentration; $p \rightarrow$ Hole concentration.
- Electron mobility $\mu_n = \frac{e\tau}{m_n^*}$; Hole mobility $\mu_p = \frac{e\tau}{m_p^*}$
  $m_n^* \rightarrow$ Effective mass of electron
  $m_p^* \rightarrow$ Effective mass of hole.

Hall Effect

If a current carrying conductor or semiconductor is placed in a transverse magnetic field, then an electric field (known as Hall Field E_H) will be developed in a direction perpendicular to both the current and the magnetic field.

- Consider a rectangular strip of a conductor with dimensions as length (l), width (w), and thickness (t).
- It carries a current (I) in $+ve\,X$ direction.
- A magnetic field of strength (B) is applied to it in $+ve\,Z$ direction.



Explanation of Hall field

- The current flowing in $+ve\,X$ direction means the electrons are actually moving with speed v_d in the $-ve\,X$ direction.
- As soon as the electron enters the specimen, it experiences a deflecting Lorentz force $(q\,\overrightarrow{v_d} \times \overrightarrow{B})$ due to the applied magnetic field.
- The negative charges will thus start getting accumulated on the front face of the strip i.e. along the $+ve\,Y$ direction.
- This accumulation of the negative charges will continue till an electric field develops in the $+ve\,Y$ direction to balance the deflecting force of the magnetic field.
- Ultimately a steady state is reached in which the net force on the moving charges in the Y direction vanishes.
- The electron can again move freely along X direction in the conductor.

Derivation of Hall field

- The value of the electric field developed in the stationary state of a Hall set-up is known as Hall electric field (E_H).
- Therefore $eE_H = ev_d B$.
- The current density is $J = \frac{I}{A} = \frac{I}{tw} = nev_d$
  n is the electron concentration.

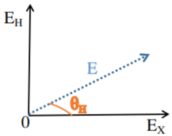
$$\boxed{\text{Hall electric field } E_H = \frac{IB}{netw}}$$

- Hall electric field E_H is developed across the width w, therefore the corresponding voltage is given by

$$\boxed{\text{Hall voltage } V_H = \frac{IB}{net}}$$

Derivation of Hall co-efficient, Hall angle

- Hall co-efficient : It is Hall electric field per unit current density per unit magnetic field strength.
  $R_H = \frac{E_H}{JB}$ or $R_H = \frac{1}{ne}$.
- The conductivity (σ) of a material is given by $\sigma = ne\mu$.
- Therefore $R_H = \frac{\mu}{\sigma}$.



- There exists an electric field $\overrightarrow{E_X}$ in the $+ve\ X$ direction.
- Hall electric field $\overrightarrow{E_H}$ is developed in the $+ve\ Y$ direction.

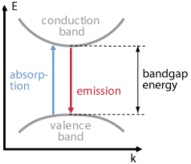
- Hall angle (θ_H) : The angle made by the resultant electric field $\overrightarrow{E}$ with $\overrightarrow{E_X}$.
- $tan\,\theta_H = \frac{E_H}{E_X} = \frac{BJ/ne}{J/\sigma}$ or $\theta_H = tan^{-1}(\sigma R_H)B = tan^{-1}(\mu B)$.

Direct and Indirect Band-Gap Semiconductor

- Semiconductors can be classified into two categories on the basis of band structure.
  Direct Band-gap Semiconductor Example: GaAs, InP, CdS
  Indirect Band-gap semiconductor Example: Si, Ge, GaP
- The band gap represents the minimum energy difference between the valence band and the conduction band.
- Thus a minimum energy equal to the band gap energy is needed to create an electron-hole pair (electron in the conduction band and hole in the valence band).
- Therefore whenever an electron returns to the valence band to recombine with a hole, same amount of energy will be released.
- The energy can be released either in the form of photon (electromagnetic radiation) or in the form of phonon (heat).

Direct Band-Gap Semiconductor

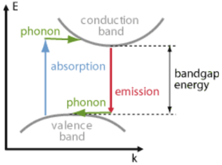
- In direct gap semiconductor, the extra energy is released in the form of photons during the recombination process of electron and hole.
- Direct gap semiconductors are helpful for opto-electronic devices like LEDs, LASERs.



- Here the top of the valence band and the bottom of the conduction band are at the same value of the electron momentum.
- The momentum of electrons in crystalline solid is characterised by the wave vector $k(= 2\pi/\lambda)$.

- Thus an electron can get excited to the conduction band without change of the wave vector by absorbing a photon of appropriate energy.
- Similarly an electron can be de-excited from the conduction band to the valence band easily by the emission of a photon.

Indirect Band-Gap Semiconductor



- The top of the valence band and the bottom of the conduction band are not at the same value of the electron momentum.
- Here the transition of electrons from conduction to valence band requires a change in the electron wave vector.

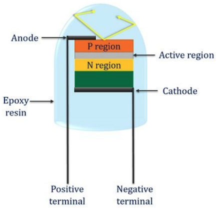
- An electron must therefore transfer its momentum to the crystal lattice.
- Thus the lattice vibration sets in the form of phonons (quantised vibrational energy).
- The extra energy is released in the form of heat.
- A common and simple method for determining whether a band gap is direct or indirect uses absorption spectroscopy.

Light Emitting Diode (LED)

- A light-emitting diode (LED) is a semiconductor light source that emits visible light when an electrical current flows through it.
- Electrons in the semiconductor recombine with holes, releasing energy in the form of photons.
- A specially doped p-n junction diode, made from a special type of semiconductor, is used to produce this electroluminescence phenomenon.
- The diode can emit light when it is in the forward biased mode.
- The light emitted is at a wavelength defined by the active region energy gap (E_g).
- Example : Yellow light is produced by GaAsP, green light by GaP, white light by GaN and blue by GaInN.

LED contd.(1)

The construction of LED is similar to the normal p-n junction diode except that gallium, phosphorus and arsenic materials are used for construction instead of Si or Ge materials.



- Construction of LED: It is designed through the deposition of three semiconducting material layers over a substrate.
- These three layers are arranged one by one where the top layer is a p-type region, the middle junction region is the active one and finally, the bottom layer is n-type region.
- The junction region of the diode is enclosed in an epoxy resin of transparent plastic material.

- Working of LED: Forward biasing of the diode pushes the free electrons from n-side and holes from p-side to the active region (depletion region).
- Recombination of charge carriers occur in the active region.
- As a result, photons having energy equal to the band-gap energy are emitted.

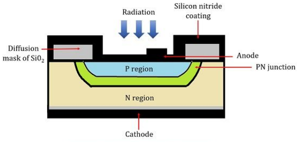
LED contd.(2)

- The device shows current dependency meaning radiation emission is possible only when certain current flows through it.
- The intensity of light emitted by the device varies in proportion with the forward current flowing through it.
- Most of the LEDs have voltage ratings from (1-3)V whereas forward current ratings range from (5-20) mA.
- Advantage: LEDs are inexpensive, small, low power device showing good reliability.
- It's a highly efficient device in terms of converting applied power into light.
- LED also gives wide temperature operating range of around 0 to 70 degrees.
- Disadvantage: If the applied voltage or the current flowing through it, is not maintained properly, the device can be damaged totally.

Photodiode

- A photodiode is a pn-junction diode that consumes light energy to produce an electric current.
- It is also known as a photo-detector, a light detector or a photo-sensor.
- These diodes are particularly designed to work in reverse biased mode.
- The reverse bias causes faster response times for the photodiode.
- When photons of sufficient energy strike the diode, electron–hole pairs are created .
- The p-n junction is made up of a light sensitive semiconductor.
- Silicon, Germanium, InGaAs, PbS etc are the semiconductors used for making photodiodes working in different wavelength range.

Photodiode contd.(1)



- Construction : The pn junction of the device is placed inside a glass material.
- This is done in order to allow the light energy to pass through it.
- As the junction is only exposed to radiation, the other portion of the glass material is painted black.
- The over-all size of the device is very small, $\sim 2.5mm$.
- The current flowing through the device is in micro-ampere range.
- Working Principle : In the photodiode, a very small reverse current flows through the device, known as dark current.
- This current is due to the flow of minority carriers and thus flows even when the device is not exposed to radiation.
- Now, the junction of the device is illuminated with light.

Photodiode contd.(2)

- This causes the generation of electron-hole pairs at the junction.
- The reverse biasing increases the electric field developed in the depletion region which quickly pulls the electrons to the n-region and holes to the p-region.
- The electrons then flow from the n-region to p-region through an external circuit.
- This movement then generates high reverse current through the device known as photocurrent.
- The increase in light intensity will generate large number of electron-hole pairs.
- The photocurrent is thus linearly proportional to the irradiance (power per unit area).

Zener Diode

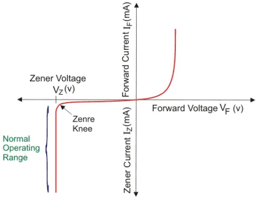
- This is the type of diodes where the reverse saturation current increases abruptly when a particular reverse voltage is reached.
- These Zener diodes are widely used in voltage regulation circuits.
- The mechanism known as Zener breakdown is responsible for the sharp increase in current.
- Zener breakdown occurs in highly doped p-n junctions through a tunneling mechanism.
- In a highly doped junction, the conduction and valence bands on opposite sides of the junction are sufficiently close during reverse bias.
- The valence band electrons on the p-side of the junction thus tunnel through the potential barrier to the conduction band on the n-side.

Zener Diode contd.(1)

- The Zener diode has a well-defined reverse-breakdown voltage, at which it starts conducting current.
- This breakdown voltage is known as Zener Voltage.
- The diode can operate continuously in the reverse-bias mode without getting damaged.
- The Zener diode's operation depends on the heavy doping of its p-n junction.
- The depletion region formed in the diode is very thin ($< 1\mu m$) and the electric field is consequently very high ($\sim 500KV/m$).
- The breakdown voltage can be controlled quite accurately in the doping process.
- Breakdown voltage for commonly available Zener diodes can vary widely from 1.2 V to 200 V.

Zener Diode contd.(2)

The V-I characteristics of a Zener diode is given below.



- When the diode is connected in forward bias, it acts like a normal diode.
- When reverse bias voltage is applied to the diode, it allows only a small amount of leakage current so long the voltage is less than Zener voltage.
- When reverse voltage reaches Zener voltage (V_Z) value, the diode starts allowing large amount of electric current to flow.
- This is the point where Zener breakdown occurs.
- At this point, a small increase in reverse voltage increases the electric current by a large amount.
- This value of the reverse applied voltage is also known as Zener knee voltage.
- If the diode is heavily doped, Zener breakdown occurs at low reverse voltages.
- For lightly doped diode, high reverse voltage is required for Zener breakdown to occur.
- This voltage (V_Z) remains almost constant even with large changes in current provided the current remains between the minimum breakdown value I_Z(min) and its maximum rated value I_Z(max).

Numerical Problems - 1

1. In a solid, consider the energy level lying $0.01eV$ below Fermi level. What is the probability of this level of not being occupied by an electron at room temperature (27°C)?
2. Find the temperature at which there is 1% probability that a state with energy $2eV$ is occupied. Given that Fermi energy is $1.5eV$.
3. Evaluate the Fermi-Dirac function for energy $K_B T$ above the Fermi energy.
4. The Fermi level for potassium is $2.1eV$. Calculate the velocity of the electron at Fermi level.
5. Calculate the probability for the electronic state to be occupied at 20°C, if the energy of this state lies $0.11eV$ above the Fermi level.

Numerical Problems - 2

6. Let E_f be the Fermi energy of a semiconductor. Calculate the energy range (in eV) for which the probability function $f(E)$ varies between 0.01 to 0.99 at $300K$.
7. If the probability that an electron has an energy ΔE below the Fermi energy is 0.8, what is the probability that it will have an energy ΔE above the Fermi energy?
8. The Fermi energy for copper is $7.0\ eV$. Determine the electron energy level for which the probability of occupation is 0.95 at $1100K$.
9. Determine the probability that a state at the bottom of the conduction band is occupied at $300K$ for each of the following values of the band gap energy (i)$1.0\ eV$ (ii) $6.0\ eV$. Assume, in each case, the Fermi energy lies in the middle of the band gap.

Numerical Problems - 3

10. A current of $90A$ passes along a silver ribbon of width $2.5cm$ and thickness $1.0mm$. A transverse magnetic field of strength $0.80T$ is applied to the surface of the strip.
    Determine (i) the drift velocity of the electrons and
    (ii) the Hall electric field.
    The density of free electrons in silver is $5.85 \times 10^{28} m^{-3}$.
11. An n-type Ge sample has a donor density $10^{21}/m^3$. It is arranged in Hall effect experiment having magnetic field of 0.5T and current density $500A/m^2$. Find the Hall voltage if the sample is $3mm$ wide.
12. Determine the majority carrier concentration and mobility from the given Hall effect parameters.
    $l = 1.0mm, w = 0.1mm, t = 0.01mm,$
    $I_x = 1mA, V_x = 12.5V, B_z = 0.05T, V_H = 6.25V.$

Numerical Problems - 4

13. A copper strip $2cm$ wide and $1mm$ thick is placed in a magnetic field of strength $B_z = 1.5wb/m^2$. A current I_x of $200A$ set up in the strip, produces a Hall voltage of $0.18V$. Calculate Hall co-efficient.
14. Find resistivity of intrinsic Ge at $300K$. Given electron mobility as $0.48m^2/V.s$ and hole mobility as $0.013m^2/V.s$, intrinsic carrier concentration $2.5 \times 10^{19}/m^3$.
15. A sample of intrinsic Si at room temperature has a carrier density $1.5 \times 10^{16}/m^3$. A donor impurity is added to the extent of 1 donor atom per million Si atoms. If the atomic density is $5 \times 10^{28}/m^3$, what will be the conductivity of the material?
    Given $\mu_n = 0.135m^2/V.s, \ \mu_p = 0.048m^2/V.s$.