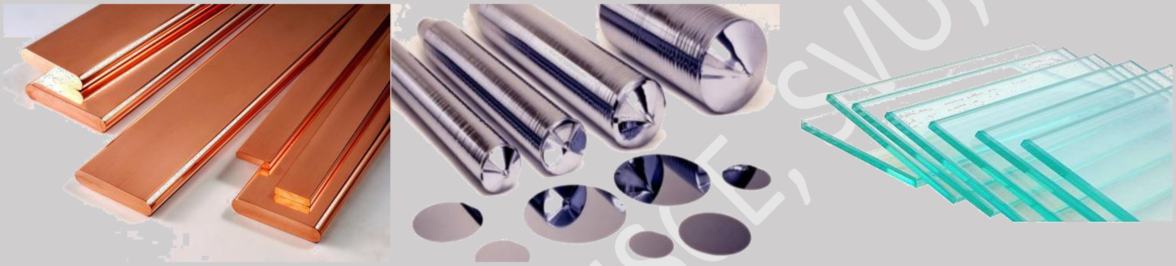
Module 2 Unit 1

SEMICONDUCTORS – NOTES (MAIN)

(As per SVU-R2020 Scheme & Syllabus)

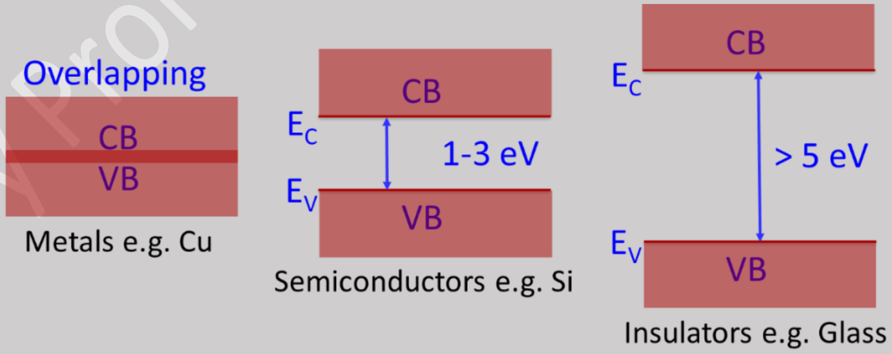
- **Introduction**

Solids are classified into three distinct categories based on their electrical properties. They are conductors, insulators and semiconductors. The range of conductivity is quite large. For metals such as copper and silver, it is about 10^{+8} S/m while that for insulator such as glass, it is about 10^{-11} S/m. It is convenient to consider another intermediate class of materials having moderate conductivity, which are known as semiconductors. A typical semiconductor such as silicon (pure) has conductivity of 10^{-3} S/m.



Thanks to the development of material engineering and semiconductor technology, it is possible to fabricate a wide variety of electronic devices from the same semiconductor wafer (chip). This is the main reason for semiconductors being so much important. All sorts of gadgets made from semiconductor devices are so much integrated with our daily needs that any branch of science and engineering cannot bypass the basic knowledge of semiconductor physics in their curriculum.

In different solids, the energy bands may be overlapping each other or they may remain separated by small or large gaps. The overlapping or separation between valence band and conduction band is of particular importance as it ultimately decides the electrical, thermal and optical properties of materials. The classification of solids based on energy bands is shown in figure below.



- **E-k diagrams**

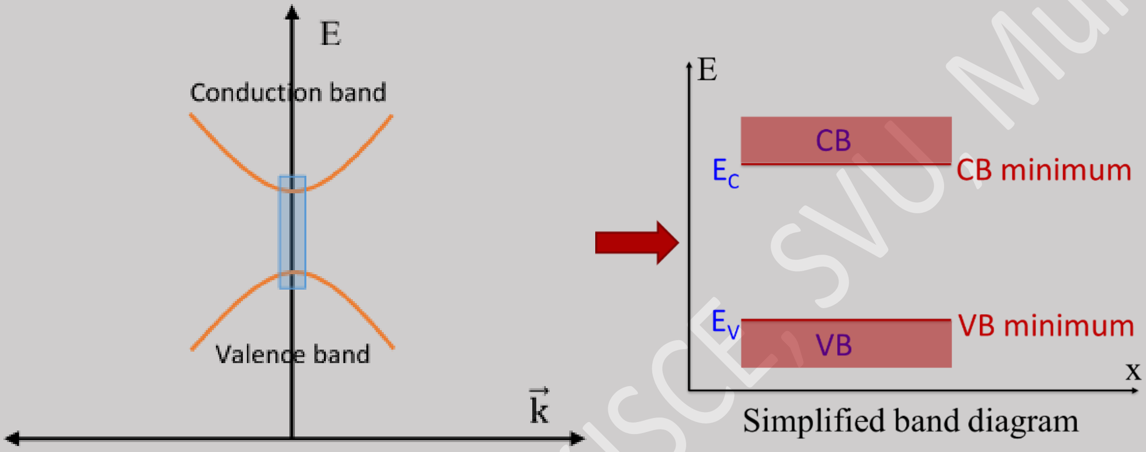
For solids, plot of the variation of total energy of electrons (E) with their wave vector (denoted by $\vec{k}$ and related to its momentum) is know as E-k diagram. This relation is complex but near the lowest of the condution band (CB) and the highest of the valence band (VB) (shaded area in the E-k diagram), it can be approximated as parabolic. Energy of electrons in CB is given by

$$E = E_C + \frac{\hbar^2 k^2}{2m^*}$$

while energy of electrons in VB is given by

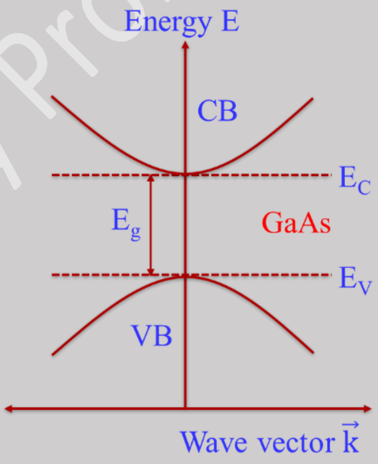
$$E = E_V - \frac{\hbar^2 k^2}{2m^*}$$

where, m* is called effective mass of electron and $\hbar = \frac{h}{2\pi}$ is called reduced Planck's constant. Typical E-k diagram for a semiconductor is shown in following figure.

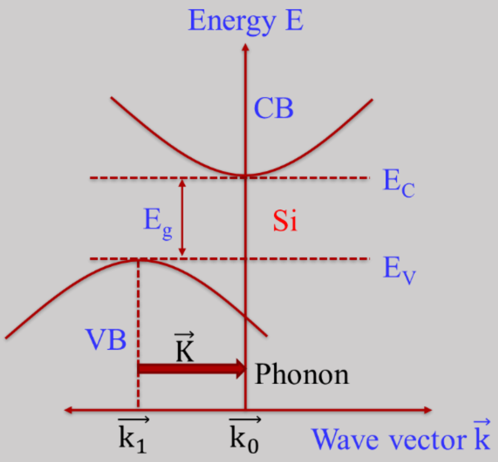


Usually, the range of $\vec{k}$-values is very large and most of the electrons (and holes) at room temeprature and at moderate biasing happen to be near to CB minima (and VB maxima). Thus, the E-k diagram is simplified by plotting it only at the CB minima and VB maxima position for all electrons and holes in the solid. This simplified energy band diagram is enenrgy v/s position (x) of electrons and holes in the semiconductors. This is sufficient for most of the device physics analysis.

- **Direct and Indirect bandgap semiconductors:**



Direct band gap semiconductor



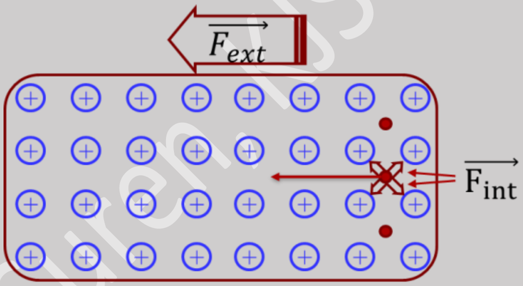
Indirect band gap semiconductor

E-k diagrams for different solids significantly differ from each other. But, a broad classification of solids can be made based on the position of CB minima (CBM) and VB maxima (VBM). In some semiconductors, the CBM and VBM occur at the same value of k. These solids are called "direct bandgap semiconductors". Examples of direct bandgap secimonductors are GaAs and InP. In some solids, CBM and VBM occur at different values of k. Such semiconductors are called inderect bandgap semiconductors. Examples of indirect bandgap semiconductors are Si and Ge.

light emitting devices such as LEDs or laser diodes are always made from direct bandgap materials like GaAs whereas Si cannot make an efficient light emitting device although Si (and Ge) are very much useful as light absorbing device i.e. photodiodes.

- **Concept of effective mass:**

Electrons, in a strict sense, are governed by laws of quantum mechanics and the ordinary laws of motion in classical mechanics cannot be directly used for describing dynamics of electrons. In quantum mechanics, eletrons (and for matter, *all* material objects) are better described by the concept of wave-particle duality in order to account for wave phenomena exhibited by electrons (and all material particles). According to quantum mechanics, the "electron wave" spreads over the solid and it is influenced by the lattie. It is possible to simplify this motion by letting the net interaction of an electron with the lattie into an "internal" force $\vec{F}_{int}$. The total force acting on an electron can be written as $\vec{F} = \vec{F}_{ext} + \vec{F}_{int}$.



The wave nature associated with an electron can thus be "absorbed" in this internal force and we can still treat electrons as perfect particles and continue using laws of mechanics i.e. Newton's second law $\vec{F} = \frac{d\vec{p}}{dt}$ and energy-momentum relation $E = \frac{p^2}{2m}$ provide, we make following (fundamental) shifts in the interpretation of physical quatities to incoprporate the wave nature of particles:

1) $m \rightarrow m^*$, Where m^* is effective mass
2) $\vec{p} \rightarrow \hbar\vec{k}$, Where $\vec{k}$ is wave vector

$\vec{k}$ is also called as "crysal momentum"

The first equation comes due to the fact that motion of electrons in solids are influenced by crystal lattice The second substitution follwos from the de'Broglie equation for matter waves:

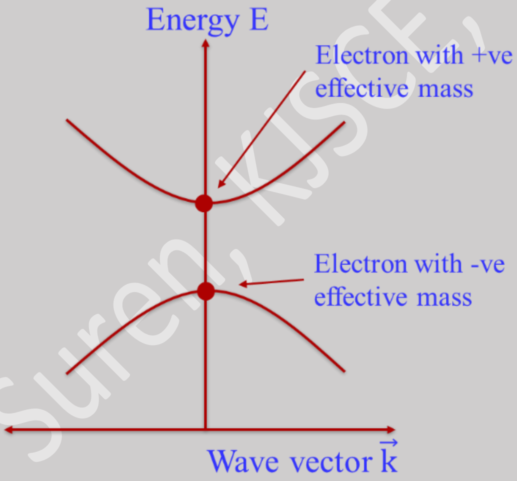
$$p = \frac{h}{\lambda} = \frac{h}{2\pi} \times \frac{2\pi}{\lambda} = \hbar k$$

as $E = E_C + \frac{\hbar^2 k^2}{2m^*}$ OR $E = E_V - \frac{\hbar^2 k^2}{2m^*}$

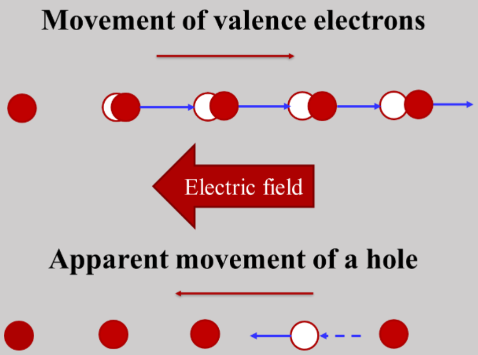
$$\frac{d^2E}{dk^2} = \frac{\hbar^2}{m^*} \Rightarrow m^* = \frac{\hbar^2}{\left(\frac{d^2E}{dk^2}\right)}$$

Normally, if we calculate the ratio of applied force to the acceleration produced then it should yield mass of the particle. But in solids, motion of any charged particle like an electron or a hole is influenced by a large number of factors such as lattice sites (atoms or ions), defects and impurities or the other electrons and holes and therefore, the ratio of force to acceleration comes out to be different from its mass if it were isolated and outside the solid. This enables the introduction of effective mass concept. Effective mass is a parameter that depends upon the material, its structure, lattice periodicity, lattice directions, interaction energy and various other factors. The effective mass calculations are complicated and they differ from solid to solid. For calculation purposes, the effective mass is given as some factor of the actual mass of particle e.g. $0.67m_e$; where m_e is the actual mass of an electron. Effective masses of both the charge carriers viz. electrons and holes in semiconductors are expressed in above manner.

- **Concept of hole as positive charge carrier:**



Curvature of E-k diagram gives estimation of effective mass. In particular, at the V. B. maxima, the second derivative is negative, which implies an electron with negative effective mass. The motion of an electron at the top of VB with negative charge and negative mass is along the electric field i.e. it is anologous to a positive charge carrier with usual mass. Hence, it is convenient to itroduce the concept of a hole as a positive charge carrier taking part in electrical conduction moving along the electric field.



By definition, a hole is an electron missing from the VB of the host atom. When an electron from a host atoms shifts to some other site, it leaves behind uncompensated host atom with a net positive charge. This site in the VB of host atom with a deficit of one electron is regarded as hole. In the next instance, electron from some other host atom would jump to this site leaving behind uncompensated host at that place with a net positive charge. This is described as movement of the hole from one place to the other. Instead of considering movements of a number of electrons from one site to the other, it is easier to trace the motion of a hole carrying positive charge in backwards direction. Under the action of external electric field, such shifts of valence electrons occur in specific direction giving an apparent shift of holes along the electric field as shown in above figure.

- **Semiconductor statistics**

The first important parameter in the study of semiconductors is to know how many electrons are available in the CB or how many vacancies i.e. holes are available in the VB. This is calculated by using two functions:

1) The Fermi-Dirac distribution function F(E), which gives the probability of occupation of an energy level by electron and
2) The density of states function N(E), which gives the number of energy states possible or available per unit volume per electron-volt.

Since the number of electrons or holes involved is very high, statistical calculations become useful. The number of electrons or holes is obtained by integrating the product of above functions over the desired energy range.

- **The Fermi-Dirac function**

This statistical function is applicable to all particles having half integral spin (spin ½ particles), which are called as “fermions”. An electron is a chief example of fermionic particle. The main feature of any fermion is that it obeys the Pauli’s exclusion principle, which states that “no two electrons can have the same energy level in an interacting system.” The Fermi-Dirac function is a function of energy and temperature. It is given by,

$\mathrm{F(E)} = \frac{1}{1+e^{(E-E_F)/kT}}$; Where,

E is energy, k is Boltzmann constant and T is absolute temperature.

The energy level E_F is called the Fermi level. It is used as a reference energy level to evaluate energies of electrons and holes and also to indicate the majority and minority carrier concentrations. The Fermi energy level is an important concept in the study of any kind of solid. More discussion o Fermi level and Fermi-Dirac function is done in further sections.

- **Density of states function**

This function is related to the degrees of freedom of electrons within any solid. It indicates the allowed energies per eV per unit volume of the solid. It is given by,

$$\mathrm{N(E)dE} = 4\pi\left(\frac{2m^*}{h^2}\right)^{3/2}\sqrt{E}\,dE$$

- **Application of Fermi-Dirac function to derive Semiconductor transport equations**

1) **Number of electrons and holes for conduction of electricity and heat:** The number of electrons in the CB is obtained by integrating the product F(E)N(E). Lowest energy possessed by a conduction electron is E_C and highest energy is taken to be infinity for mathematical simplicity. Thus,

$$n = \int_{E_C}^{\infty} F(E)N(E)dE = \int_{E_C}^{\infty} \frac{1}{1+\exp\left(\frac{E-E_F}{kT}\right)} 4\pi \left(\frac{2m^*}{h^2}\right)^{3/2} \sqrt{E}\, dE$$

The above integral evaluates to $n = N_C \exp\left(-\frac{E_C-E_F}{kT}\right)$; where N_C is called density of states in the CB. It is a temperature and material dependent parameter.

Since a hole is nothing but deficiency of electron or electron missing from the VB, the probability factor for finding hole in the VB is taken as 1 – F(E). Highest energy possessed by a hole in the VB is E_V and lowest energy is taken to be negative infinity for mathematical simplicity. Thus,

$$p = \int_{-\infty}^{E_V} [1 - F(E)]N(E)dE = \int_{-\infty}^{E_V} \left[1 - \frac{1}{1+\exp\left(\frac{E-E_F}{kT}\right)}\right] 4\pi \left(\frac{2m^*}{h^2}\right)^{3/2} \sqrt{E}\, dE$$

It evaluates to $p = N_V \exp\left(-\frac{E_F-E_V}{kT}\right)$; where N_V is called density of states in the VB which is also a temperature and material dependent parameter. The values of N_C and N_V are close to each other for most of the semiconductors.

2) **Intrinsic concentration:** The number of free electrons or number of holes in the VB per unit volume is called as intrinsic carrier concentration. Since number of free electrons and holes is same for an intrinsic material, we write

$n = p =$ say n_i

$$\therefore n_i^2 = n.p = N_C \exp\left(-\frac{E_C - E_F}{kT}\right). N_V \exp\left(-\frac{E_F - E_V}{kT}\right)$$

$$\therefore n_i^2 = N_C N_V \exp\left(-\frac{E_C - E_V}{kT}\right)$$

The difference $E_C – E_V$ is called the “energy band gap” denoted by “Eg”. Thus,

$$\therefore n_i = \left(\sqrt{N_C N_V}\right) \exp\left(-\frac{E_g}{2kT}\right)$$

3) **Charge neutrality condition:** In any semiconductor, the sum of all kinds of charges is zero which is written as:

$$n + N_D^+ = p + N_A^-$$

This is called charge neutrality condition.

4) **Mass-action law:** At thermal equilibrium, the product “n x p” is constant and it holds for any material, whether intrinsic or extrinsic. This is called the mass-action law. In mathematical form it is written as $np = n_i^2 = \text{constant at equilibrium condition}$. Equilibrium referes to state of

semiconductor in the absence of external field, illumination or change in temperature. Excess charge carriers are generated when equilibrium is disturbed.

5) **Extrinsic concentration:** In extrinsic materials, there is an additional source for one type of impurity; electrons in n-type and holes in p-type. Accordingly they are called as majority carriers. On the contrary, holes in n-type and electrons in p-type material are very small in number and they are called as minority carriers. In n-type material at RT, most of the electrons from donors are available free and since each donor contributes one electron number of majority carriers (i.e. electrons) is the same as number of donors added. Number of minority carriers is obtained by using mass action law given above. Thus,

- For n-type material at RT: Majority carrier concentration $n_n \approx N_D$, Minority carrier concentration $p_n \approx \frac{n_i^2}{N_D}$. N_D is number of donors per unit volume.
- For p-type material at RT: Majority carrier concentration $p_p \approx N_A$, Minority carrier concentration $n_p \approx \frac{n_i^2}{N_A}$. N_A is number of acceptors per unit volume.

6) **Conductivity and resistivity:** The conductivity of semiconductor is proportional to the total number of charge carriers i.e. number of electrons plus number of holes. With increasing temperature, more and more charge carriers become free for conduction and conductivity of semiconductors increases with increasing temperature. Hence, semiconductors have negative temperature coefficient of resistance. For intrinsic material, both types of charge carriers contribute evenly while for extrinsic materials, one type of charge carrier dominates and contribution of the other can be neglected. Thus,

- For n-type: $\sigma = qn\mu_n$; where μ_n is called “mobility of electrons”.
- For p-type: $\sigma = qp\mu_p$; where μ_p is called “mobility of holes”.

  Mobility is defined in further seciton.
- For intrinsic: $\sigma = qn_i(\mu_n + \mu_p)$

SI unit of conductivity is siemens/m (S/m).

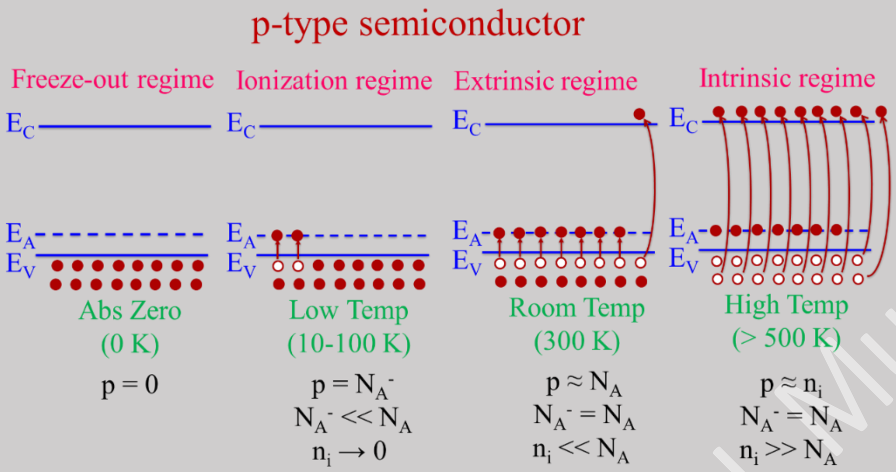
Resistivity is the reciprocal of conductivity. Thus, $\rho = \frac{1}{\sigma}$.

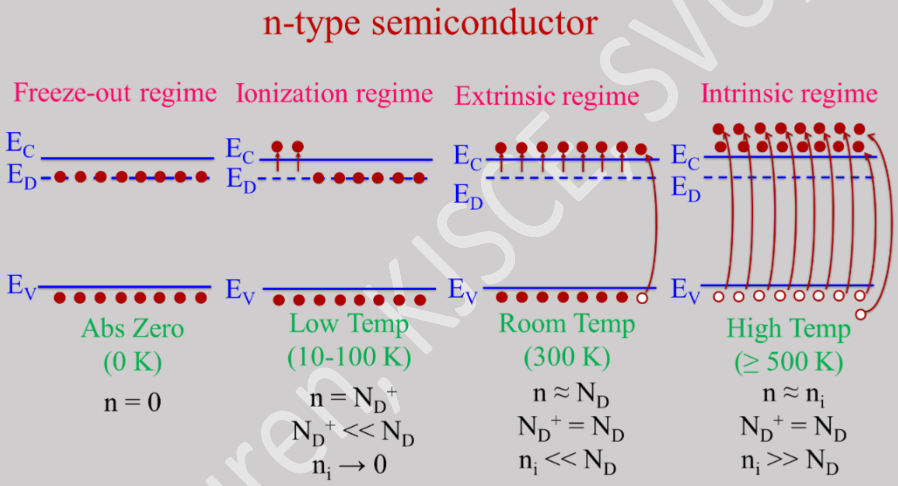
SI unit of resistivity is Ω-m.

7) **Temperature dependence of conductivity of extrinsic semiconductors:** The contribution to conductivity of an extrinsic semiconductor comes from different mechanisms at different temepratures.

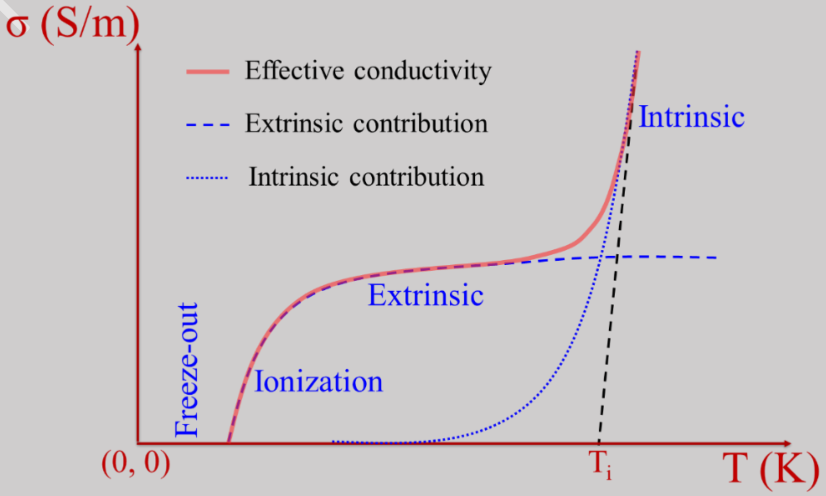
i) At very low temperatures (< 10 K), all the electrons occupy lowest enenrgy states. VB is full and CB is empty. This is called “freeze-out” regime and the semiconductors behaves as an insuator.

ii) At low temperatures (10-100 K), electrons and holes from donors and acceptors are liberated due to increased thermal energy. CB gets filled up and VB starts acquiring holes. This is called “ionization” regime and the semiconductor starts conducting.





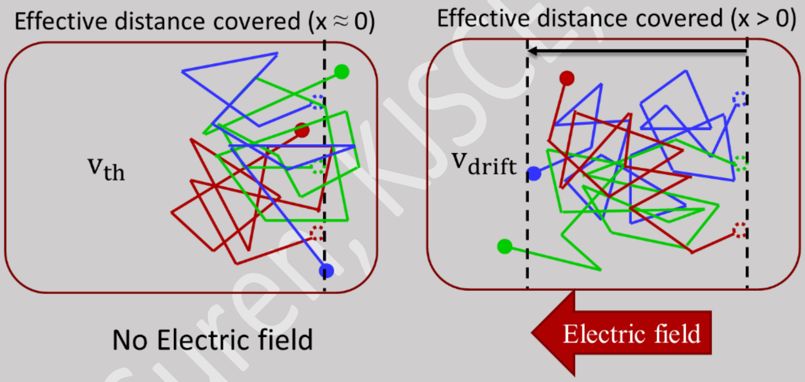
iii) At room tempeature (300 K), almost all the donors and acceptors are inonized and conductovity of semiconductor is predominently decided by the impurity concentration. This is called “extrinsic” regime and the conductivity attains plateau till a certain temperature called the “intrinsic temperature” (T_i).



iv) At room tempeature (300 K), almost all the donors and acceptors are inonized and conductovity of semiconductor is predominently decided by the impurity concentration. This is called "extrinsic" regime and the conductivity attains plateau till a certain temperature called the "intrinsic temperature" (T_i).

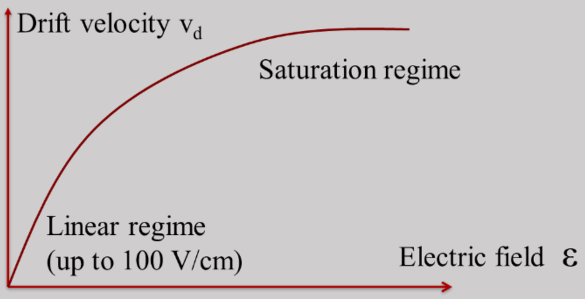
v) For temperaures beyond T_i, there is no further contribution from donors or acceptors as they are already been depleted. However, due to high temperatures, breaking bonds of host atoms becomes signifiant and the intrinsic charge carriers start controlling the conductivity. This is called "intrinsic" regime and the semiconductor behaves as if it is undoped. The conductivity in this regime rises exponentially with temperature.

8) **Carrier drift and drift velocity:** Motion of a charged particle under the influence of electric or magnetic field is called "drift". If we apply an electric field across a semiconductor, its charge carriers viz. electrons and holes do not move in straight lines towards the field. Since the solid is packed by atoms, the charge carriers are continuously deviated from their paths and they end up in a random walk. In the absence of the external field, the net path covered is zero but under the influence of electric field, there is a definite shift towards the electric field (in case of a positive charge) as shown in the diagram:



Although the actual path covered by the particle is large, the effective path covered along the direction of electric field is small. The ratio of effective path covered to the total time taken is called as "drift velocity" of the charge carriers.

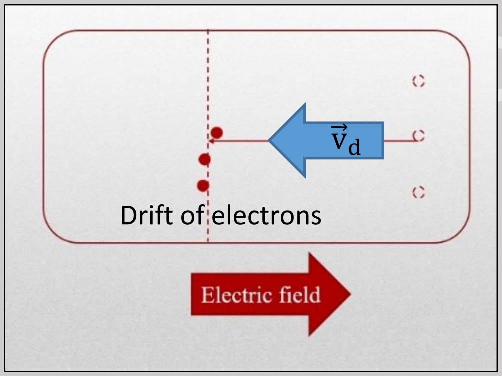
9) **Mobility:** The drift velocity is linearly proportional to the electric field intensity (until drift velocity gets saturated at certain critical field intensity). Thus, $v_d \propto \mathcal{E} \Rightarrow v_d = \mu\mathcal{E}$; Where the symbol "$\mathcal{E}$" is used for electric field intensity. The constant of proportionality is called "mobility" of charge carriers. It indicates how fluently a charge carrier can sweep through the electric field. It can be defined as the drift velocity acquired per unit electric field intensity. It SI unit is m^2/V-sec.



The variation of drift velocity with electric field is shown in following diagram. Mobility depends upon a numer of factors such as electric field, temperture, crystal structure, defects, impurities, grain boundaries but at low fields and at room temperature, we an regard it as constant for a given material.

10) **Ohm's law:** In semiconductor physics, the Ohm's law is expressed in terms of more fundamental relation, which is $J = \sigma\mathcal{E}$; where, J is the current density i.e. current per unit area normal to it and σ is conductivity

11) **Drift current density:** The current per unit area perpendicular to the direction of current, which arises due to drift of charge carriers under the influence of electric field is called "drift current density".



The drift current density is given by $\vec{J}_{drift} = qn\vec{v}_d$. Symbol "n" used in the equation here referes to any particle in general (electron or hole) and it is called the particle density (Unit: m^{-3} or cm^{-3}). In particular, for elecrons,

$\vec{J}_{drift}(\text{eletrons}) = (-q) \times n \times (-\vec{v}_d)$ … as electrons are negatively charged and they drift opposite to electric filed. Here, "n" is electron density i.e. number of electrons per unit volume.

$\therefore J_{drift}(\text{eletrons}) = qnv_d$ numericaly

For holes,

$\vec{J}_{drift}(\text{holes}) = (+q) \times p \times (+\vec{v}_d) = qp\vec{v}_d$ … as holes are positively charged and they drift along the electric field. Here, "p" is hole density i.e. number of holes per unit volume

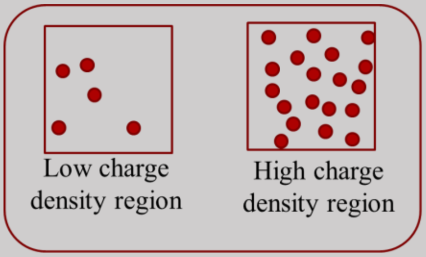
$\therefore J_{drift}(\text{hole}) = qpv_d$ numericaly

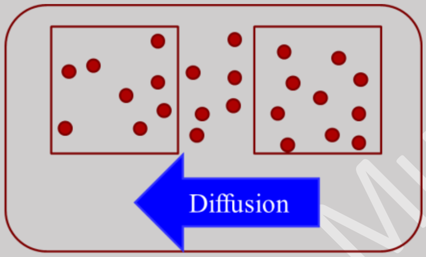
Using the relation between drift velocity and electric field, we summerize:

- For n-type: $J_n = qn\mu_n\mathcal{E}$
- For p-type: $J_p = qp\mu_p\mathcal{E}$
- For intrinsic: $J = q\mathcal{E}(n\mu_n + p\mu_p)$

12) **Diffusion and diffusion coefficient:** All particles have a tendency to spread out from region of high concentration to region of low concentration. This tendency is called as diffusion. A concentration

gradient exists as we move from one region to the other having different concentration of particles. In one dimension, the concentration gradient is nothing but spatial variation of number of particles per unit volume. Due to the concentration gradient, a particle flux is generated in the direction of decreasing concentration gradient. This particle flux is called as “diffusion current density”.





For electrons and holes, we have $\vec{J}_{\text{diffusion}} \propto -\frac{dn}{dx}\hat{\imath}$. Symbol “n” here is the particle density as before and here it referes to any particle in general (electron or hole). Negative sign is taken because the current flows in the direction of *decreasing* concentration gradient.

For electrons,

$$\vec{J}_{\text{diffusion}}(\text{eletrons}) = (-q) \times D_n \times \left(-\frac{dn}{dx}\right)\hat{\imath}$$

$\therefore J_{\text{diffusion}}(\text{eletrons}) = qD_n\frac{dn}{dx}$ numerically. Here $\frac{dn}{dx}$ is the conentration gradient for electrons. The constant of proportionality is called diffusion coefficient (D_n) of electrons. Its SI unit is m^2/s.

For holes,

$$\vec{J}_{\text{diffusion}}(\text{holes}) = (+q) \times D_p \times \left(-\frac{dp}{dx}\right)\hat{\imath}$$

$\therefore J_{\text{diffusion}}(\text{holes}) = -qD_n\frac{dp}{dx}$ numerically. Here $\frac{dp}{dx}$ is the conentration gradient for holes and D_p is diffusion coefficient for holes.

Thus,

- For n-type: $J_n = qD_n\frac{dn}{dx}$
- For p-typ: $J_n = -qD_p\frac{dp}{dx}$
- For intrinsic: $J = q\left(D_n\frac{dn}{dx} - D_p\frac{dp}{dx}\right)$

13) Einstein’s relations: Einstein’s work in statistical mechanics yields an important relation: The ratio of diffusion coefficient to mobility of any type of charge carrier at a given temperature is constant and it is expressed as:

$$\frac{D_n}{\mu_n} = \frac{D_p}{\mu_p} = \frac{kT}{q} = \text{constant at a given temperature}$$

14) Total current density: In any semiconductor or a p-n junction device, there are four currents flowing across the junction: the drift currents and diffusion currents due to electrons and holes. Electron diffusion and hole drift is directed from p-side to n-side while hole diffusion and electron drift is directed from n-side to p-side. Their summation gives the total current density as follows:

$$J_{total} = qD_n\frac{dn}{dx} + qp\mu_p\mathcal{E} - qD_p\frac{dp}{dx} + qn\mu_n\mathcal{E}$$

$$\therefore J_{total} = q\left[\left(D_n\frac{dn}{dx} - D_p\frac{dp}{dx}\right) + (n\mu_n + p\mu_p)\mathcal{E}\right]$$

- **The Fermi level**

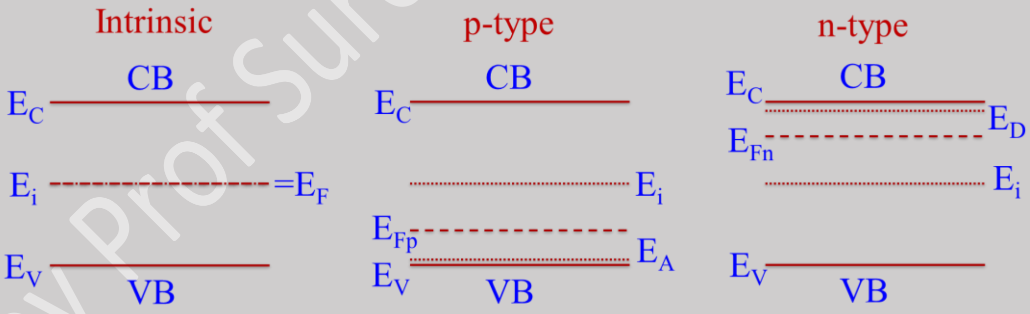
For metals and non-metals, the Fermi level can be defined in some different ways. For metals,it is convinient to define it as:

Definition 1 of Fermi level: The Fermi level is the highest available energy level at absolute zero temperature. It may or may not be actually occupied by an electron.

For semiconductors, it is useful to define the Fermi level in different way as:

Definition 2 of Fermi level: The Fermi level is that energy level for which, the probability of occupation is 50% at all temperatures except absolute zero temperature.

The concept of Fermi energy level is very useful in all of solid state physics. For semiconductors in particular, the Fermi level position depends upon whether the semiconductor is pure or doped with n or p type impurities. For pure or intrinsic semiconductors, since number of electrons and holes are equal, the Fermi level is located between E_C and E_V i.e. at the centre of the forbidden energy region. For n-type material, it is closer to the CB since electrons are excess in number. In p-type material, it is closer to the VB since holes are excess in number.



The energy band diagrams for n and p-type material show additional energy levels called donor level E_D and acceptor level E_A in n-type and p-type material respectively.

- **For intrinsic material, the Fermi level is located midway between the CB and VB**

For intrinsic materials we have, n = p

$$\therefore N_C\exp\left(-\frac{E_C-E_F}{kT}\right) = N_V\exp\left(-\frac{E_F-E_V}{kT}\right) \therefore \exp\left(-\frac{E_C-E_F}{kT}\right).\exp\left(+\frac{E_F-E_V}{kT}\right) = \frac{N_V}{N_C}$$

$$\therefore \exp\left(\frac{-E_C+2E_F-E_V}{kT}\right) = \frac{N_V}{N_C}$$

Taking logarithm on both sides,

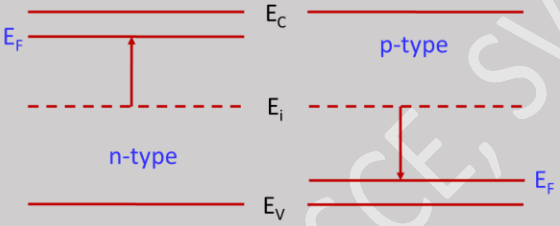
$$\frac{-E_C+2E_F-E_V}{kT} = \ln\left(\frac{N_V}{N_C}\right) \therefore E_F = \frac{E_C+E_V}{2} + \frac{kT}{2}\ln\left(\frac{N_V}{N_C}\right)$$

For semiconductors, the values of N_C and N_V are close to each other. (For example in silicon at RT, $N_C = 3.2 \times 10^{25}/m^3$ and $N_V = 1.8 \times 10^{25}/m^3$). Further, value of kT ≈ 0.026 eV at RT hence the second term on RHS becomes negligible as compared to the band gap. (For Si, it is 1.1 eV at RT). So, neglecting the second term on RHS we get

$$E_F = \frac{E_C+E_V}{2} \qquad \text{(intrinsic semiconductors)}$$

Thus, Fermi level is located midway between the CB and VB.

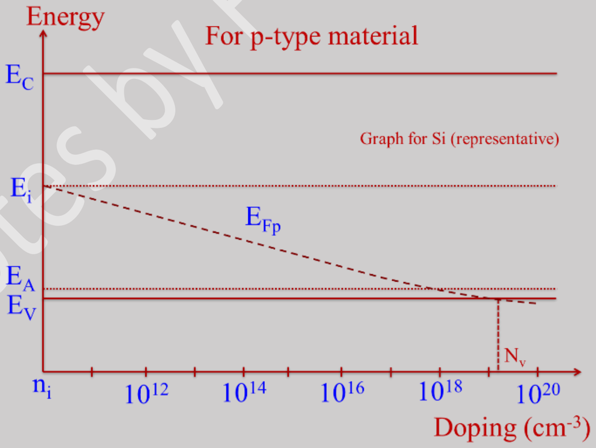
- **Effect of impurity concentration on Fermi level**

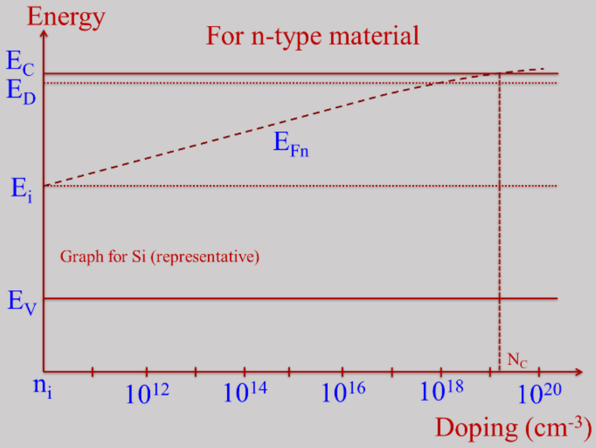


As impurities are added to a semiconductor, electrical conduction is dominated by one type of charge i.e. electrons in n-type and holes in p-type. The Fermi level is an indicator of majority carriers. Hence, as impurities are added, the Fermi level shifts from its central position. In either material, the shift of Fermi level from the central position is directly proportional to the logarithm of donor or acceptor concentration. it is given by,

- For n-type: $E_F - E_i = kT\ln\left(\frac{n}{n_i}\right)$; $n \approx N_D$ at RT
- For p-type: $E_F - E_i = -kT\ln\left(\frac{p}{n_i}\right)$; $p \approx N_A$ at RT

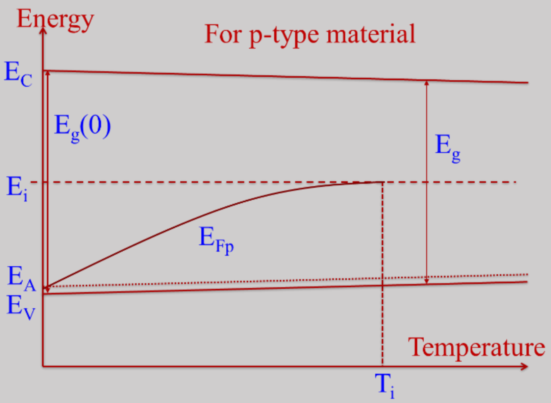
E_i is called the "intrinsic level" or the midway position. Variation of Fermi level over a rage of doping concentration is shown in following figure.

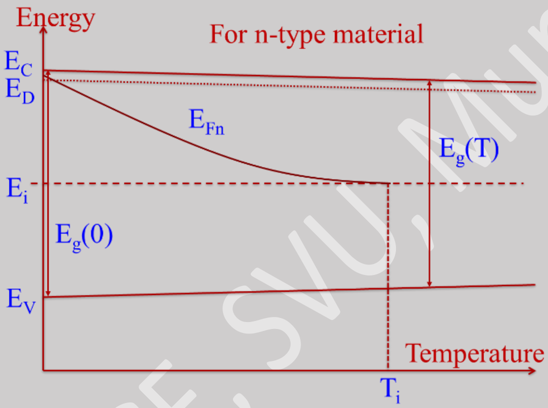




For very high doping concentrations i.e. when the doping density exceed effective densities of states, the Fermi level penetrates into the CB and VB in n-type and p-type semiconductors respectively. Such semiconductors are called “degenerate” semiconductors. Degenerate semiconductors are rrequired for certain applications such as zener diodes, laser diodes, microwave devices etc.

- **Effect of temperature on Fermi level**





The density of electrons or holes is a strong function of temperature and along with the density, there is a shift in the Fermi level also. Temperatuer dependance of conductivity is discussed earlier. Its reflection on the Fermi level is shown in figure above.

At low temperatures in extrinsic semiconductors, the Fermi level is close to CB or VB in n or p type semiconductor respectively. As temperature increases, it deviates away from these positions. At the intrinsic temperature, Fermi level approaches centre of the bandgap and stays there for further increase in temperature. For intrinsic semiconductors, the Fermi level stays at the centre at all temperatures. With increasing tempertares, the energy bandgap of semiconductor also slowly decreases as shown in the diagram.

- **Temperature dependence of Fermi-Dirac function**

The Fermi Dirac function is given by,

$$F(E) = \frac{1}{1 + \exp\left(\frac{E - E_F}{kT}\right)}$$

At all temperature except absolute zero, for E = E_F, we get

$$F(E) = \frac{1}{1+\exp\left(\frac{E-E_F}{kT}\right)} = \frac{1}{1+e^0} = 0.5 \text{ or } 50\%.$$

Interpretation: The value 50% indicates an important feature of intrinsic semiconductors. In intrinsic semiconductors, the moment we make an electron free from the VB and transfer it to the CB, a hole automatically get created. Thus, as many electrons are available in the CB for conduction, those many holes are available in the VB. The result 50% indicates that the probabilities that we may find an electron in the CB or a hole in the VB are equal.

At absolute zero

a) For E > E_F, we get $F(E) = \frac{1}{1+\exp\left(\frac{E-E_F}{kT}\right)} = \frac{1}{1+\exp\left(\frac{+\text{ve number}}{0}\right)} = \frac{1}{1+e^{+\infty}} = \frac{1}{\infty} = 0$

b) For E < E_F, we get $F(E) = \frac{1}{1+\exp\left(\frac{E-E_F}{kT}\right)} = \frac{1}{1+\exp\left(\frac{-\text{ve number}}{0}\right)} = \frac{1}{1+e^{-\infty}} = \frac{1}{1+0} = 1$

Interpretation: In intrinsic semiconductors, the Fermi level is taken at the centre of the forbidden energy gap that is between the CB and the VB. The choice E > E_F means electron present in the CB. Similarly, the choice E < E_F means electron present in the VB. Both parts together imply that at absolute zero temperature, the probability that an electron can be present in the CB is zero and getting in the VB is 100%. It means the CB is empty and VB is full so no vacancies or holes. Since neither electrons nor holes are available for conduction, the semiconductor would behave as an insulator at absolute zero.

The complete plot for all temperature is shown in following figure