

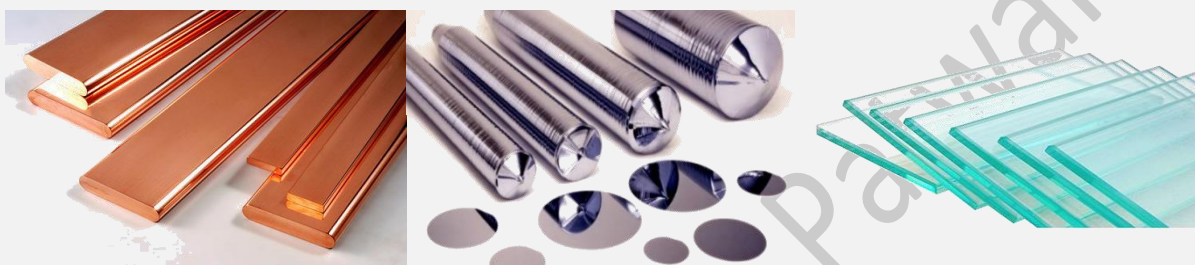
Module 2 Unit 1

SEMICONDUCTORS

(As per Revised Curriculum SVU R-2023)

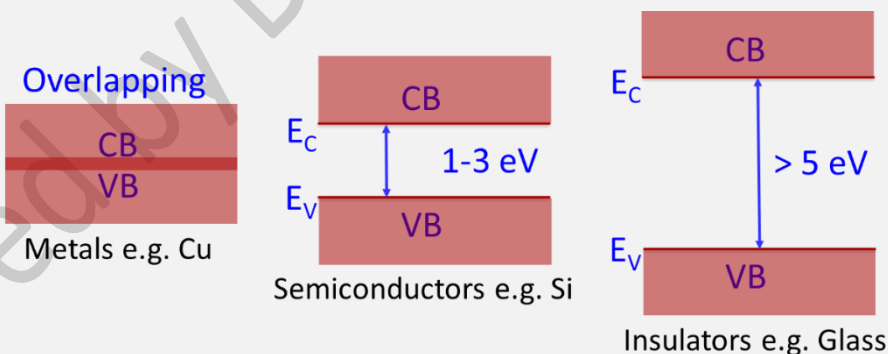
- Introduction**

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.



- Intrinsic semiconductors, doping and extrinsic semiconductors**

A. Intrinsic semiconductor: Semiconducting element in which, the electrical conduction is possible only by breaking covalent bonds between host atoms is called as intrinsic semiconductor. With each bond broken, we get an electron-hole pair for electrical conduction. Thus, for any intrinsic semiconductor, the number of electrons and holes are almost equal at any temperature and electrical conduction takes place with the help of both these charge carriers. The number of charge carriers available for conduction in intrinsic semiconductors (at room temperature) is usually low and these materials are almost insulating. For example, for pure/intrinsic Si at RT,

intrinsic carrier concentration is on the order of $10^{10}/\text{cm}^3$ and its corresponding conductivity is about a $2.4 \times 10^{-4} \text{ S/m}$.

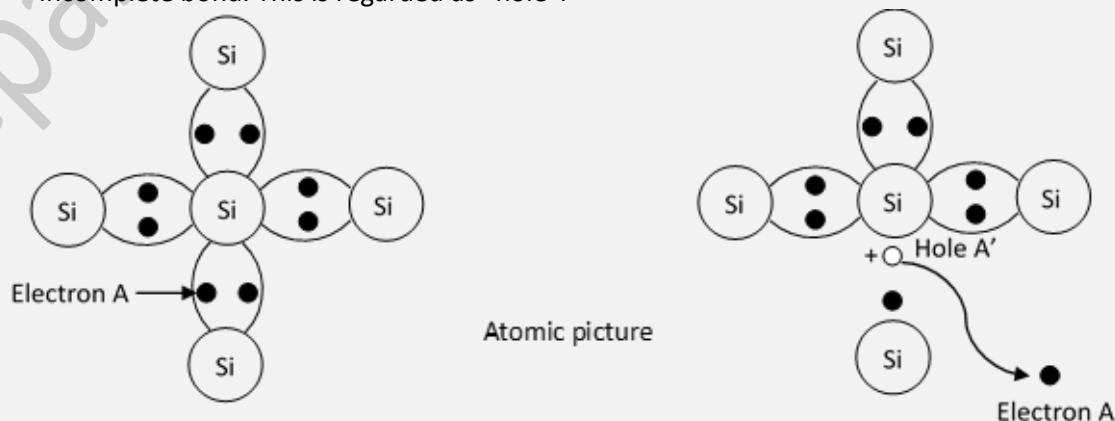
B. Doping and its need: Usually, impurities in semiconductors hamper its performance e.g. defects in crystals. However, certain impurities typically those which are referred as “shallow impurities” (dopants with energy levels close to CB or VB of host semiconductor) are found to be useful for electrical as well as thermal transport in semiconductors. Boron or Phosphorous are some of the popular impurities for Si (Si itself serves as shallow impurity in some other semiconductors such as GaAs). Conductivity of semiconductors can drastically improve if these impurities are purposefully added to a semiconductor at a low dose (typically 1 ppm to 1 ppb). For example, conductivity of Si doped with $10^{15}/\text{cm}^3$ phosphorous atoms improves to about 20 S/m. Doping is a carefully engineered process of adding specific amount of foreign atoms into host semiconductor. The level of doping depends upon application. For example, in rectifier diodes, the doping levels vary from $10^{15} - 10^{17}/\text{cm}^3$ while in laser diodes, the doping level exceeds $10^{20}/\text{cm}^3$ (note that there are about 10^{23} atoms per cm^3 for any solid). Typical methods used for doping are high temperature (800-900°C) diffusion using vapours of dopants or ion implantation at room temperature using bombardment of dopant ions having few keV of energy.

C. Extrinsic semiconductor: Semiconducting elements in which, electrical conduction is carried predominantly by electrons or holes obtained from donor or acceptor impurities are called as extrinsic semiconductors. The number of electrons or holes obtained is large as compared to number of electron-hole pairs obtained by breaking bonds. However, this number is a strong function of temperature. At very low temperatures (< 10 kelvin), no charge carriers are free, at moderate temperatures (10-100 kelvin), some of the electrons and holes from dopants (i.e. extrinsic charge carriers) become free but the thermal energy is not yet sufficient to break covalent bonds and the charge carriers from host atoms (intrinsic charge carriers) are negligible. Till RT and at moderately higher temperatures (about 100°C), the extrinsic charge carrier number dominates. Hence, in most of the calculations in semiconductor device Physics, contribution of only the extrinsic charge carriers is considered as most the semiconductor-based electronic gadgets work in this range of temperatures.

- **Charge carriers in semiconductor**

A. Intrinsic

Silicon is used for fabricating almost 70% of the total electronic devices worldwide and hence it becomes a representative of semiconductors family. Following diagram shows typical bonding structure of Si. (It is a simplified 2-D picture while the actual geometry is tetragonal). A particular electron “A” is a part of one of the covalent bonds. The same is indicated in an equivalent energy band diagram. It takes 1.1 eV of energy (at RT) to break a covalent bond in Si. When we do that, electron A becomes free and a vacancy bearing positive charge is created due to incomplete bond. This is regarded as “hole”.





The same is indicated in the energy band picture by showing electron “A” making a “jump” from VB to CB. Thus, it takes a minimum of 1.1 eV to create free electron-hole pair for conduction in intrinsic silicon. This value varies depending upon semiconductors e.g. in GaAs, it is 1.4 eV.

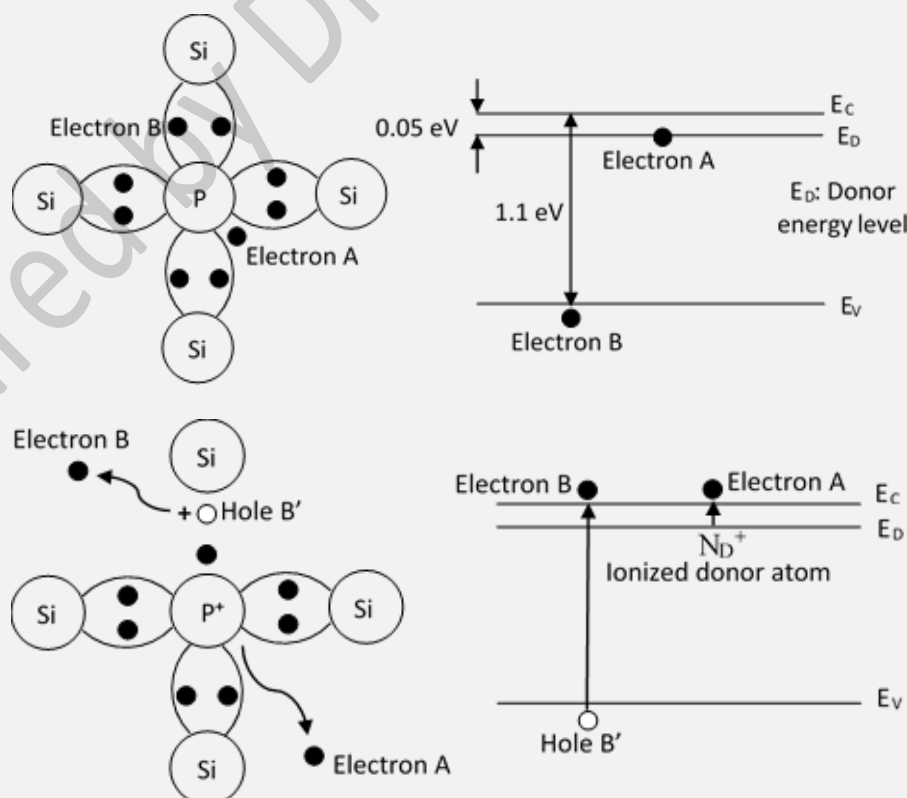
The intrinsic carrier concentration often denoted by “ n_i ” is given by the formula:

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

Where N_C and N_V are called effective density of states in the CB and VB. These are temperature and material dependent parameters and measured in number of energy levels per unit volume per eV while E_g the energy band gap, k is Boltzmann constant and T is absolute temperature.

B. Extrinsic semiconductor – N-type:

When we dope a pure semiconductor such as silicon with pentavalent impurity such as phosphorous, all four covalent bonds are completed. It takes very small amount of energy (merely 0.05 eV) to remove the fifth electron from the impurity. Electron-holes pairs are still created by breaking bonds between silicon atoms but now their proportion is very low (at RT). Thus for electrons, there are two sources: one, from host atoms by bond breaking and second, from donors but for holes, there is only one source that is bond breaking. Therefore, electrons become excess in number in n-type material and they are called as “majority carriers” while holes are called as “minority carriers”.



The addition of impurity is shown by indicating a “donor” level just below the CB in the energy band diagram

For n-type material at RT:

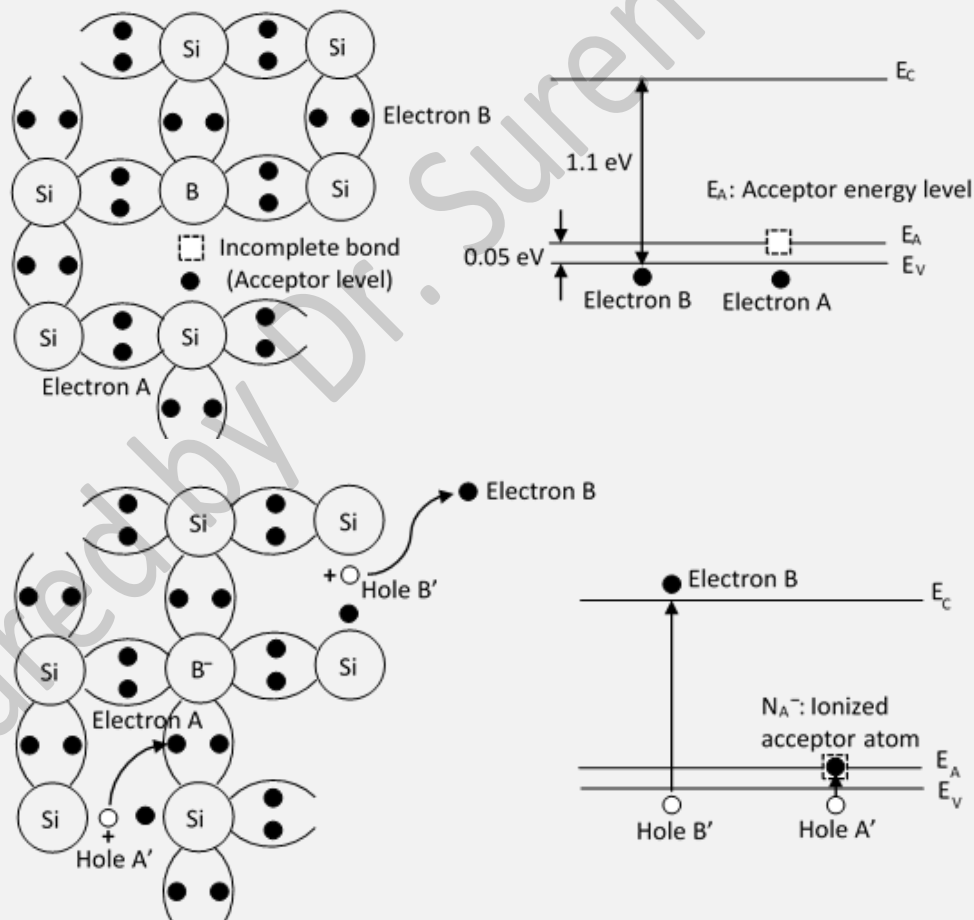
Majority carrier concentration $n_n \approx N_D$

Minority carrier concentration $p_n \approx \frac{n_i^2}{N_D}$

N_D is number of donors per unit volume.

C. Extrinsic semiconductor – P-type:

When we dope a pure semiconductor such as silicon with trivalent impurity such as boron, only three silicon atoms around it can form bonds with it and the forth bond is incomplete. But this is not a hole. When an electron shared by a neighbouring pair of silicon atoms jumps to boron to complete the forth covalent bond between boron and silicon, it leaves behind “uncompensated” silicon atom with deficit of one electron from its valence level. This is regarded as hole. Since the silicon atom is uncompensated, it acquires a net positive charge, which is assigned to the hole. In semiconductors at RT, such processes occur at all times and it can be called as “bond exchange”. Although it appears like breaking the bond between two host atoms, it doesn’t take full 1.1 eV of energy but it happens at merely 0.05 eV of energy. This is the energy required to create a “free hole”.



Electron-holes pairs are still created by breaking bonds between silicon atoms but now their proportion is very low (at RT) Thus for holes, there are two sources: one, from host bond breaking and second, bond exchange with acceptors but for electrons, there is only one source that is bond breaking. Therefore, holes become excess in number in p-type material and they

are called as “majority carriers” while electrons are called as “minority carriers”. The addition of impurity is shown by indicating a “acceptor” level just above the VB in the energy band diagram. For p-type material at RT:

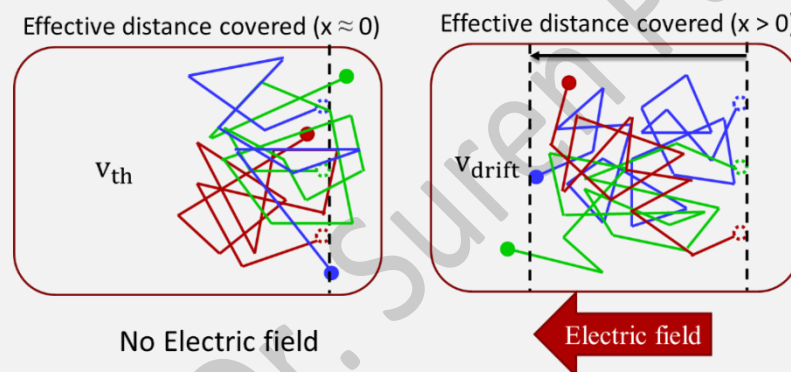
Majority carrier concentration $p_p \approx N_A$

Minority carrier concentration $n_p \approx \frac{n_i^2}{N_A}$

N_A is number of acceptors per unit volume.

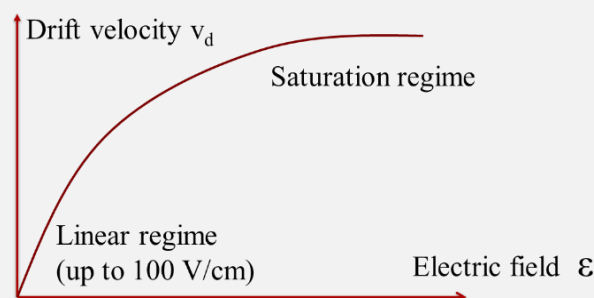
- **Charge carrier transport and current mechanisms**

- 1) **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.

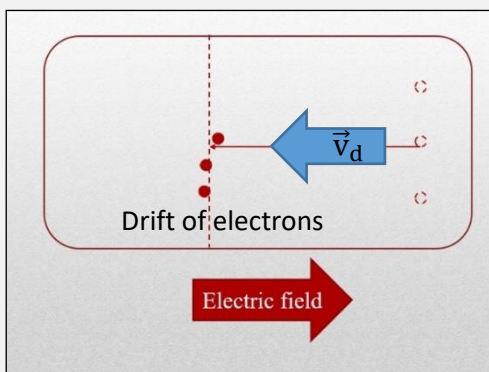
- 2) **Mobility:** The drift velocity is linearly proportional to the electric field intensity (until drift velocity gets saturated at certain critical field intensity). Thus, $v_d \propto \mathcal{E} \Rightarrow v_d = \mu \mathcal{E}$; Where the symbol “ \mathcal{E} ” is used for electric field intensity. 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. Its SI unit is $m^2/V\text{-sec}$.



The variation of drift velocity with electric field is shown in following diagram. Mobility depends upon a number of factors such as electric field, temperature, crystal structure, defects, impurities,

grain boundaries but at low fields and at room temperature, we can regard it as constant for a given material.

- 3) **Microscopic Ohm's law:** In semiconductor physics, the Ohm's law is expressed in terms of more fundamental relation, which is $J = \sigma E$; where, J is the current density i.e. current per unit area normal to it and σ is conductivity
- 4) **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 $\vec{J}_{\text{drift}} = qn\vec{v}_d$. Symbol "n" used in the equation here refers to any particle in general (electron or hole) and it is called the particle density (Unit: m^{-3} or cm^{-3}). In particular, for electrons,

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

$\therefore J_{\text{drift}}(\text{electrons}) = qnv_d$ numerically

For holes,

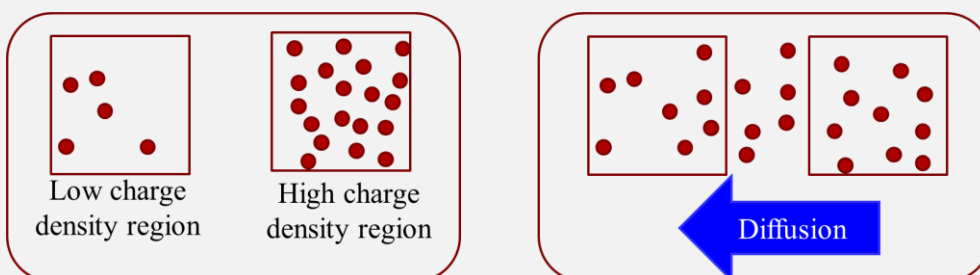
$\vec{J}_{\text{drift}}(\text{holes}) = (+q) \times p \times (+\vec{v}_d) = qp\vec{v}_d \dots$ as holes are positively charged and they drift along the electric field. Here, "p" is hole density i.e. number of holes per unit volume

$\therefore J_{\text{drift}}(\text{hole}) = qp v_d$ numerically

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

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

- 5) **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 $\vec{J}_{\text{diffusion}} \propto -\frac{dn}{dx}\hat{i}$. Symbol “n” here is the particle density as before and here it refers 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,

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

$\therefore J_{\text{diffusion}}(\text{electrons}) = qD_n \frac{dn}{dx}$ numerically. Here $\frac{dn}{dx}$ is the concentration gradient for electrons.

The constant of proportionality is called diffusion coefficient (D_n) of electrons. Its SI unit is m^2/s .

For holes,

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

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

Thus,

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

- 6) 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:

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

- 7) 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:

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

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

- 8) 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 mobility of electrons.
- For p-type: $\sigma = qp\mu_p$; where μ_p is mobility of holes.
- 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, $\rho = \frac{1}{\sigma}$.

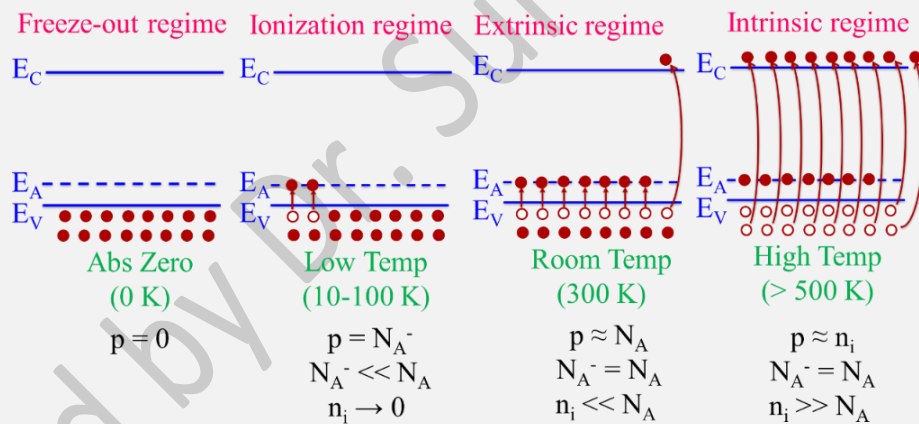
SI unit of resistivity is $\Omega\text{-m}$.

9) Temperature dependence of conductivity of extrinsic semiconductors: The contribution to conductivity of an extrinsic semiconductor comes from different mechanisms at different temperatures.

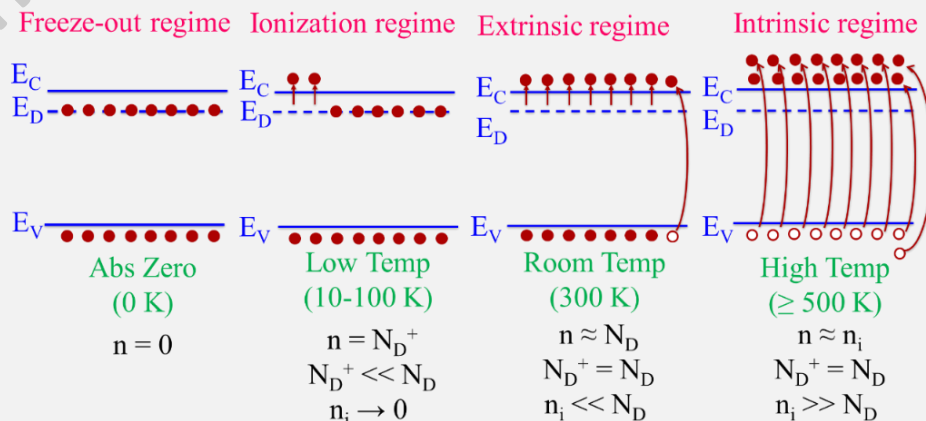
- At very low temperatures (< 10 K), all the electrons occupy lowest energy states. VB is full and CB is empty. This is called “freeze-out” regime and the semiconductor behaves as an insulator.
- At low temperatures (10-100 K), electrons and holes from donors and acceptors are liberated due to increased thermal energy. CB gets filled up and VB starts acquiring holes. This is called “ionization” regime and the semiconductor starts conducting.
- At room temperature (300 K), almost all the donors and acceptors are ionized and conductivity of semiconductor is predominantly 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).
- For temperatures 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 significant 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.

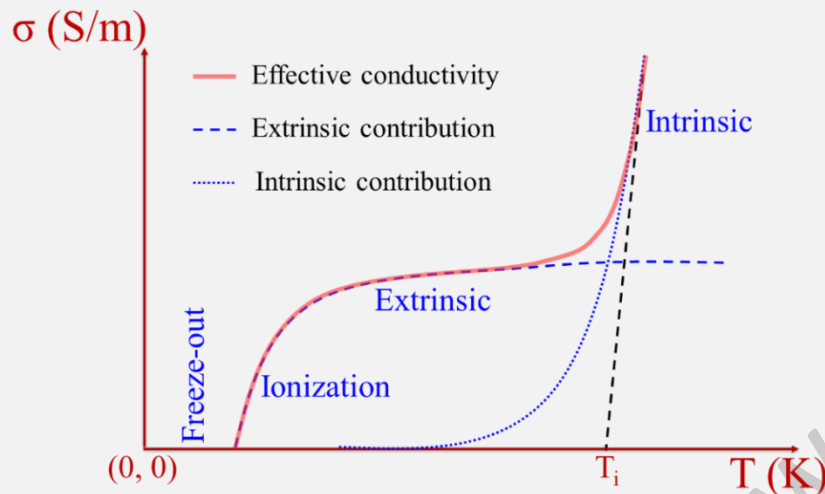
The variation in charge carrier concentration and hence the conductivity of semiconductors due to all the regimes mentioned above is shown in following diagrams:

p-type semiconductor



n-type semiconductor





- **The Fermi-Dirac function**

The Fermi-Dirac (F-D) function is one of the three statistical functions used in Physics for a system consisting of a large collection of particles (or identical, individual units in general). The other two are namely Maxwell-Boltzmann (M-B) and Bose-Einstein (B-E) statistics. The M-B statistics applied to systems such as gases. The B-E statistics applies to all particles having integral spin, which are also called as “boson”. Chief examples of bosonic particles are photons and the recently discovered Higg’s bosons. The F-D statistics is applicable to all particles having half integral spin (spin $\frac{1}{2}$ particles), which are also 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,

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

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,

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

Here, m^* is called the “effective mass” of a charged particle, which is different than its usual mass.

- **Illustrative application of Fermi-Dirac function to find number of electrons and holes:**

Electrons: The number of electrons in the CB is obtained by integrating the product $F(E) g(E)$. Lowest energy possessed by a conduction electron is E_C and highest energy is taken to be infinity for mathematical simplicity. Thus,

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

The integral evaluates to $n = N_C \exp\left(-\frac{E_C - E_F}{kT}\right)$ (derivation not expected in exam)

Holes: 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,

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

It evaluates to $p = N_V \exp\left(-\frac{E_F - E_V}{kT}\right)$ (derivation not expected in exam)

- Temperature dependence of Fermi-Dirac function**

The Fermi Dirac function is given by,

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

Case 1: 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 that in intrinsic semiconductors, the moment we make an electron free from the VB and transfer it to the CB leading to the equal number of electrons and holes as described earlier. The result 50% means the probabilities of finding an electron in the CB or a hole in the VB are equal.

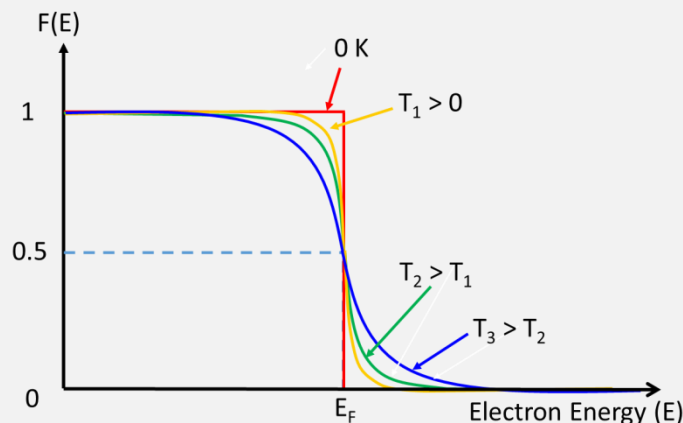
Case 2: At absolute zero

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

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

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 (a) and (b) imply that at absolute zero temperature, the probability that an electron can be present in the CB is zero and getting it 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 below:

Note: At absolute zero, $E = E_F$ is undefined.



- **The Fermi level**

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. For semiconductors, the Fermi level is usually defined in the following manner:

Definition 1 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.

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

Definition 2 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 intrinsic material, the Fermi level is located midway between the CB and VB**

For intrinsic materials we have, $n = p$

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

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

Taking logarithm on both sides, $\frac{-E_C + 2E_F - E_V}{kT} = \ln\left(\frac{N_V}{N_C}\right) \therefore E_F = \frac{E_C + E_V}{2} + \frac{kT}{2} \ln\left(\frac{N_V}{N_C}\right)$

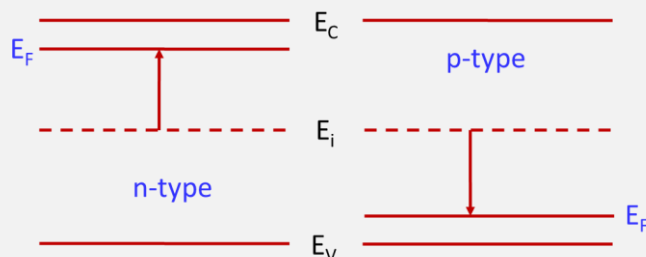
For semiconductors, the values of N_C and N_V are close to each other. (e.g. in silicon at RT, N_C and N_V are $3.2 \times 10^{25}/m^3$ and $1.8 \times 10^{25}/m^3$ respectively). Further, value of $kT \approx 0.026$ eV at RT hence the second term on RHS becomes negligible as compared to the band gap.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

$$E_F = \frac{E_C + E_V}{2} \quad (\text{Intrinsic semiconductors})$$

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.

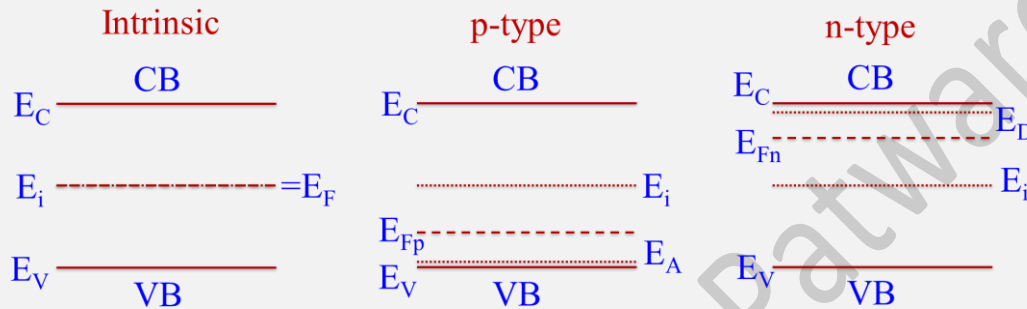


In either material, the shift of Fermi level from the central position is directly proportional to the logarithm of donor or acceptor concentration. It is given by,

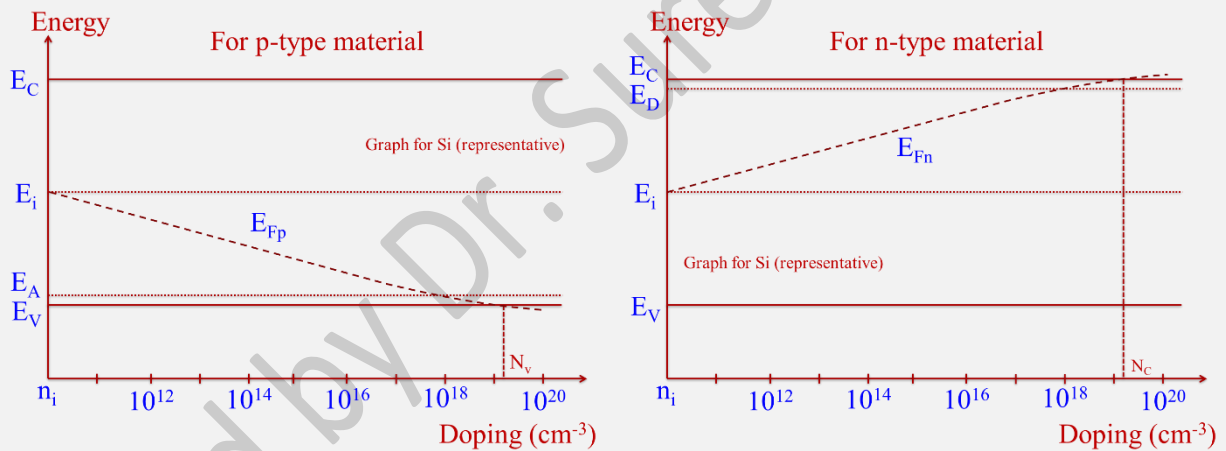
- For n-type: $E_F - E_i = kT \ln \left(\frac{n}{n_i} \right)$; $n \approx N_D$ at RT
- For p-type: $E_F - E_i = -kT \ln \left(\frac{p}{n_i} \right)$; $p \approx N_A$ at RT

E_i is called the “intrinsic level” or the midway position.

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.



- Variation of Fermi level over a range of doping concentration



For very high doping concentrations i.e. when the doping density exceeds 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 required for certain applications such as zener diodes, laser diodes, microwave devices etc.

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