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Energy Band and charge carriers in Semiconductor

Semiconductor :- (Intrinsic)

If the electrical conductivity of a semiconductor is entirely determined by the carriers which are generated by thermal excitation from the valance band to conduction band, the semiconductor is referred to as a pure or intrinsic semiconductor.

Si, Ge are available in the form of crystalline solids. Each atom forms four covalent bonds with four nearest neighbouring atoms by sharing of valance electrons with opposite spin. At 0K no free carrier is available and the crystal behaves as perfect insulator. However at room temperature (~300K) a few of the electrons acquire sufficient Kinetic energy from thermal agitation & break their covalent bonds & conduction is possible. The dislodged electrons can wander freely in a random fashion throughout the crystal. The minimum energy required to break such a covalent bond is about 0.72 eV for Ge and 1.1 eV for Si. When an electron escapes from covalent bond, an electron vacancy is created in the bond and such an incomplete bond is called a hole. The hole may be imagined to behave like a positively charged particle and can take part in the conduction of electricity. Under the action of an external electric field an electron from nearby filled covalent bond may come and fill the hole. The electron also leave a covalent bond vacancy or hole. So hole behaves like a particle of same and opposite charge to that an electron.

The generation of free electron & a hole by thermal breakage of a covalent bond is commonly known as 'electron hole pair' generation.

In pure or intrinsic semiconductor the number of free electron is equal to the number of holes. So, free electron concentration n must be equal to the hole concentration p,

i.e $n = p = n_i$

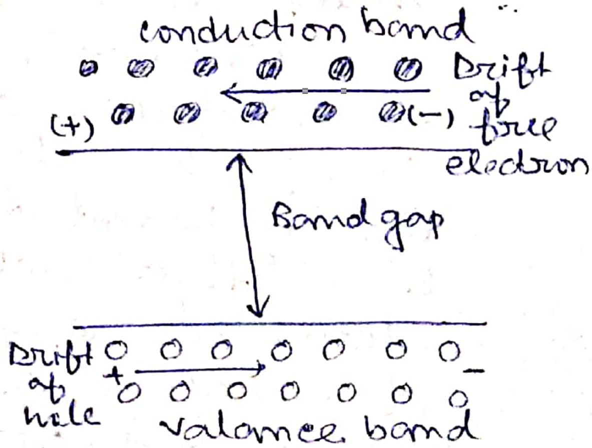
where n_i is called the intrinsic concentration.

Effective Mass :-

when an external field is applied to a semiconductor, the charge carrier i.e the electron and holes, experience forces due to applied field and also due to internal field produced by the crystal. If the applied field is much weaker than the internal field, the effect of the latter is to modify the mass of the carrier in such a way that the carrier responds to the applied field with the modified mass obeying classical mechanics. This modified mass is termed the effective mass.

Drift electrons and holes in an external field

The electrons in the conduction band & holes in the valance band move random fashion. when an external field is applied a drift velocity is superimposed on the random motion of electron and hole.



The drift of electron in conduction band hole in the valance band

③ produce electric current. The electron move towards positive electrode and hole toward negative electrode. Thus the conventional current flows with in the semiconductor from positive electrode to the negative electrode.

Recombination of electron and holes:

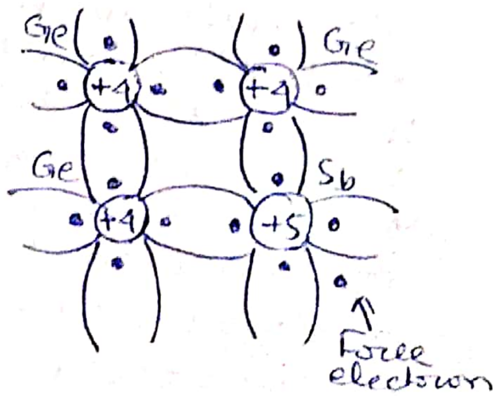
Recombination is the process in which the free electrons in the conduction band jump into the valance band to combine with holes. The rate of recombination is approximately proportional to the product of electron & hole concentration. In the process of recombination the electron hole pair is destroyed, new pair are generated due to thermal excitation. The rate of recombination & rate of generation of e-h pair are equal.

Extrinsic semiconductor:

The addition of small percentage of impurity atoms to a semiconductor is called doping and the impurity that is added is termed dopant. A semiconductor having impurities is referred to as a doped or extrinsic semiconductor.

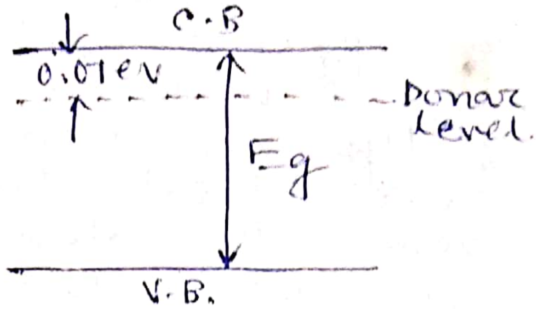
n-type semiconductor:-

Let a small amount of a group V element such as P, AS or Sb be added to a Ge or Si crystal. Four of the five valance electrons of the pentavalent impurity atom will form covalent bonds with the four valance electron. The fifth electron is loosely bound and it can be easily detach from the atom. The energy required for that is about 0.01eV for Ge and 0.05 eV for Si. This energy is much less than the band gap Eg.



Since the impurity atoms of concern here donate excess free electrons, they are known as donar. The electron being negatively charge and contain donar impurity are referred to as n-type semiconductor.

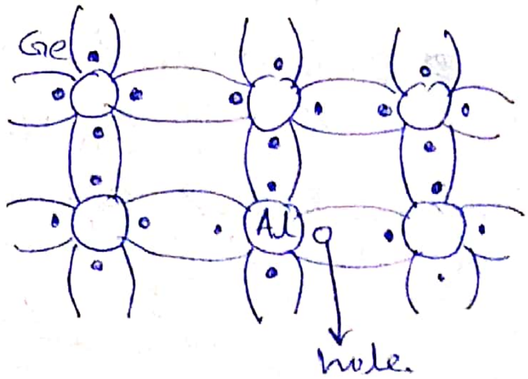
In this semiconductor, an allowable energy level corresponding to the loosely bound valance electron is introduced in the forbidden gap just below the conduction band. This new allowable energy level is a discrete level, called the donar level.



p-type semiconductor;

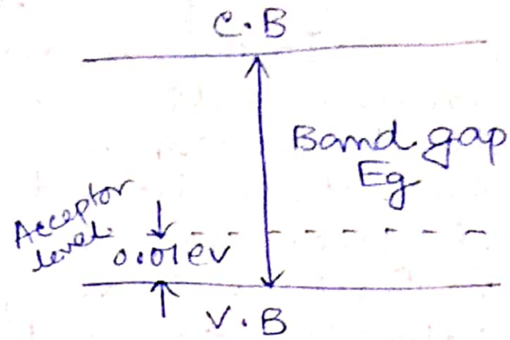
Let a small amount of a group III element like Al, B or In be added to Ge or Si semiconductor. If a trivalent impurity atom ~~can accept one electron~~, replace a host crystal atom, only three of the four covalent bonds can be filled and one remain vacent. The energy required for this purpose is about 0.01 ev for Ge and 0.05 ev of Si. The vacancy that exists in the fourth bond constitues a hole. So, corresponding to each impurity atom ~~exists in the~~ added a hole is formed which can accept one electron.

Moreover, there are equal number of holes and electrons formed due to thermal breakage of a few covalent bonds. The presence of large number of holes increases recombination rate and decreases the electron concentration below the intrinsic level. So, the number of holes exceeds the number of electrons. So, the holes are called



(5) majority carrier and electrons are called minority carrier. The semiconductor is known as acceptor type or p-type semiconductor.

Here the unfilled energy level produced by introducing of p-type impurities in a semiconductor lies just above the valence band. This allowed energy level is called the acceptor level.



Mass - action law :-

Under thermal equilibrium, the product of the free electron concentration n and the hole concentration p is a constant equal to n_i^2, where n_i is the intrinsic carrier concentration. The result is known as Mass action law and is expressed by,

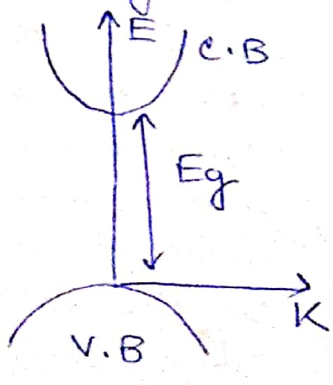
$$np = n_i^2$$

n_i is the function of temperature. When n (or p) is increased by the addition of impurities, the corresponding p (or n) must decrease to make np equal to const. (n_i), at a particular temperature.

Direct and indirect bandgap semiconductor

On the basis of the energy band structures, semiconductor can be classified as direct and indirect band gap types.

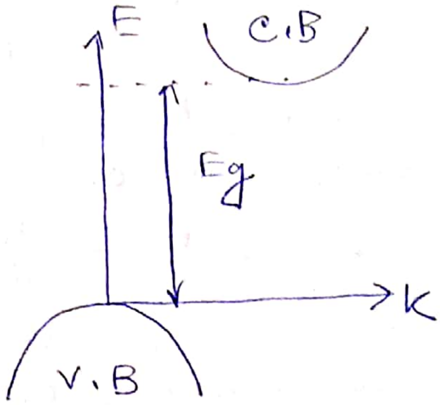
In a direct band gap semiconductor (GaAs, InP), the minimum of conduction band and the maximum of valance band are at same point in wave vector ($\vec{K}$) space. Here an electron may jump



from ~~from~~ the minimum of conduction band to the maximum of valance band without change in $\vec{K}$. Thus momentum is automatically conserved and there is direct recombination of electrons and holes and the excess energy is emitted in the form of photons. The minimum freq. of the emitted photon is given by $E_g = h\nu$, where h = Planck's constant.

Application :- LASER and light emitting diode.

In indirect gap semiconductor (Ge, Si), the valance band maximum and the conduction band minimum do not occur at the same point in $\vec{K}$-space. So, the transition of electron from minimum conduction band to maximum valance band involves change in energy as well as momentum. So, there is no direct recombination of electron and hole. Recombination take place via traps or recombination centres which contributes defect states in the band gap. As a result the energy liberated generally goes to heat the crystal.



Application :- Diode, transistor.

Degenerate and non-degenerate semiconductor :

For a semiconductor with low impurity concentrations the number of electron in the conduction band and holes in the valance band is usually much less than the number of quantum states in these band. Here the impurity states are discrete levels and the carriers obey classical distribution law. This type of semiconductor is called non-degenerate semiconductor.

When an impurity concentration become very high the impurity levels develop into energy band, the number of carrier approach or become greater than the number of quantum states. In this case classical distribution laws become inapplicable. Such semiconductors are called degenerate semiconductor.

FD distribution function :-

FD distribution function is found to be,

$$f(E) = \frac{1}{1+\exp[(E-E_F)/K_B T]} \quad \text{—— (1)}$$

where $f(E)$ = probability of occupancy of the state with energy E,

E_F = characteristic energy for a particular solid, referred as Fermi level.

T = absolute temperature.

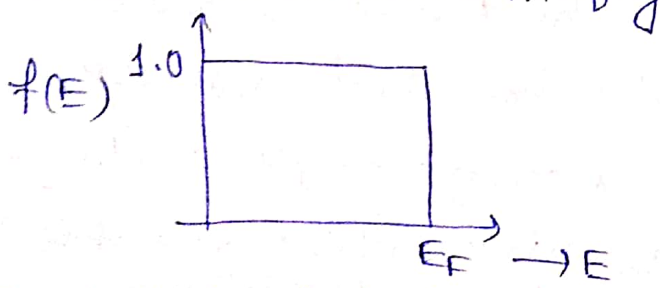
K_B = Boltzmann constant.

$T = 0K$ from eq. (1), we get,

$f(E) = 1$ when $E < E_F$

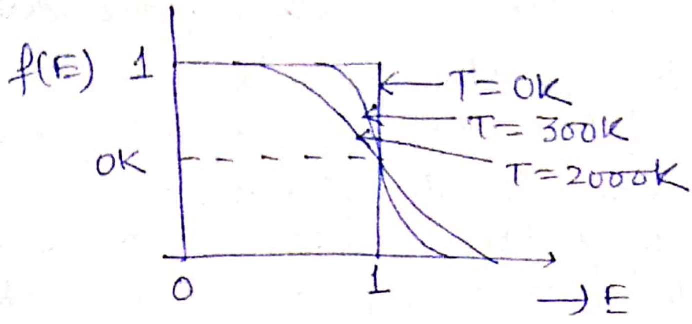
$= 0$ when $E > E_F$

at absolute temperature $f(E)$ is a step function as shown in fig,



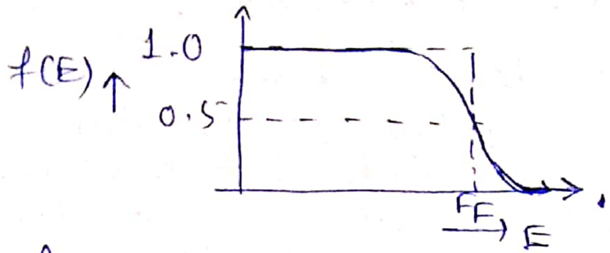
Thus at absolute temperature, the fermi energy or Fermi level represent the highest occupied energy level.

As temperature increase $f(E)$ change from 1 to 0 more and more gradually as shown in fig.



At all non-zero temperature i.e $T>0$ when $E_i = E_F$

$$f(E) = \frac{1}{1+e^0} = \frac{1}{2}$$

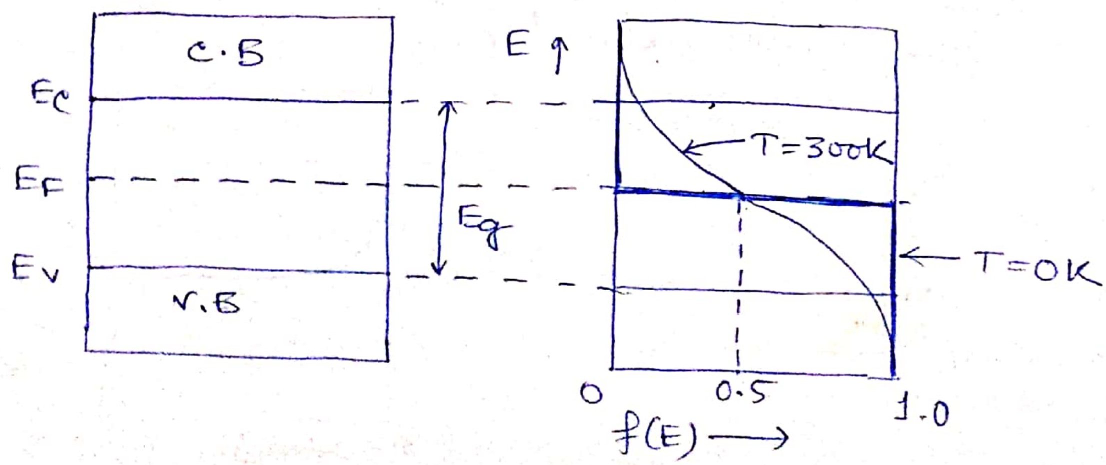


Thus fermilevel is the energy level for which the probability of electron occupation at $T>0$ is $1/2$ i.e 50% of the quantum state are occupied and 50% are empty.

Position of Fermilevel for intrinsic semiconductor:-

At absolute zero of temperature, the probability of an electron occupying a state in the conduction band is zero, and valance band being totally full. The Fermilevel E_F which can be the highest occupied energy level at T=0K lies near the middle of the band for an intrinsic semiconductor.

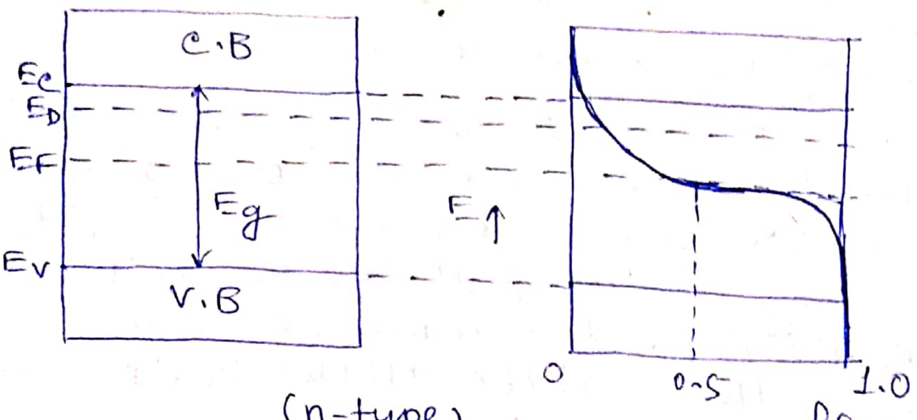
At room temperature T=300K, some of the electron jump from valance band to conduction band and fill the state near the



botton of the conduction band. The tail of $f(E)$ now extends into the conduction band, the probability of occupancy of state there being non-zero. An equal number of holes exists near the top of the valence band so that the probability of occupancy there falls below unity.

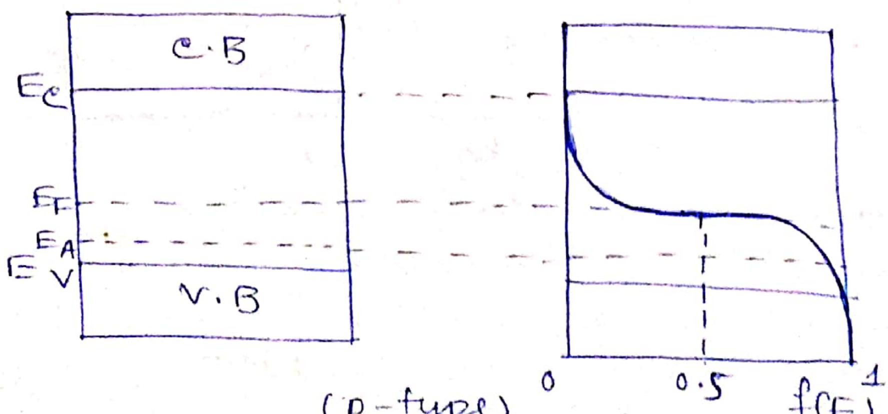
Fermilevel position of Extrinsic Semiconductor:

Here E_D denote the donar level. Assuming complete ionization of the donar atoms at a finite temperature, we find that free electrons coming from the donar atoms fill the state near the bottom of the conduction band. So it is more difficult for the electrons in the valence band to cross the bandgap by the thermal agitation. Therefore the number of



(n-type)

holes in the valence band decrease. As the Fermi level E_F is the energy for which the probability of occupancy is half, E_F must move closer to the conduction band for an n-type semiconductor.



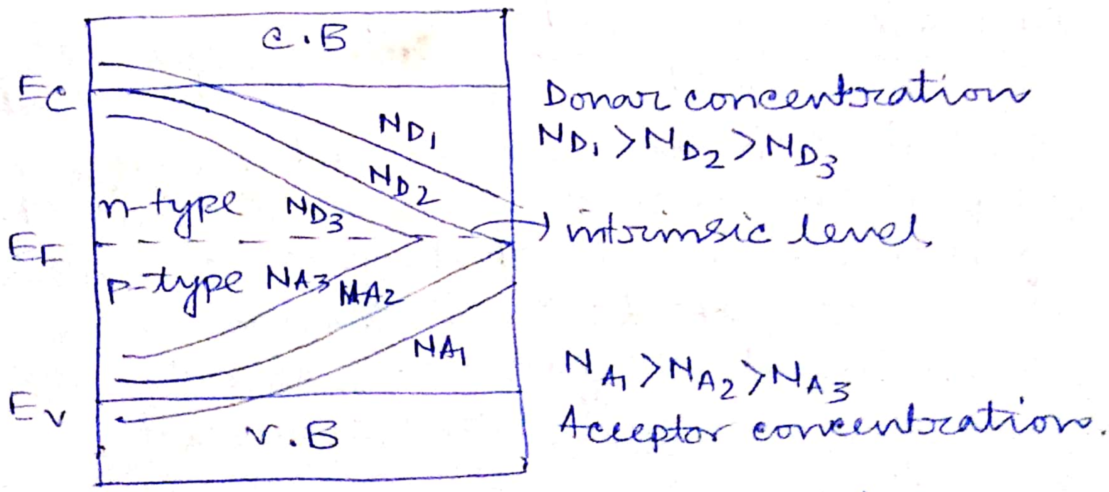
(p-type)

Similarly arguments show that E_F must move from centre of the band gap closer to the valance band for a p-type semiconductor.

Fermi level shift with doping and temperature:-

If the doping is very high, the fermi level moves into the conduction for an n-type semiconductor, and into the valance for a p-type material.

As the temperature of the semiconductor rises, we have seen that both n type and p-type semiconductors become essentially intrinsic. When temperature of n-type or p-type semiconductor increases, the Fermi level E_F moves towards the centre of the band gap. as shown in fig below:-



Electric conduction in Semiconductor:-

In semiconductor current is carried by free electron and holes. But