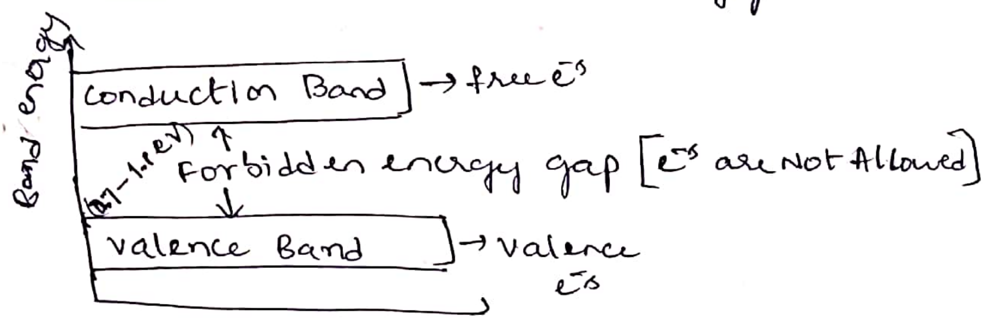
Introduction to Semiconductors

Semiconductors are materials which have a conductivity between conductors (generally metals) & Insulators

It depends on the forbidden energy bands.

"The range of energies possessed by an electron in a 'Solid' is known as energy bands.



Properties:

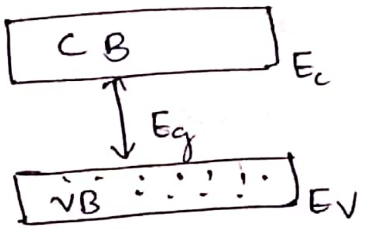
1. The Resistivity lies between 10^{-4} to $0.5\,\Omega m$
2. At 0K, they behave as Insulators
3. The Conductivity of a Semiconductor increases both due to Temp & impurities
4. They have negative temp coefficient of resistance
5. In Semiconductor both the e^- & p (holes) are charge carriers & will take part in conduction.

Types of Semiconductors

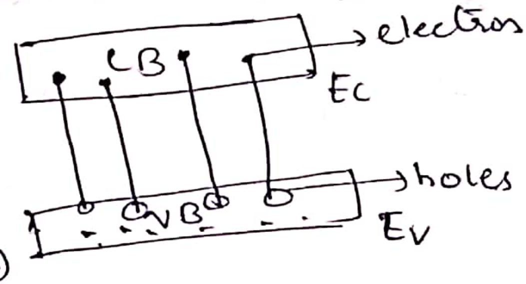
Intrinsic Semiconductors: Semiconductor in a pure form is
835
called Intrinsic Semiconductor. Here the charge carriers are produced only due to Thermal agitation.

they have low electrical conductivity.

eg: Si, Ge [elements of IV group of periodic table)
~~GaAs~~ (~~gallium Arsenide~~), ~~SiC~~ (~~Silicon Carbide~~), ~~PbS~~



a) AT T=0
VB is completely filled
& CB is completely empty



b) At T>0
Some e^-s excited from VB to CB & holes appear in VB.

At T=0K Intrinsic Semiconductor behaves as Insulators

At T>0 (higher Temp) such that thermal energy K_BT is more than that of energy gap ΔE_g. The excitation of e^-s from VB to CB takes place.

It creates equal no of holes in VB & free e^-s in CB.. Both holes & e^-s serves as charge carrier in electrical conductivity.

[hole → empty space (energy levels) in VB]

For Intrinsic Semiconductor no of e^-s in CB (n) & no of holes in VB (p) are always same

mathematically, $n = p$

$n = p = n_i \xrightarrow{836}$ no of Intrinsic charge carriers

this leads to conduction & hole current.

Fermi Level in Semiconductor

WKT. At T=0K all the electronic states of the valence band are full & those of CB are empty. so, semiconductor behaves as Insulator at 0K.

But as Temp increases some electrons from the VB get sufficient energy & become free. they move to CB & take part in conduction & give rise to conductivity in semiconductor.

* Now we want to discuss the phenomenon quantum Mechanically.

→ Classically all $\bar{e}$'s have zero energy at 0K. but quantum mechanically e^{-}'s cannot have ~~ok~~ zero energy at 0K.

The Maximum energy that electrons may possess at 0K is the fermi energy (E_F)

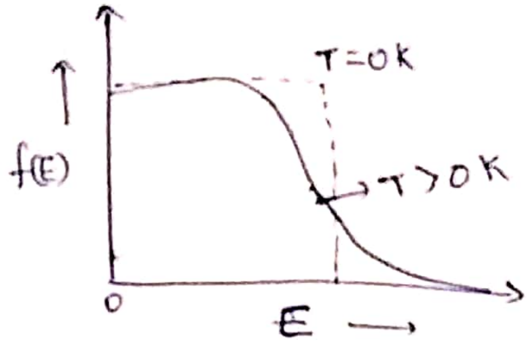
So, quantum mechanically, the electrons actually have energies extending from 0 to E_F at absolute zero Temp.

Now in order to know how many of the electronic energy states in the valence Band & conduction band will be occupied at different Temperatures, we Introduce a Fermi-factor ($f(E)$) or fermi function, which is the number that expresses the probability that a state of a given energy (E) is occupied by electron under conditions of thermal equillibrium.

This number has a value between zero & unity & is a function of energy & Temp.

~~required: Set<Lark>~~
~~Found: HashSet~~

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



E → given energy level
E_F → fermi-energy level
f(E) → fermi function
K → Boltzmann Const, T → Absolute Temp

for (i) if $E \gg E_F$ (becoz $e^{\infty} = \infty$)

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

(ii) $E \ll E_F$ (becoz $e^{-\infty} = 0$)

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

(iii) $E = E_F$

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

thus at T=OK. f(E) = 1, when $E < E_F$, which means all the levels below E_F. i.e, valence bands are filled up by electrons & f(E)=0, when $E > E_F$. that is (i.e.) all the ~~elect~~ levels above E_F i.e, conduction bands are empty.

Because at OK no heat energy is present, so no covalent bonds are being broken & the semiconductor behaves as insulator

Expression for Fermi-level in an Intrinsic Semiconductor (3)

In an Intrinsic semiconductor at a Temp well above 0K

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choiceArray = (T[]) choices.toArray();
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there are thermal electrons in the CB & equal number of holes in VB.

i.e., $n_i = p_i \longrightarrow (1)$

$n_i \rightarrow e^-$ concentration
$p_i \rightarrow$ hole conc

WKT electron concentration in CB is.

$$n_i = 2\left(\frac{2\pi KT}{h^2}\right)^{3/2}\left(m_e^*\right)^{3/2} \exp\left(\frac{E_F - E_c}{KT}\right) \rightarrow (2)$$

Also hole conc in VB is

$$p_i = 2\left(\frac{2\pi KT}{h^2}\right)^{3/2}\left(m_p^*\right)^{3/2} \exp\left(\frac{E_V - E_F}{k_B T}\right) \rightarrow (3)$$

$m_e \rightarrow e^-$ rest mass
$m_p \rightarrow$ hole rest mass
$E_V \rightarrow$ valence band energy
$E_C \rightarrow$ CB energy
$k \rightarrow$ Boltzmann Const
$h \rightarrow$ Plancks const

In Intrinsic Semiconductor $n_i = p_i = n_i$
hole $= e^-$ = Intrinsic charges

equate right hand sides

$$\cancel{2\left(\frac{2\pi k_B T}{h^2}\right)^{3/2}}\left(m_e^*\right)^{3/2} \exp\left(\frac{E_F - E_c}{k_B T}\right) = \cancel{2\left(\frac{2\pi k_B T}{h^2}\right)^{3/2}}\left(m_p^*\right)^{3/2} \exp\left(\frac{E_V - E_F}{k_B T}\right)$$

$$\left(m_e^*\right)^{3/2} \exp\left(\frac{E_F - E_c}{k_B T}\right) = \left(m_p^*\right)^{3/2} \exp\left(\frac{E_V - E_F}{k_B T}\right)$$

$$\frac{\exp\left(\frac{E_F - E_c}{k_B T}\right)}{\exp\left(\frac{E_V - E_F}{k_B T}\right)} = \left(\frac{m_p^*}{m_e^*}\right)^{3/2}$$

$$\frac{e^a}{e^b} = e^{a-b}$$

$$\exp\left(\frac{(E_F - E)}{k_B T} - \frac{(E_V - E_F)}{k_B T}\right) = \left(\frac{m_p^*}{m_e^*}\right)^{3/2}$$

$$\exp\left(\frac{E_F - E_c - E_v + E_F}{k_B T}\right) = \left(\frac{m_p^*}{m_e^*}\right)^{3/2}$$

$$\exp\left(\frac{2E_F - E_v - E_c}{k_B T}\right) = \left(\frac{m_p^*}{m_e^*}\right)^{3/2}$$

$$\frac{2E_F - E_c - E_v}{k_B T} = \ln\left(\frac{m_p^*}{m_e^*}\right)^{3/2}$$

$$2E_F - E_c - E_v = (kT)\,3/2\, \ln\left(\frac{m_p^*}{m_e^*}\right)^{3/2}$$

$(\ln 1 = 0)$

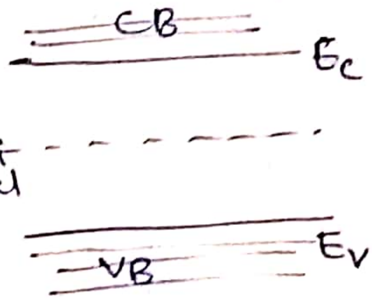
$(E_c + E_v = E_g)$

when $m_p^* = m_e^*$

$$2E_F - E_c - E_v = 0$$

$$2E_F = E_c + E_v$$

or $$\boxed{E_F = \frac{E_c + E_v}{2}}$$ or $\left(E_F = \frac{E_g}{2}\right)$



In case $m_e^* = m_h^*$ then the fermi level lies exactly in between VB & CB i.e. middle of the forbidden gap. or Energy gap.

However in general $m_h^* > m_e^*$, the fermi level is raised slightly as T increases.

Extrinsic semiconductor

The electrical conductivity of Intrinsic semiconductor is very small. To increase the conductivity of Intrinsic semiconductor a small percentage of trivalent or pentavalent atoms (impurities) is added to the pure semiconductor in the process of crystallisation, which is called doping & results the impure semiconductor being called extrinsic semiconductor.

The conductivity of extrinsic semiconductor is much higher, say for example 12 times than Intrinsic semiconductor when an impurity is added 1 part in 10^8.

The Impurity atom has a size which is almost of the same order of the host lattice. Since percentage of Impurity atoms is very small, so every atom is surrounded by normal lattice so basic structure of crystal will not get altered after doping.

There are two types of extrinsic Semiconductor

N-type & P-type.

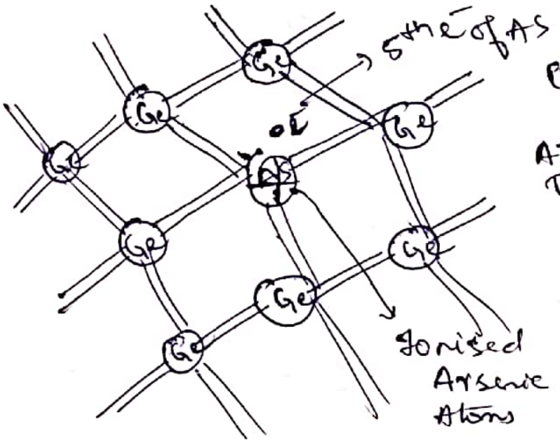
N-type Semiconductor

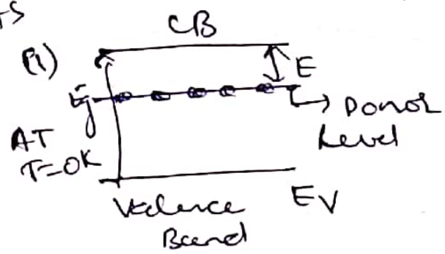
When Intrinsic Germanium is doped (It is a process of homogeneous mixing of a small quantity of known Impurity into the host material) with one of the group V elements:

Since the host germanium atoms are tetravalent (4). only four of the five valence electrons of the impurity are able to form covalent bond, leaving one electron weakly bounds to its parent atom.

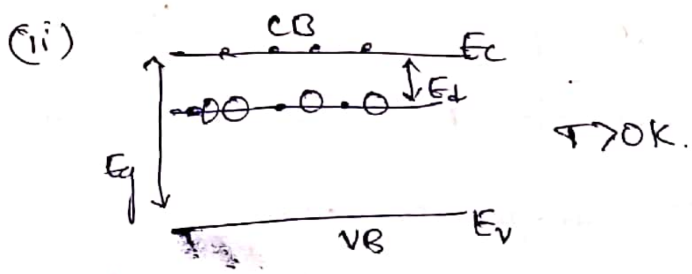
This electron can be easily excited into the CB by supplying an energy equal to $E_d = 0.013eV$.

this $\bar{e}$ leaves the atom & is free to move in the Germanium lattice, such an $\bar{e}$ behaves as conduction $\bar{e}$





[Energy levels of one of the 5 $\bar{e}^s$ of every Arsenic atoms are donor levels]



In Terms of Band theory, the energy levels of 5th $\bar{e}$ of impurity atoms occupy position between VB & CB as shown these levels are at a distance E_d (~0.013eV) below the CB.

At T=0K all these levels are occupied but at even moderately low Temp most of the $\bar{e}^s$ move to CB becoz of small E_d. The remaining +ve charge (a hole) on Arsenic atom is localized & doesnot take part in electrical conductivity.

the impurities are called donors which supply $\bar{e}^s$ without simultaneously creating holes. ∴ $\bar{e}^s$ are majority charge carriers. & holes in VB is minority charge carriers.

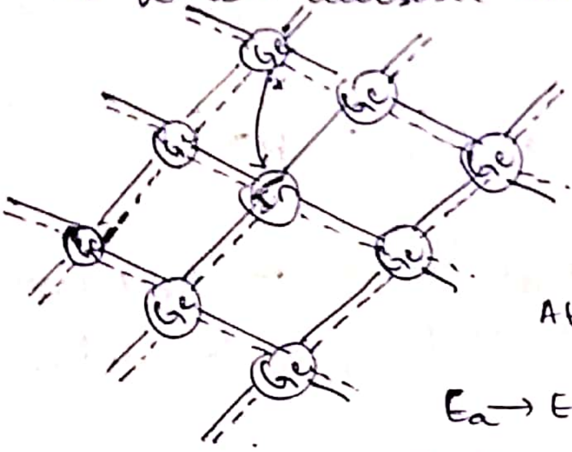
The Semi-conductor doped with donor impurity is called N-type semiconductor.

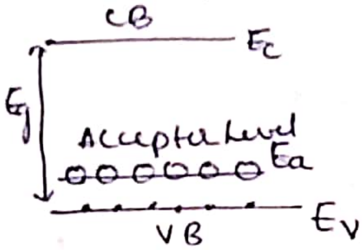
ex!

p-type Semiconductor

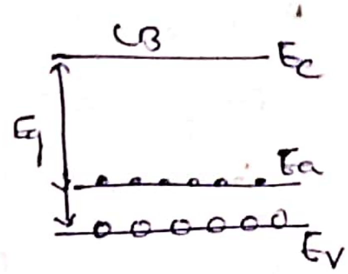
when the Germanium/silicon is doped with a trivalent impurity such as Indium. it is found that impurity atoms occupy the sites normally occupied by Ge atoms the Indium atom is short of one $\bar{e}$ to establish bonds with all the four nearest neighbours.

However, It can borrow the required $\bar{e}$ from a Ge atom. if an energy equal to $E_a \simeq 0.01eV$ is supplied to system. The transfer of an $\bar{e}$ from Ge atom leaves a hole in the VB which causes a break in one of the neighbouring Ge bonds





At T=0K



T>0K

$E_a \rightarrow$ Energy levels of unpaired bonds of Indium atoms are acceptor levels $\simeq 0.01eV$

The Impurities which trap $\bar{e}$'s & add holes to VB of parent atom without simultaneously adding conduction $\bar{e}$'s are termed as Acceptors

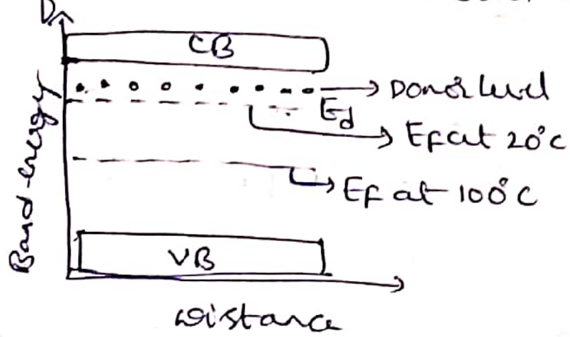
The semi-conductors doped with Acceptor impurities are Known as ptype Semi-conductors

In this case the holes are majority carriers in the VB & $\bar{e}$'s in CB (if any) are minority carriers

Fermi-Level in an Extrinsic Semi-Conductor

In an Intrinsic semi-conductor $(n = p) = n_i$
$e^- =$ holes

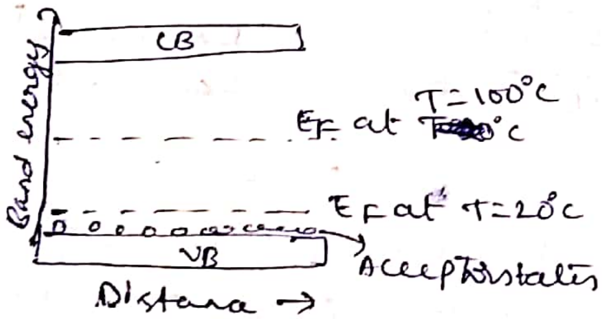
But in N-type extrinsic semiconductor no of e^-s is increased due to doping of pentavalent atoms $(n_e > n_i)$
& no of holes is decreased by $(p_e < p_i)$



At low Temp E_F lies closer to CB. $n_e > p_e$.
At high Temp E_F lies in between CB & VB.

lly for P-type

No of electrons are decreased by $(n_e < n_i)$ & $(p_e > p_i)$



for P type $(p_e > p_i)$ so E_F must move centre of E_g to closer to VB.

As the Temp rises the material becomes more & more intrinsic & Fermi level moves closer to Intrinsic position i.e, at the centre of Energy gap.

Charge carrier density in extrinsic Semi-conductor

In both n-type & p-type semiconductors e^-s which create the ions receive relatively higher energy than needed to create $(e^- - p)$ pairs. ∴ it is possible to establish conductivity at low temp compare to Intrinsic. Hence the density of conduction e^-s can be assumed to be equal to the density of Donor impurity (N_D). Likewise.

the density of holes in VB is equal to density of acceptor impurities (N_A).

It is to be noted that conc of majority charges is increased over its intrinsic value by doping. The conc of minority charges is found to decrease by by same amount to maintain conc product n_i^2 const.

i.e., $n_p P_p = n_i^2 \longrightarrow (1)$ mass Action Law

$(n_i p_i = n_i^2)$

where $n_i \rightarrow$ Intrinsic $\bar{e}$ density

$n_p, p_p \rightarrow$ $\bar{e}$ & hole densities in p type material.

Based on the above considerations, the amount of reduction in minority charges can be determined by use of eqn expressing overall charge neutrality of material is.

$$p + N_D = n + N_A \longrightarrow (2)$$

Now use eqn (1) $np = n_i^2$ we have

$$n = \frac{n_i^2}{p} \quad \& \quad p = \frac{n_i^2}{n}$$

so, eqn (2) becoms

$$p + N_D = \frac{n_i^2}{p} + N_A$$

$$p^2 + \cancel{(N_D - N_A)}p - n_i^2 = 0 \rightarrow (3)$$

If it is n-type semiconductor

$N_A = 0$ & $n \gg p$

$\therefore N_D \simeq n$

where $n_n \rightarrow \bar{e}$ conc in n type

$P_n \rightarrow$ hole conc in p type

From mass action Law $n.p = n_i^2 \Rightarrow P_n = \frac{n_i^2}{n_n} = \frac{n_i^2}{N_D}$

Illy for p type $N_D = 0$ $p \gg n$, $N_A \simeq p$

$$n_p = \frac{n_i^2}{P_p} = \frac{n_i^2}{N_A}$$

consider eq^n (2)

$$p + N_D = \frac{n_i^2}{p} + N_A$$

where
$n = \frac{n_i^2}{p}$
$N_D \rightarrow$ Donor concn
$N_A \rightarrow$ Acceptor conc

$$p^2 + (N_D - N_A)p - n_i^2 = 0 \rightarrow (3)$$

This is similar to quadratic eq^n of the form $ax^2+bx+c=0$ | $x = \frac{-b \pm \sqrt{b^2-4ac}}{2a}$

$$\therefore p = \frac{(N_A - N_D) \pm \left[(N_A - N_D)^2 + 4n_i^2\right]^{1/2}}{2} \rightarrow (4)$$

$$p = \frac{(N_A - N_D)}{2} \pm \cancel{\frac{2}{2}}\left[\frac{(N_A - N_D)^2}{4} + n_i^2\right]^{1/2} \rightarrow (5)$$

for Intrinsic SC $\quad N_A = N_D = 0$ & $n = p = n_i$

Case I $\underline{n\text{-type}}$: $N_D >> n_i$ & $N_A \simeq 0$

$$\therefore \text{eq}^n (5) \Rightarrow p_n = -\frac{N_D}{2} + \left[\frac{N_D^2}{4} + n_i^2\right]^{1/2}$$

$$p_n = -\frac{N_D}{2} + \frac{N_D}{2}\left(1 + \frac{4n_i^2}{N_D^2}\right)^{1/2} \longrightarrow (6)$$

second term under radical is less than unity expand is power series

$$p_n = -\frac{N_D}{2} + \frac{N_D}{2}\left(1 + \frac{1}{2}\left(\frac{4n_i^2}{N_D^2}\right) \pm \cdots\right)$$

$$p_n = -\frac{N_D}{2} + \frac{N_D}{2}\left(1 + \frac{2n_i^2}{N_D^2}\right) = \frac{n_i^2}{N_D}$$

$$\therefore \boxed{p_n = \frac{n_i^2}{N_D}} \longrightarrow (7)$$

IIIly

$$n_n = \frac{N_D}{2} + \frac{N_D}{2}\left(1 + \frac{2n_i^2}{N_D^2}\right) = N_D + \frac{n_i^2}{N_D}$$