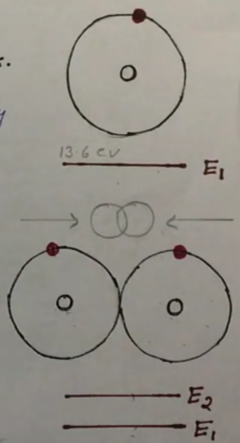
Formation of Energy Bands in a Solid

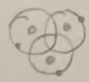
Hydrogen - atomic no. - 1

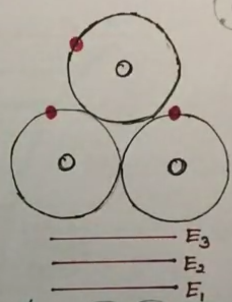
$H \rightarrow 1S^1$



- According to Quantum Mechanics the energies of electrons in a free atom can not have arbitrary values but only some (quantized) values.
- In an isolated atom the electrons are tightly bound & have discrete, sharp energy levels.
- If an atom belongs to a crystal, then the energy levels are modified.
- This modification is not in the case of energy levels of electrons in the inner shells.
- But in the outermost shells, modification is appreciable.
- When two identical atoms are brought closer the outermost orbits of these atoms overlap & interact. When the wave functions of the electrons of the different atoms begin to overlap considerably, the energy levels corresponding to those wave functions split into two.

- If more atoms are brought together more levels of an atom splits into N levels of Energy.
- The width of energy band depends on the energy level of each isolated atom and on the separation between the atoms of the crystal.
- The width of energy band of low energy level is less & that of high energy level is more.



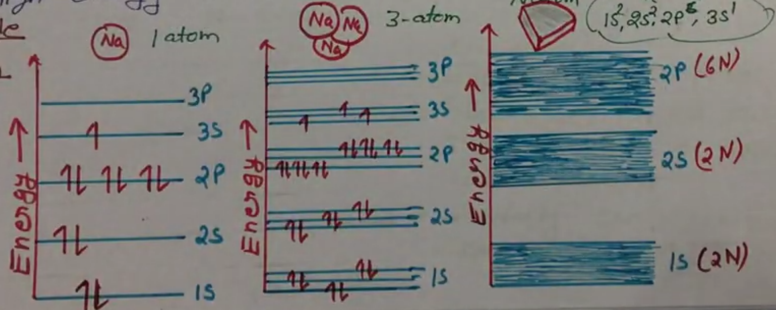


example

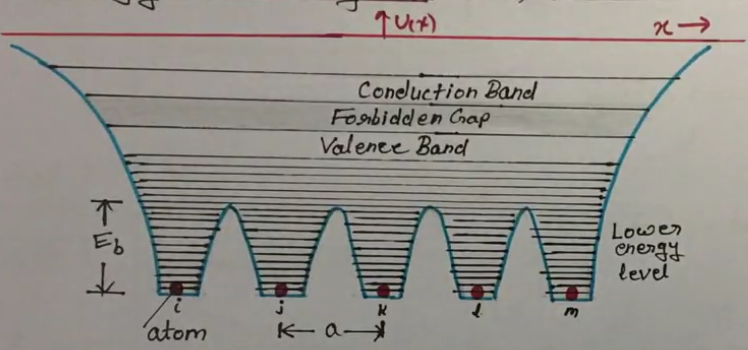
Sodium

atomic Number 11

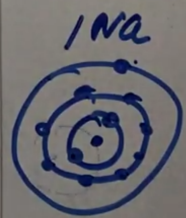
Confi.



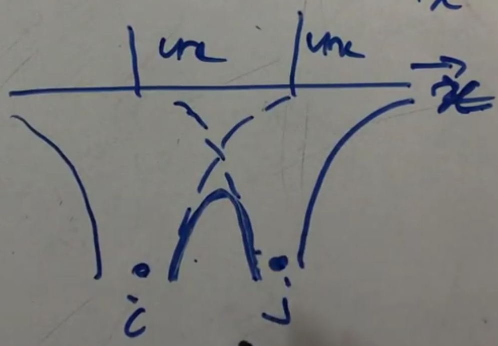
Energy Level Diagram (1-D) Pot^n well (Periodic)

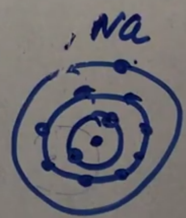


- Electron in a completely filled band can not move since all states occupied (Pauli Principle)
- Similarly can not move in completely empty band.

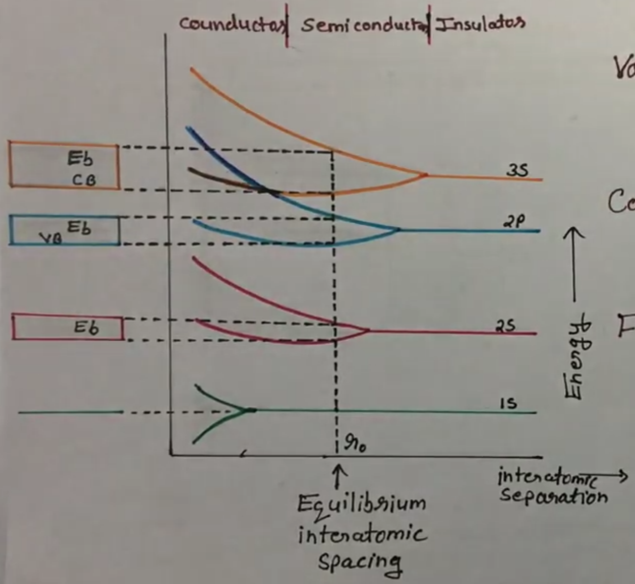


$$U_x = \frac{-2e^2}{4\pi\varepsilon_0 x}$$





Formation of energy levels and energy band in a solid



Valence band – filled –
– highest occupied energy levels

Conduction band – empty –
– lowest unoccupied energy levels

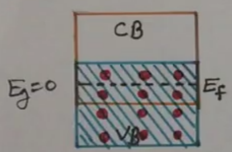
Forbidden gap – gap betn VB & CB

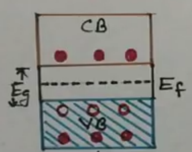
Solids : Metals / Non metals / Insulator →

10^{-08} to 10^{-6}	Electric resistance (resistivity Ω m)	10^{09} to 10^{11} Ω

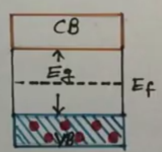
Low ⟷ High

Conductor | Semi Conductor (10^{-4} Ω m) | Insulator





(at any temp)



Conductor

Gold
Silver
Copper
Iron
Aluminium

- E_{bg} – 0 eV
- (mostly metals)
- temp coff. of resistance → +ve

Semi Conductor

Silicon
Germanium
Selenium
Grafts

- E_{bg} – 0.1 to 1 eV
- temp coff. of resistance – (–ve)
- (mostly Non metals)

★ (T = 0 K – insulator)

Insulator

Glass
Rubber
oil
Plastic
Diamonds

- E_{bg} – 3 to 7 eV
- (metalloids)

INTRINSIC SEMICONDUCTOR

Semiconductor

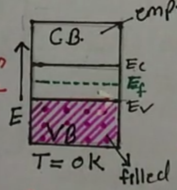
- Intrinsic (Pure/ शुद्ध /basic)
  - ex: Si, Ge
- Extrinsic
  - P-Type
  - N-Type

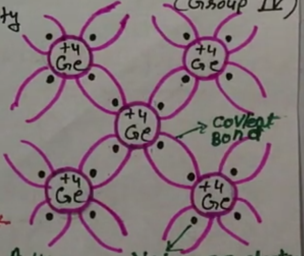
Si – atomic no. → Z–14 → electronic confi → 2, 8, 4 → Valence electron

Ge – atomic no. → Z–32 → 〃 → 2, 8, 18, 4 (Group IV)

Crystal structure → Diamond

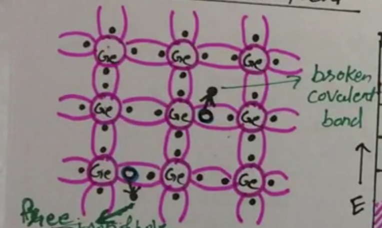
- Each atom shares its four valence electrons with its four immediate neighbours, so that each atom is involved in four covalent bonds

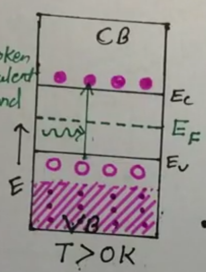




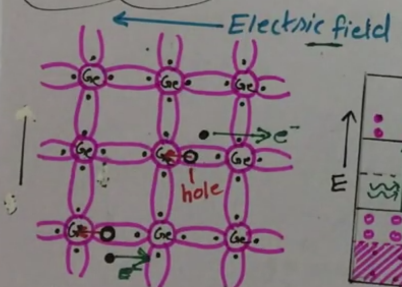
- At normal temp. there is no flow of current
- & T=0k, — insulator

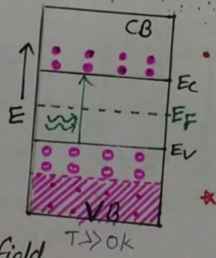
Absence of electric field





hole — (+)ve
electron — (−)ve

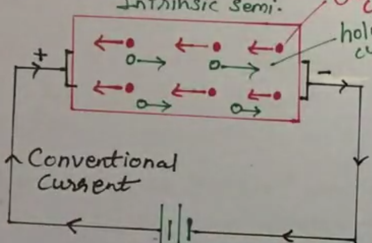




Presence of electric field

- temp.↑ → K.E.↑ → Thermal agitations
  ↓
  break covalent bond
  ↓
  electron free
  ↓
  hole produce
- as temp. increases ↓
  produce electron-hole pair
- electron and hole both participate in electric conduction
- apply external electric field (A.C) vacancy of electron produced due to breaking of covalent bond is filled up by the electron of neighbouring covalent bond & create hole in their position
- $n_e = n_h = n_i$

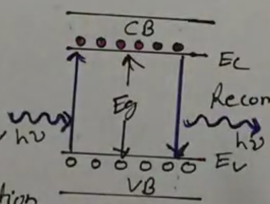
Intrinsic semi.



Concentration → $n_e = n_h = n_i$ → (intrinsic Carrier density)
आंतर वाहक घनत्व

$I_e > I_h$

Recombination →



generation of electron hole Pair (g)

Recombination of electron hole pair (r)

At T>0K – along with generation of the electron-hole Pair, recombination Process also take Place.

at equilibrium state

rate of generation = rate of recombination

- When electric field apply the conduction electrons start moving with certain velocity opposite to field direction This is called drift velocity (अनुगमन वेग)
- In an electric conduction the substance remains electrically neutral because $n_e = n_h$
- 300k → Ge → 2.5×10^{19} electron-hole pairs per meter^3
  0.5 Ω meter — resistivity
  → Si → 1.6×10^{16} electron-hole pairs per meter^3
  2300 Ω meter — resistivity
- A small amount of energy needs to make electrons free for Ge — 0.7 eV & for Si → 1.1 eV
- Depends on temperature only.
- Electrical conductivity low
- At ok fermi level exactly lies betn VB & CB

Fermi Level in an Intrinsic Semiconductor
(आन्तर अर्द्धचालक में फर्मीस्तर)

- The spin of electron is $\frac{1}{2}$.
- Not more than one electron can be in the same state. (Pauli's)
- Electron has two state of spin $m_s = \pm\frac{1}{2}$.
- Degeneracy due to spin $g_s = 2$
  (अपभ्रष्टता)
- Electrons obey the "Fermi Dirac Statistics" inside the semiconductor.
- If total no. of electron is constant then total energy of sys^m also constant.

So function according to "Fermi Dirac Statistics" (फर्मी डिराक सांख्यिकी)

$$\boxed{f_{(E)} = \frac{1}{1+e^{(E-E_F)/kT}}} \quad \text{—— (1)}$$

T → absolute temp.

k → Boltzmann's cons.

$f_{(E)}$ → fermi function (The quantum difference which arises from the fact that Particles are indistinguishable)

E → energy of any state.

E_F → energy of fermi level

At $T=0$

1) if $E > E_f$

$$\frac{E-E_f}{kT} = +\infty$$

so $\boxed{f_E = \frac{1}{1+e^{\infty}} = 0}$

* There is no probability of finding an occupied quantum state of energy greather than E_f at $T=0$

2) if $E < E_f$

$$\frac{E-E_f}{kT} = -\infty$$

so $\boxed{f_E = \frac{1}{1+e^{-\infty}} = 1}$

* There is we conclude that all quantum state with energies less than E_f will be occupied at absolute zero

At any temp. "T" ($kT << E_f$)

1) $E > E_f$

$\boxed{f_E = 0}$

2) $E = E_f$

$$f_E = \frac{1}{1+e^{(E-E_f)/kT}} = \frac{1}{1+e^{0}} = \frac{1}{1+1} = \frac{1}{2}$$

$\boxed{f_E = \frac{1}{2}}$

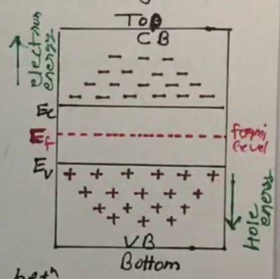
3) $E < E_F$

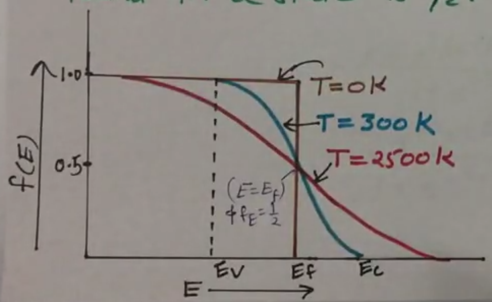
$f_E < 1$

Fermi Level "Fermi level is the energy that corresponds to the centre of gravity of the conduction electrons & holes weighted according to their energies."

"फर्मी स्तर वह ऊर्जा है जो चालन इलेक्ट्रान व होल के गुरुत्व केन्द्र के संगत उनकी ऊर्जा के अनुसार भारित होती है"

- "The energy level corresponding to $E = E_f$ is called fermi level."
- "Fermi energy is the energy corresponding to which the probability for electron to be found in a state is 1/2."





At $T=0$, E_f betⁿ E_V & E_c in forbidden gap

because ∵ $E = E_V < E_f$ ∴ $f_{(E)} = 1$

VB is completely filled

& $E = E_c > E_f$ ∴ $f_{(E)} = 0$

CB is completely empty.

let fermi function in CB $\rightarrow f_{(E_c)}$

& —— " —— VB $\rightarrow f_{(E_v)}$

the $\boxed{f_{(E_c)} = \frac{1}{1+e^{(E_c-E_f)/kT}}}$ & $\boxed{f_{(E_v)} = \frac{1}{1+e^{(E_v-E_f)/kT}}}$ —— (2)

But sum of probability of hole in VB & electron in CB is always $=1$

$\therefore$ $$f_{(E_v)} + f_{(E_c)} = 1$$

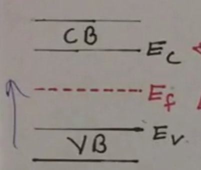
or $$f_{(E_c)} = 1 - f_{(E_v)}$$

So
$$\frac{1}{1+e^{(E_c-E_f)/kT}} = 1 - \frac{1}{1+e^{(E_v-E_f)/kT}}$$

$$= \frac{\cancel{1} + e^{(E_v-E_f)/kT} - \cancel{1}}{1+e^{(E_v-E_f)/kT}}$$

$$= \frac{e^{(E_v-E_f)/kT}}{1+e^{(E_v-E_f)/kT}} \quad \text{—— (3)}$$

at ordinary temp.



- $E_f - E_v \gg kT$ so $e^{(E_v - E_f)/kT} \ll 1$

  means $\left(e^{(E_v - E_f)/kT} + 1 \approx 1\right)$

&

- $E_c - E_F \gg kT$ so $e^{(E_c - E_F)/kT} \gg 1$

  means $\left(e^{(E_c - E_F)/kT} + 1 \approx e^{(E_c - E_F)/kT}\right)$

Using eq^n

$$\frac{1}{e^{(E_c - E_f)/kT}} \approx e^{(E_v - E_f)/kT}$$

or $$e^{-(E_c - E_f)/kT} \approx e^{(E_v - E_f)/kT}$$

or $$e^{(E_f - E_c)/kT} \approx e^{(E_v - E_f)/kT}$$

or $$\frac{E_f - E_c}{\cancel{kT}} \approx \frac{E_v - E_f}{\cancel{kT}}$$

or $$E_f - E_c \approx E_v - E_f$$

$$E_f = \frac{E_v + E_c}{2}$$

∵ E_v is energy level (upper) of electron in VB

Now

$$E_F = \frac{E_C + E_V + E_V - E_V}{2}$$

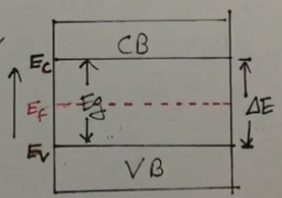
$$= \frac{E_C - E_V}{2} + \frac{2E_V}{2}$$

$$= \frac{E_C - E_V}{2} + E_V$$

$$= \frac{\Delta E}{2} + 0$$ (∵ suppose E_V is taken as zero level)

$$\boxed{E_F = \frac{E_g}{2}}$$ ($\Delta E = E_c - E_V$)

Thus in an intrinsic semiconductor, the fermi level lies just in the middle of F. Gap.



—— X ——

EXTRINSIC SEMICONDUCTORS

Intrinsic Semiconductor (10^7 atom) + small quantity of impurity (1 atom) → Extrinsic semiconductor

↓

Conductivity increase

↓

This Processes in Known as **"Doping"**

Controlled by

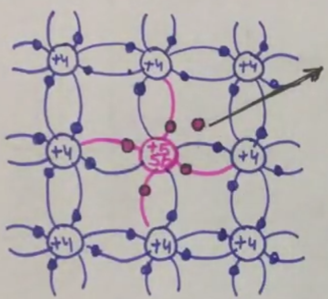
- Type of impurity
  - **Pentavalent** (P, As, Sb) → no. of electron increases
  - **Trivalent** (Al, In, Ga) → no. of holes increases
  - → increase the conductivity
- amount of impurity
  - ↓ 10^{20} atom (donor/acceptor) + $1m^3$ Ge (4.42×10^{28} atom)
  - ↓ resistivity decreases (from $0.47\,\Omega m$ to $0.10\,\Omega m$)

increase the conductivity $\xrightarrow{\text{depend on}}$ amount →

increase the conductivity ↓ depend on Nature

- **N-Type** (Donor) ($n_e >> n_h$)
- **P-Type** (Acceptor) ($n_e << n_h$)

N-Type Semiconductor



- Pure Semiconductor (Ge) + Pentavalent (Sb, As, P .) impurity

Fifth valance electron bound with very small energy $\approx$ 0.01eV

↓

This atom can be free by near 0.01 eV energy

↓

free electron → charge carrier

↓

Conductivity increases due to (−ve) charge carrier

↓

N−Type

Penta Valent impurity donate the free electron to semiconductor

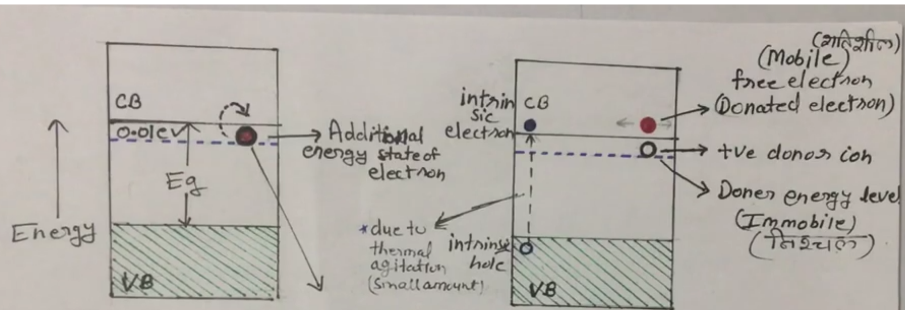
* At room temp. due to thermal agitation,

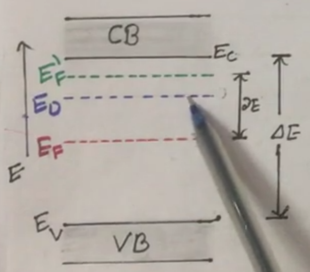
Few electron present in CB Majority charge carrier

Few holes present in VB majority charge carrier

* In N−Type

- Majority charge carrier → e^-
- Minority —— " —— → hole



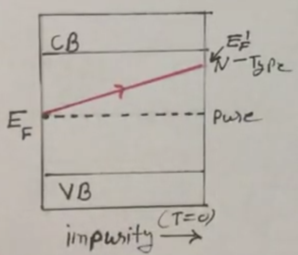


- This electron is bound with a very week force & it can be made free from its Doner atom by small amount of energy (0.01eV) which provided by the agitation (ऊष्मीय प्रक्षोभ).
- In this process, no hole is created in the VB and electric conduction takes place due to motion of electron in the CB
- संपूर्ण पदार्थ विद्युत उदासीन (electrically neutral) ही रहता है क्योंकि doner atom के ions का उतना ही +ve charge रहता है जितना कि CB में electrons का (-)ve charge होता है।

*

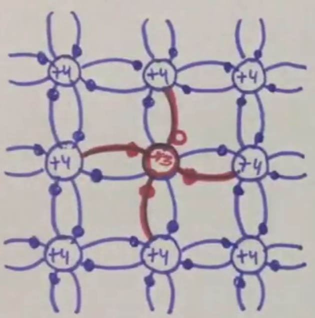
- So number of holes in VB no more increases.
- Fermi level is the energy state for which the Probability of being filled is "1" at $T=0$.
- So in N-Type the fermi level E_F' does not remain in the middle of E_g (forbidden gap), it lies below the CB just middle of E_c & E_D.

* As dopping increases the fermi level reaches close to CB



N- Type

P-Type Semiconductor



- Pure Semiconductor (Ge) + Trivalent (Al, B, In ---)
- Covalent bond — 3 Ge + 3 In
- lack of one electron for the rhombohedral (चतुर्भुजाकार) covalent shape. → "**Hole**" (+ve)

  कमी
- Hole become available for movement inside Semiconductor
- If hole → right side, then electron → left side.
- So +ve holes are responsible to increase conductivity.
- This is Known as **P-Type**
- Impurity atom — acceptor (it accept the electron in the process of Hole formation)

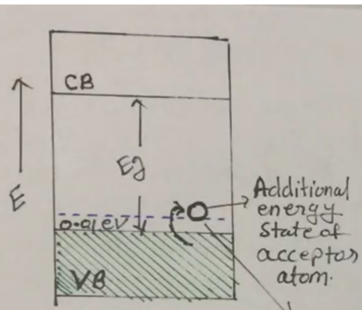
* at room temp due to thermal agitation

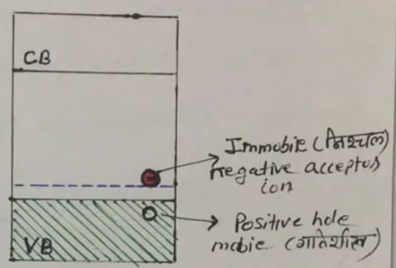
few electron in CB

few holes in VB

* In P-Type

- Majority charge carrier — hole
- minority — " — e^-





- When acceptor atom accept the electron from Ge to complete the covalent bond it becomes a (–)ve ion. ↓ for this
- Very small amount of energy is needed, hence new energy state lies above the VB

↓

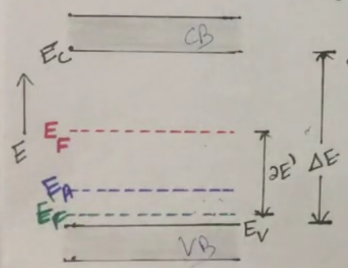
- At room temp. due to thermal agitation electron of VB comes in additional ergy state after receiving required energy

↓

Now hole is created in VB for electric conduction

↓

(–)ve acceptor ion (immobile) is left



- If all the accepter atom get ionised → holes are found in near top VB
- due to thermal agitation only few electron from VB to jump CB

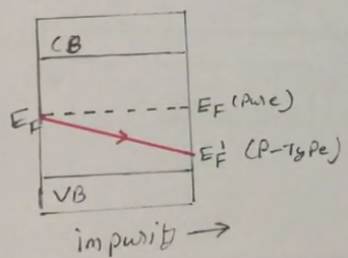
↓

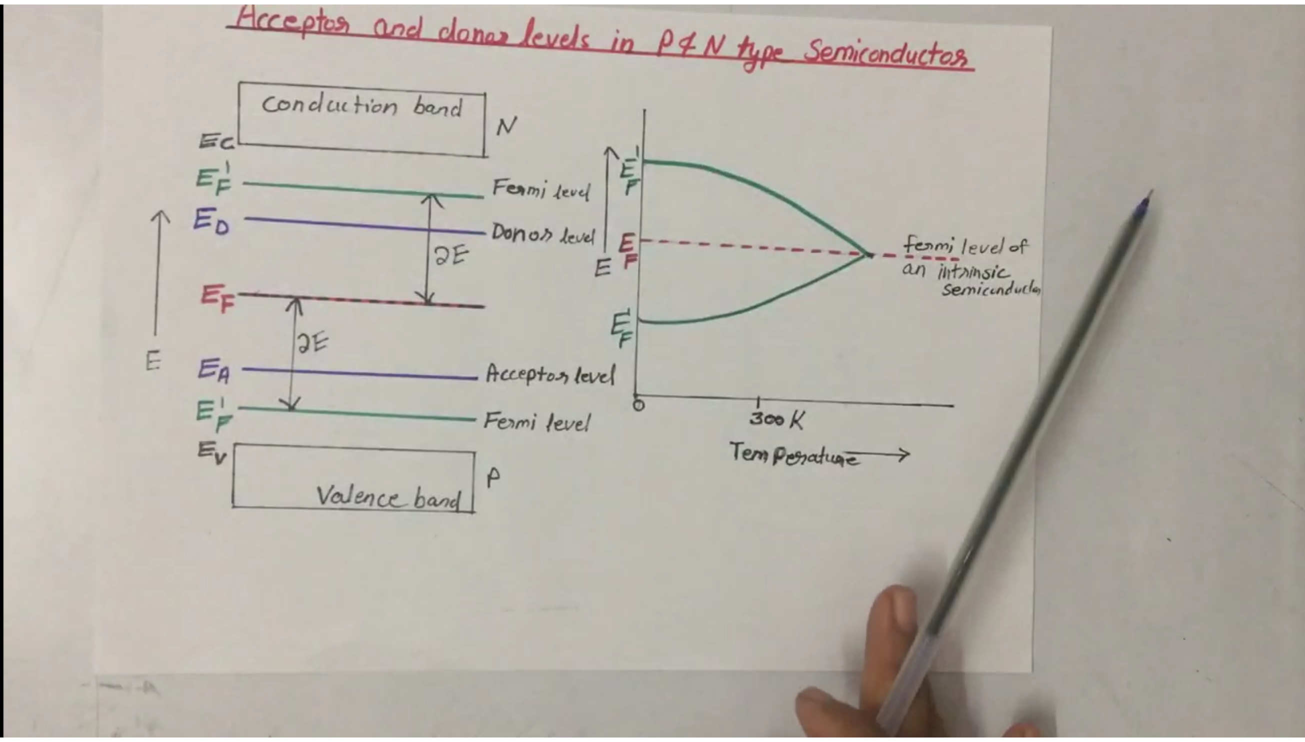
∴ no. of holes in VB is very large in comparison to electron in CB

↓

hence fermi level E_F' now does not remain in the middle of E_g & lies near the VB just in middle of top of VB, E_V & E_A

* As doping of acceptor atoms increases, the acceptor level shifts towards the valence band.





Acceptor and donor levels in P & N type Semiconductor
Conduction band
N
E_C
E_F'
Fermi level
E_D
Donor level
∂E
E_F
∂E
E
E_A
Acceptor level
E_F'
Fermi level
E_V
Valence band
P
E_F'
E_F
E
E_F'
fermi level of an intrinsic semiconductor
0
300 K
Temperature

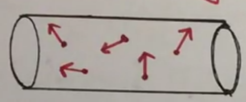
Mechanism of current flow in N&P type semiconductor
(N व P प्रकार के अर्द्धचालकों में धारा प्रवाह की प्रक्रिया)

Current flow in External semiconductor due to

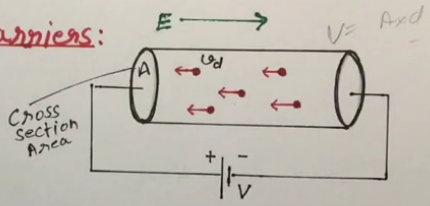
Drift (अनुगमन) of charge carrier
↓
(Due to External electric field
↓
Drift current ∝ · Intensity of External E. field
· concentration of charge carrier
↓
Contribute the majority charge carrier

Diffusion (विसरण) of charge carrier
↓
Due to concentration gradient
↓
Diffusion current ∝ concentration gradient of charge carrier
↓
Minority charge carrier
↓
it is slow process

Drift of majority charge carriers:



(a) In the absence of E. field



(b) In the presence of E. field

- N – Type — electron
  P – Type — hole
  } move randomly due to their thermal energy
- Direction of motion changes due to collision with the acceptor or donor ions.

- Electrons initially accelerate but soon reach a steady state average velocity.
- This average velocity is in the opposite direction of E.field is known as drift velocity.
- In steady state

  rate of gain in momentum due to efield
  =
  rate of loss in momentum due to collision
- Now charges get a steady drift velocity due to which current flows.

Now $\bar{F} = e\bar{E}$

accel. $\bar{a} = \frac{\bar{E}}{m} = -\frac{e\bar{E}}{m}$ (opposite to the field direction)

drift velocity = $\bar{v}_d = \bar{a}\,\tau$ → relaxation time

$\therefore v_d = -\frac{e\bar{E}}{m}\tau$

$\therefore \boxed{v_d \propto E}$

Now $I = \frac{Q}{t} = \frac{nAel}{t}$

total mobile charge in length l of the conductor

n → no. of charges per unit volume

A → Area of cross section

l → length

$= nAe\frac{l}{t}$

$= nAev_d \quad (\because v = \frac{l}{t})$

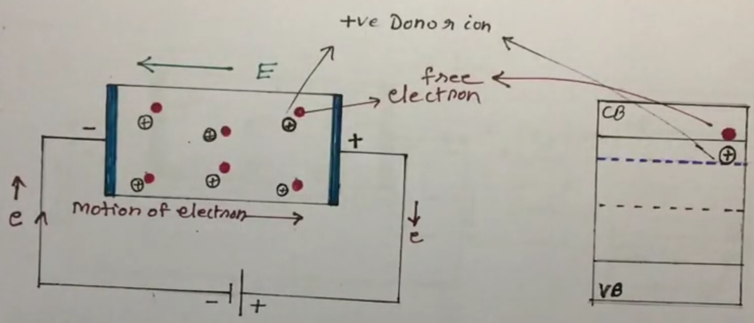
$\therefore \boxed{I \propto v_d}$

or $\frac{I}{A} = nev_d$

$\boxed{J = v_d ne}$

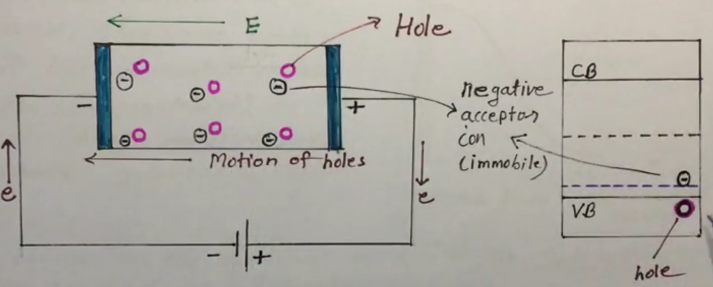
current density

Drift in N-Type semiconductor (N प्रकार के अर्द्धचालकों में अनुगमन)



- Free electron drift towards +ve electrode, & taken by metal of the electrode.
- Immobile +ve ion near -ve electrode do not get neutralised.
- These ion attract from (-)ve electrode.
- Thus electrons flow from (-)ve to +ve terminal
- rate of flow of electron depend on Potn diff. & conductivity of semi.

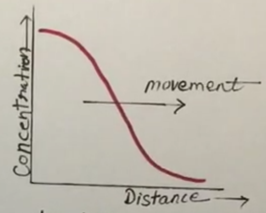
Drift in a P-Type semiconductor (P प्रकार के अर्द्धचालकों में अनुगमन)



- Holes drift towards (−)ve electrode & combine with electrons of metal electrode.
- Simultaneously equal no. of holes are created near +ve electrode.
- The rate of formation of holes = rate of disappear holes at (−)ve electrode
- This rate depend on the Pot^n diff applied & conductivity of semiconductor
- Within P-type semiconductor, current is from +ve → (−)ve electrode due to hole. while in the external ckt the current is due to motion of electrons.

Diffusion of minority charge carriers (अल्पसंख्यक आवेश वाहकों का विसरण)

"Due to non uniform concentration of charge carriers, they move from a region of higher concentration to a region of lower concentration. This movement of charge carriers due to concentration gradient is called **Diffusion**."



material down a concentration gradient

- Concentration of electrons "n_e" varies with distance "x" i.e. $n_e \downarrow$ with $x \uparrow$

  concentration gradient $\rightarrow -\frac{dn_e}{dx}$ along +ve X-axis

$$\therefore \; J_e = -eD_e \frac{dn_e}{dx}$$

($\because D_e$ – Diffussion coff. for electron)

- Similarly current density due to diffusion of hole

$$J_h = -eD_h \frac{dn_h}{dx}$$

($\because D_h$ – Diff. coff. for hole)