# Fundamentals of Electrical & Electronics ⟹ 4 credits $\left(\underset{L}{1}+\underset{T}{1}+\underset{P}{1}\right)$

## Books for unit-3 (Semi-Conductor Devices)

- Integrated Electronics — Millman & Halkias.
- Micro Electronic Circuits — Sedra & Smith.

# SEMI-CONDUCTOR THEORY

Metals → No Bandgap

✓Semi-conductor → small Band gap → (usually < 4 eV)

Insulator → High Bandgap → (usually > 4 eV)

0-2 eV ⇒ Narrow Band Gap S.C.

2-4 eV ⇒ wide Band gap S.C.

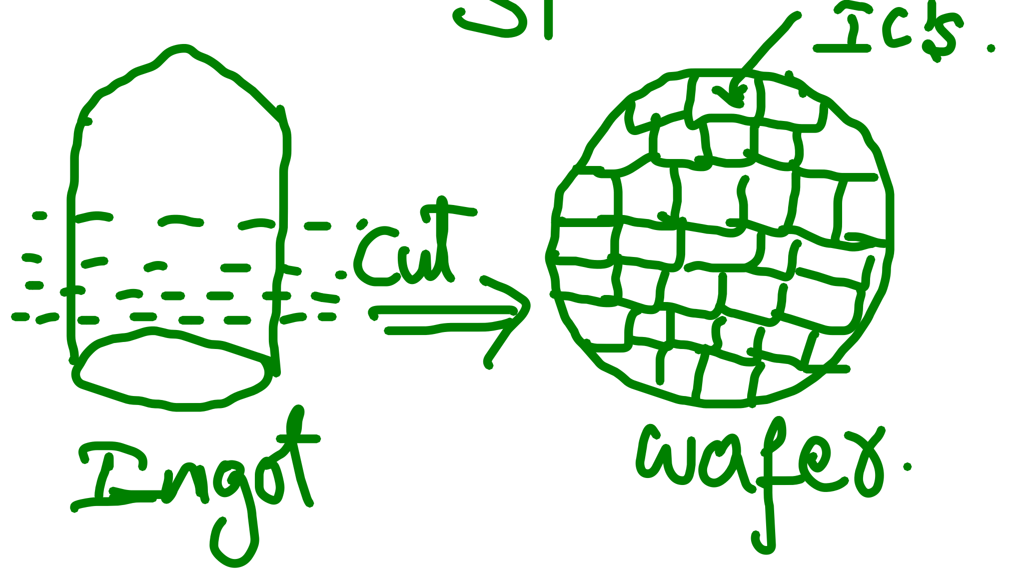
| | | Si ✓ | Ge ✗ |
|---|---|---|---|
| Material | ① Availability → | ↑ | ↓ |
| | ② Band gap → | ↑ | ↓ |
| | ③ Exciton Bohr Radius → | ↓ | ↑ |
| Device | ④ Peak Inverse voltage (PIV) → | ↑ | ↓ |
| | ⑤ Leakage current → | ↓ | ↑ |

Sand

$SiO_2$

$\Downarrow$ High Temp.

Si



- High Band gap $\Rightarrow$ Higher thermal range of the device.
- Exciton Bohr Radius $\longrightarrow$ below this Quantum confinement will takeplace.

  $\hookrightarrow$ Electron in conduction Band & hole in valence band, if both are bound by coulomb interaction. Then it results in Exciton.

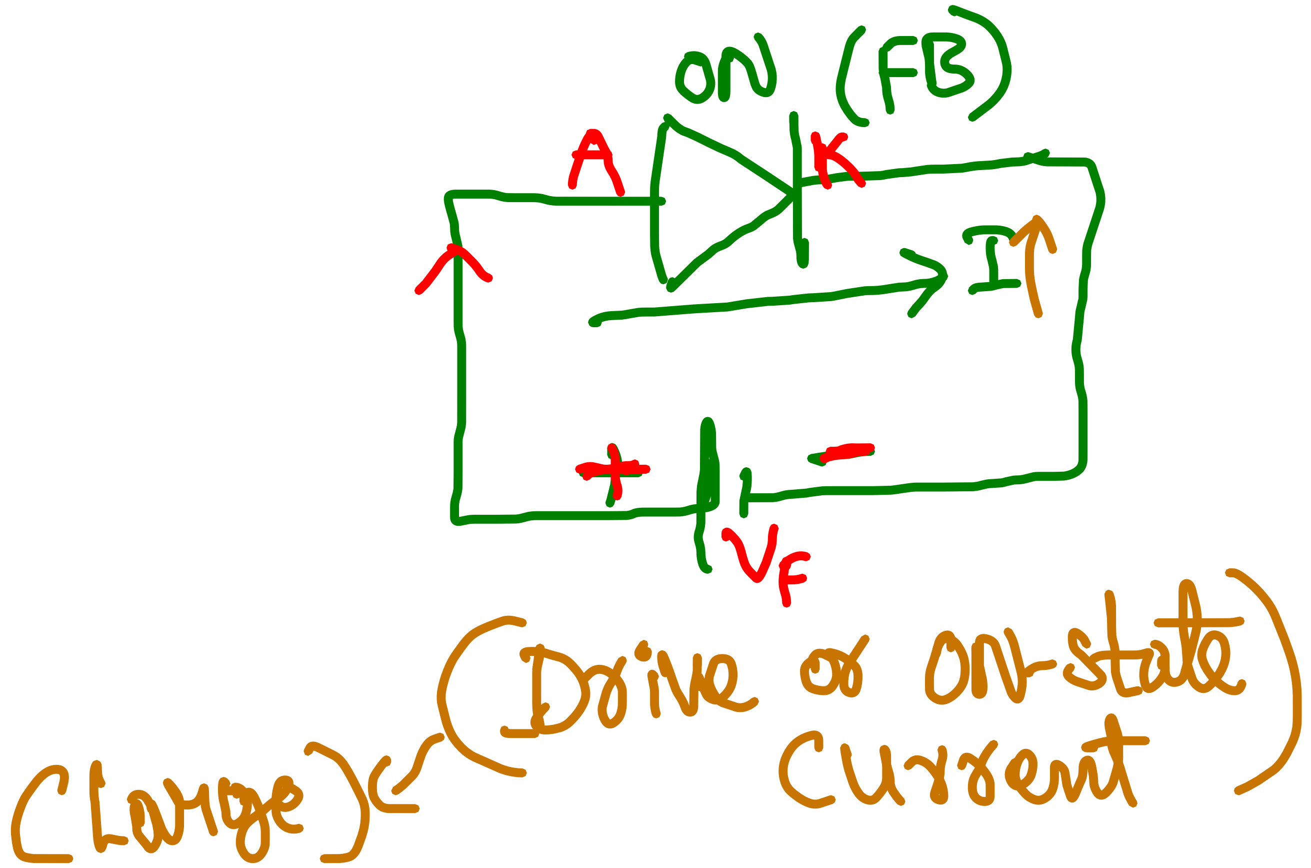
  The distance between $\bar{e}$ & hole of exciton $\Rightarrow$ Exciton Bohr radius.

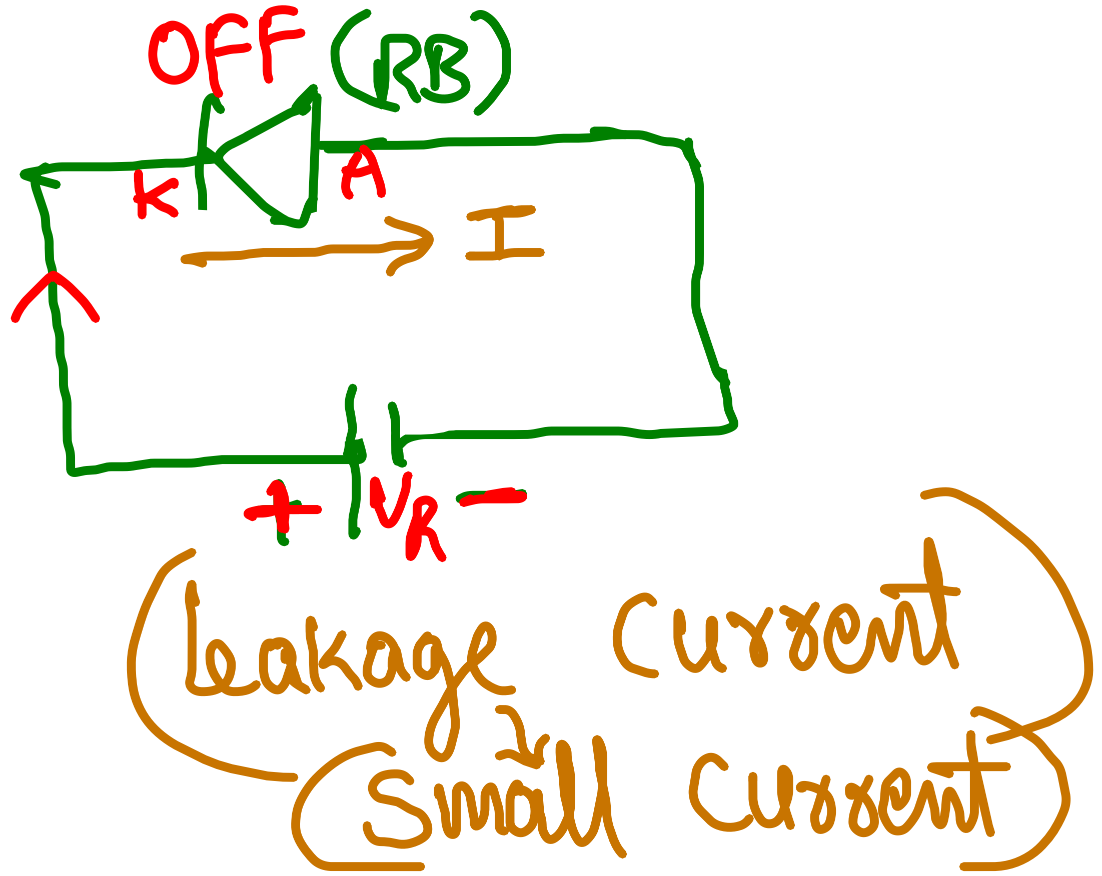
  Si $\approx$ 5 nm      Ge $\approx$ 24 nm

  Below these dimensions Quantum confinement will takesplace.

Quantum confinement → Continuous energy bands will split-up into discrete energy levels. usually, this increases the Band gap.

- PIV is High ⇒ Device can sustain high Reverse Voltage.
- Leakage current → current in OFF-state through the device.



# Types of Semi-conductors

pure S.C.
(or)
Intrinsic S.C

Impure (or) Doped S.C.
(or)
Extrinsic S.C

p-type S.C.

n-type S.C.

## ↳ Intrinsic S.C :—
(pure)

✓ Si (14) $\rightarrow \underbrace{1s^2\ 2s^2\ 2p^6}_{\text{core}}\ \boxed{3s^2\ 3p^2}$ Valence electrons.

× Ge (32) $\rightarrow \underbrace{1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^6}_{\text{core}}\ \underbrace{3d^{10}}_{\text{semi-core}}\ \boxed{4s^2\ 4p^2}$ Valence.

Si has 4 valence electrons.

Si (4) sharing Si (4)

Gain $4e^-$ for stability
(or) Lose $4e^-$ for stability

Lose : Gain $= 4:4$
$= 1:1$

$$\left[ Na\ (11) \xrightarrow{1e^-} Cl\ (17) \right] \Rightarrow \text{Ionic Bonding.}$$

NaCl

Na: lose : Gain

1 : 7

Cl: lose : Gain

7 : 1

- Si lose : Gain = 1:1
- So, Si undergoes Covalent Bonding, where sharing of $\bar{e}$s happens.

Ionic Bonding (High difference of electroneg.)

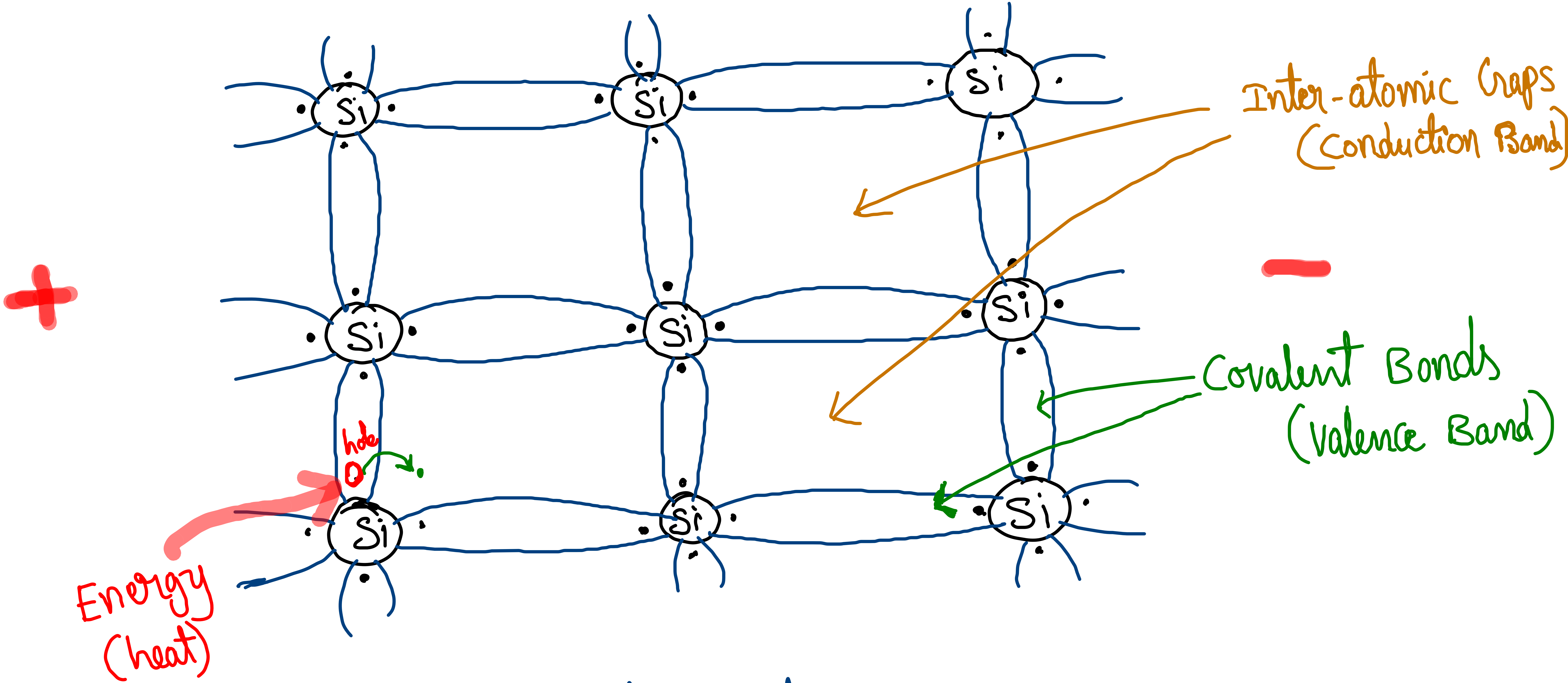
Covalent Bonding

Dative Bonding

Metallic Bonding

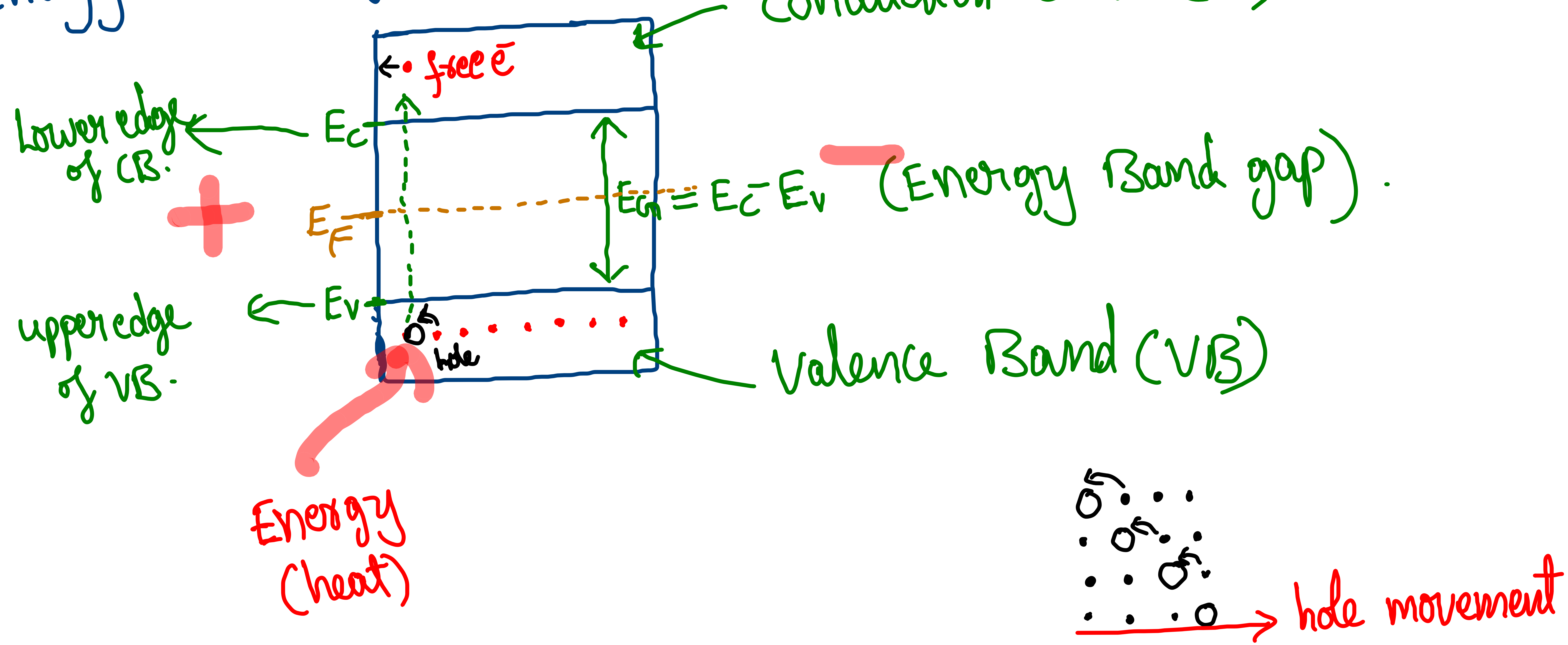
Hydrogen Bonding

⋮




Si - Crystal Structure

# Energy Band Diagram




- Vacancy created by $\bar{e}$ in the VB is called 'Hole'.
- Movement of $\bar{e}$'s in the VB is treated as movement of hole.
- Free $\bar{e}$s can move in the CB, holes can move in the VB.

- Electron mobility > Hole mobility.

| | Si | Ge | units |
|---|---|---|---|
| Hole mobility ($\mu_p$) → | 500 | 1800 | $cm^2/VS$ [(Centimeter)$^2$/volt second] |
| Electron mobility ($\mu_n$) → | 1300 | 3800 | |
| Band Gap ($E_G$) → | 1.21 eV (0 K)<br>1.1 eV (300K) | 0.78 eV (0K)<br>0.72 eV (300K) | |
| Intrinsic carrier Concentration → | $1.5 \times 10^{10}/cm^3$ (300K) | $2.5 \times 10^{13}/cm^3$ (300 K) | |

- Band gap & Temperature relation,

$$E_G = E_{G0} - \frac{\alpha T^2}{(T+\beta)}$$

$E_{G0}$ → Band gap at $0^\circ K$.

$\alpha$ & $\beta$ are material dependent constants.

If $T \uparrow \Rightarrow E_G \downarrow$

- Intrinsic carrier concentration means how many free electrons or holes are available in a intrinsic SC at a given temperature.

• <u>Fermi Level</u> :— "Maximum occupancy energy level".

All the energy states below the fermi level are filled with $\bar{e}$.

" " " above " " are Empty.

In Intrinsic SC, $E_F$ is in the middle of Energy Band Gap.

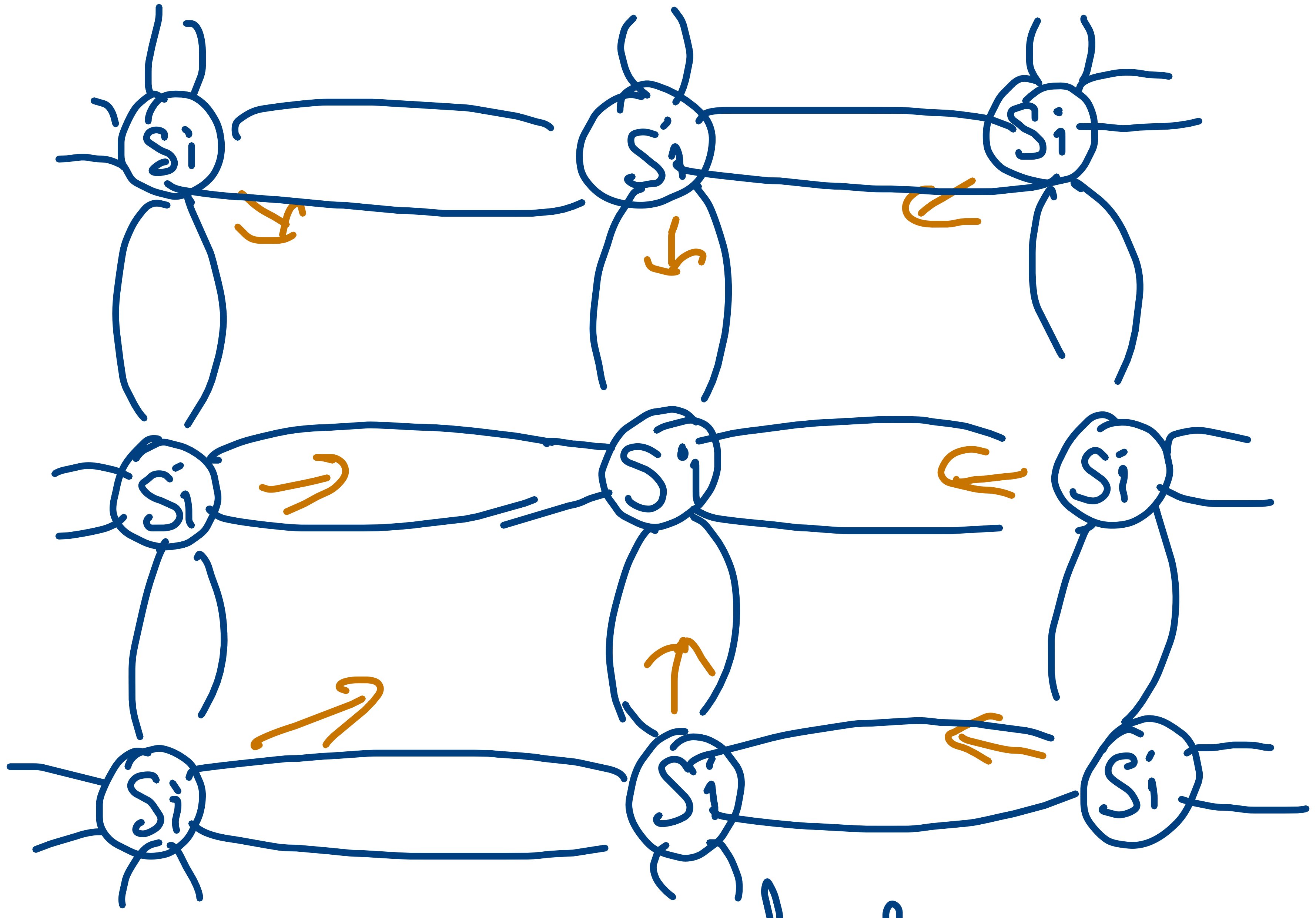
# Energy Bands Formation in Si-crystal :—

$Si = [Ne]\ 3s^2\ 3p^2$

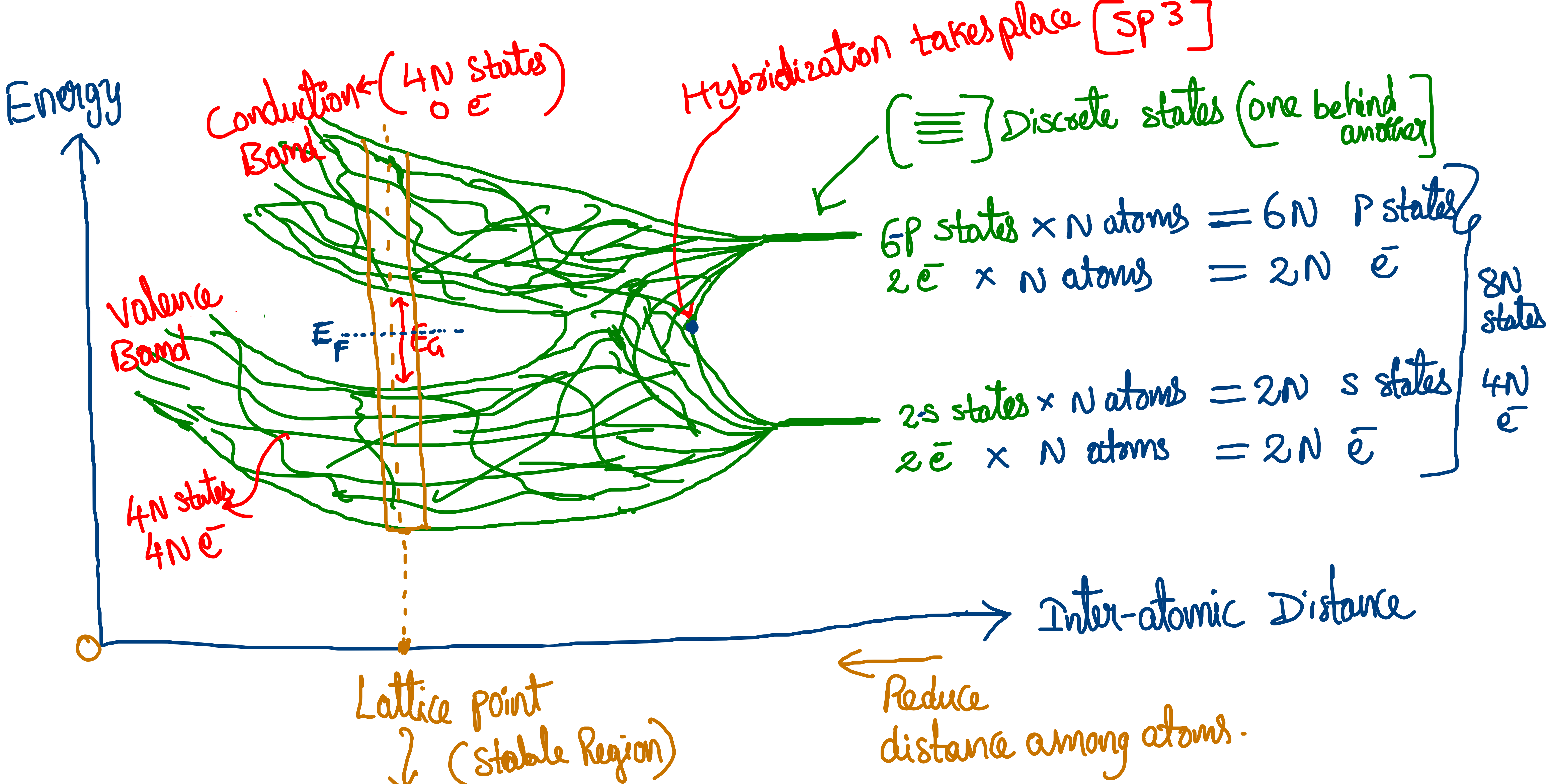
$3s$: ↑↓ → 2-s states, $2\ e^-$

$3p$: ↑ | ↑ |   → 6-p states, $2\ e^-$

* one Energy state accommodates only one $\bar{e}$.
* these states exist in pairs.




N atoms




Energy of crystal is minimum
Forces between atoms is optimum
optimum Bond length.

↳ Extrinsic S.C :—

[Si valence is 4]

p-type S.C.

↓

Add Trivalent atoms to intrinsic S.C

(valence-3)

Ex: B, Al, Ga, In

n-type S.C.

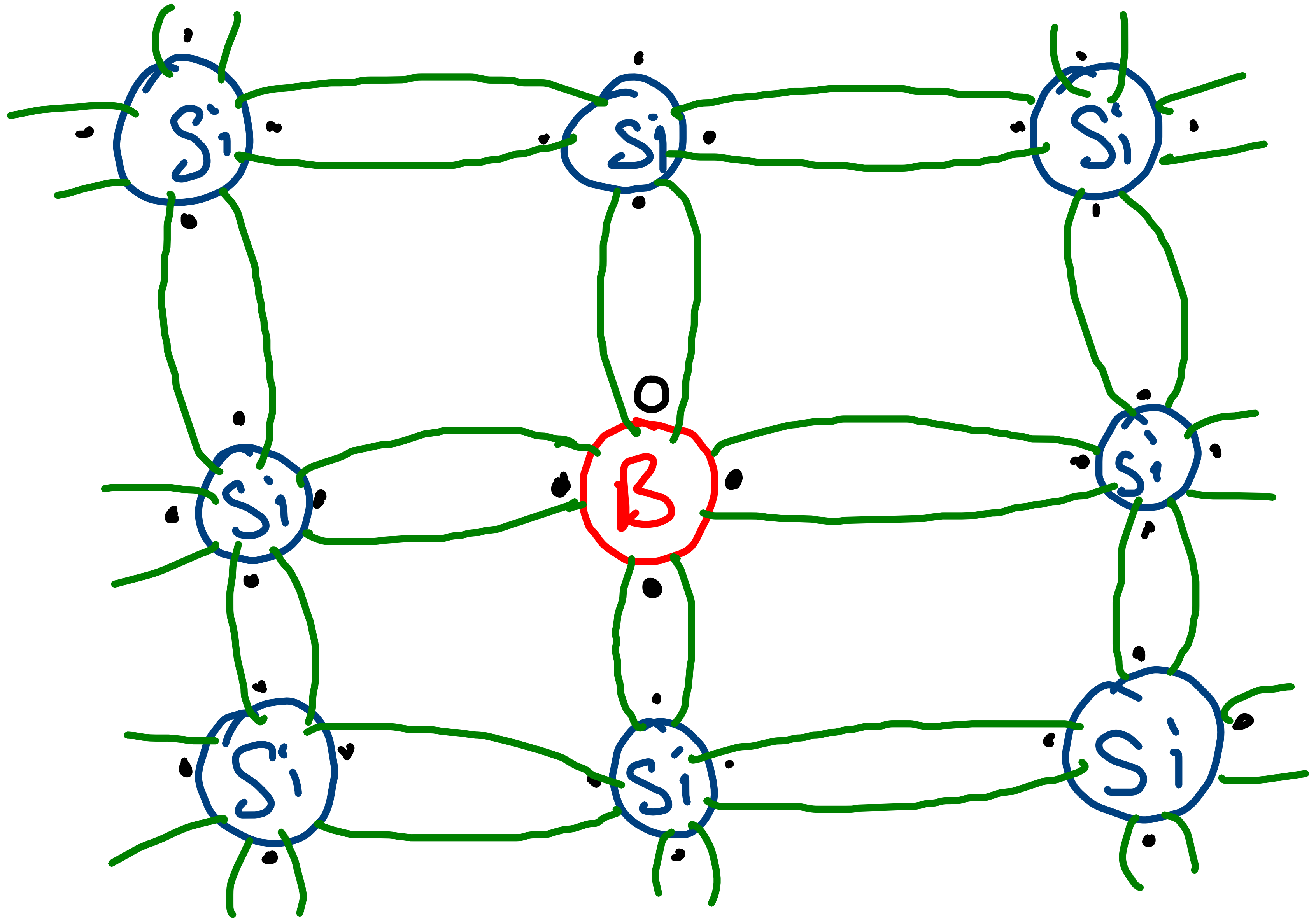
↓

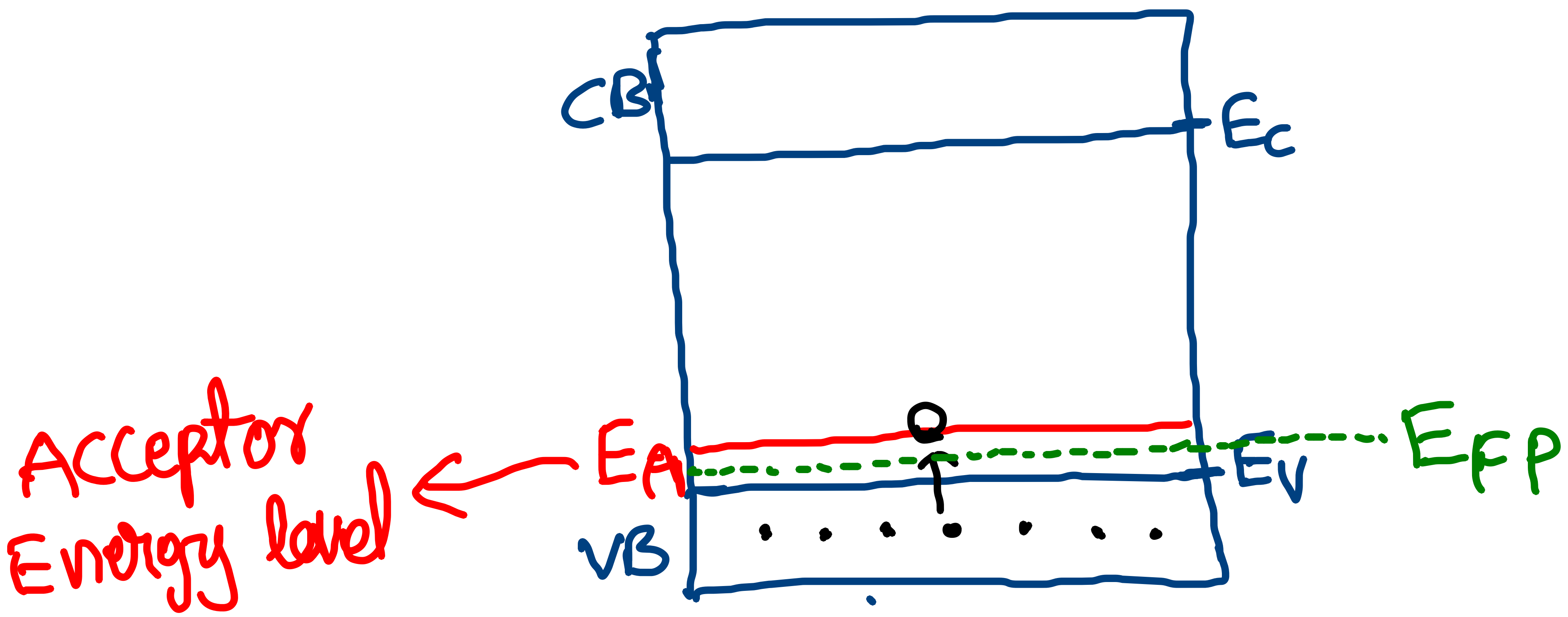
Add pentavalent atoms to intrinsic S.C

(valence-5)

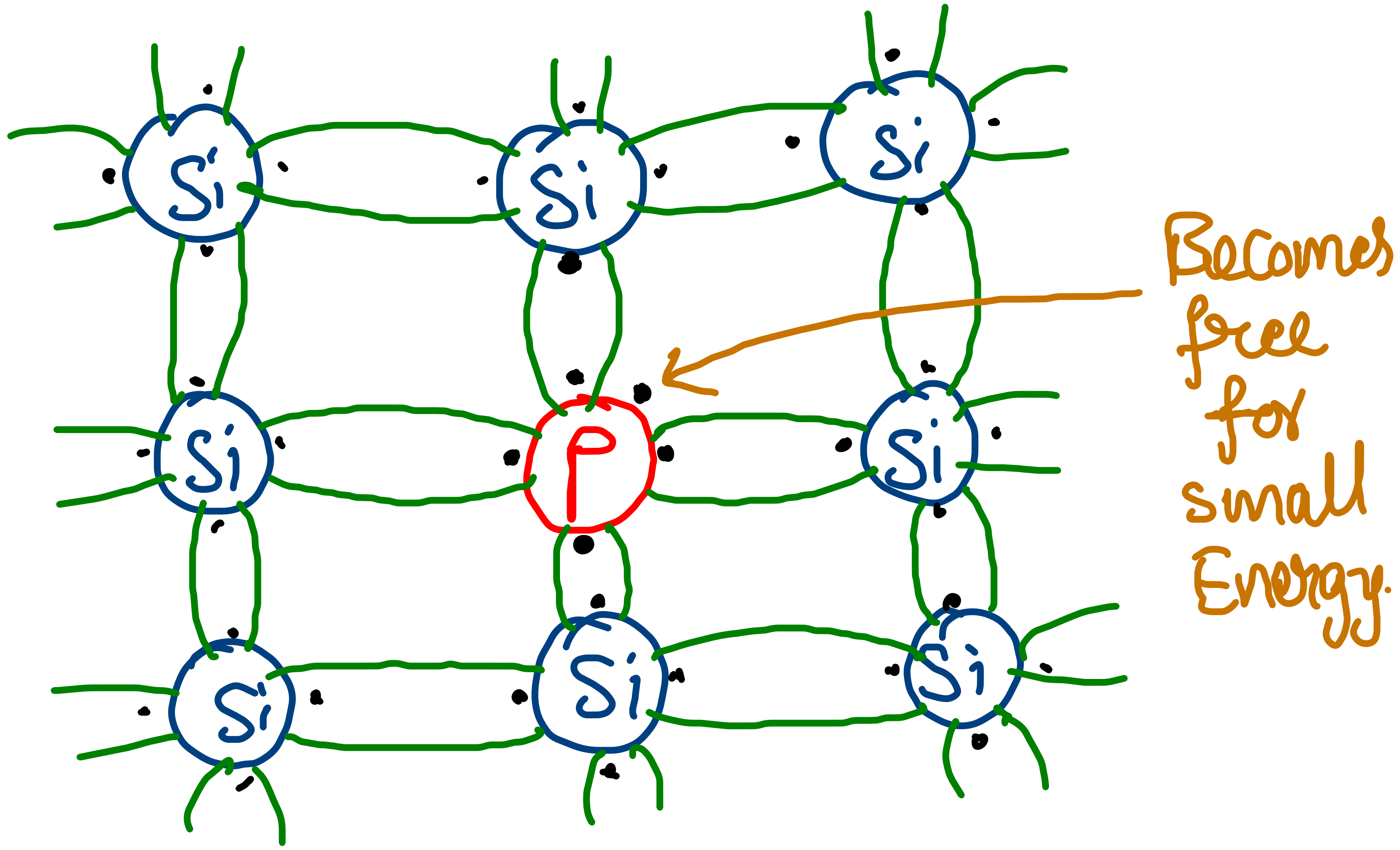
Ex: P, As, Sb, Bi

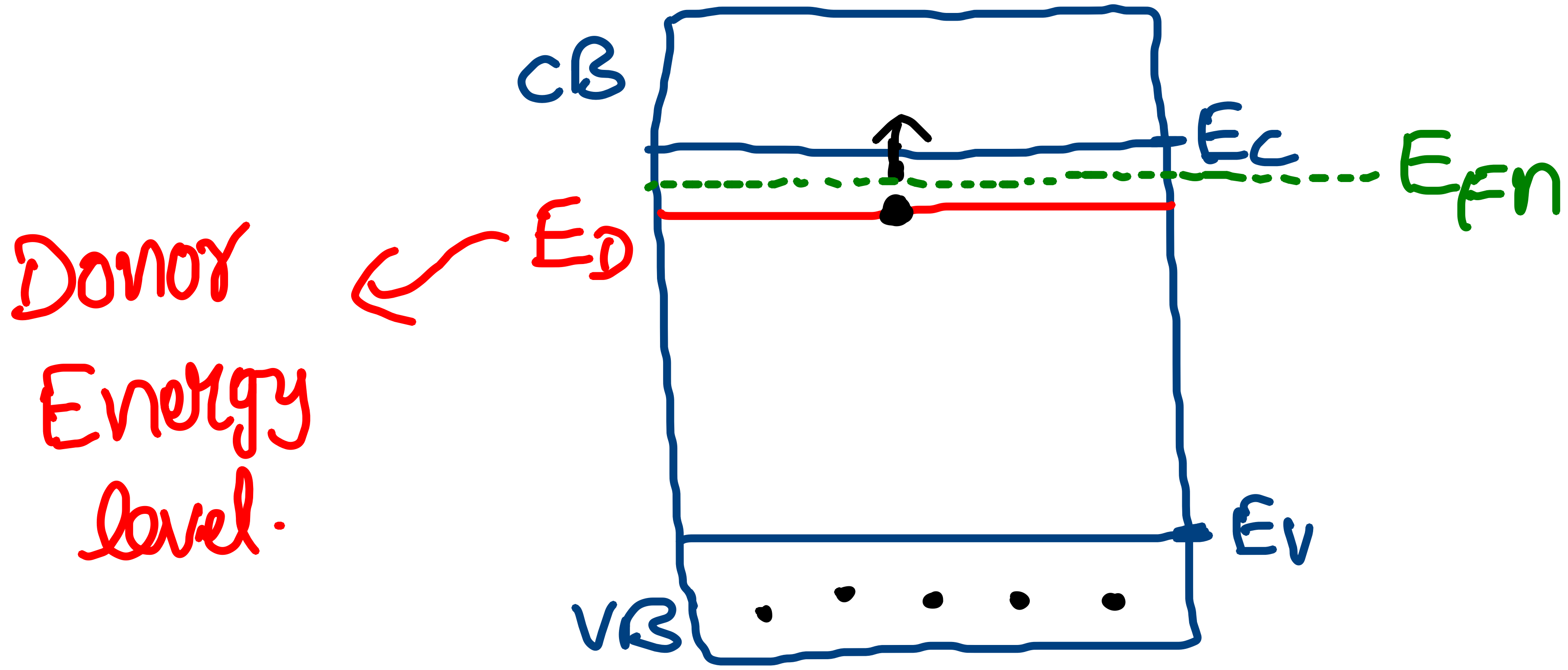
## P-type Si

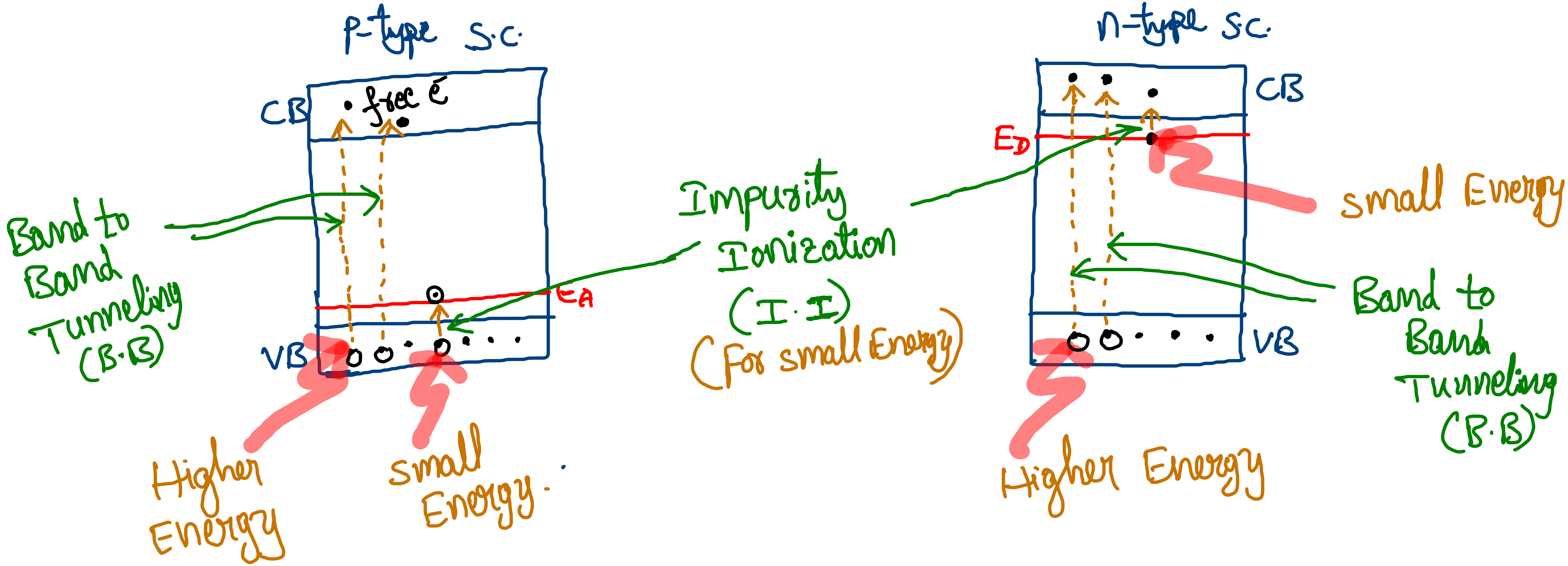



## n-type Si

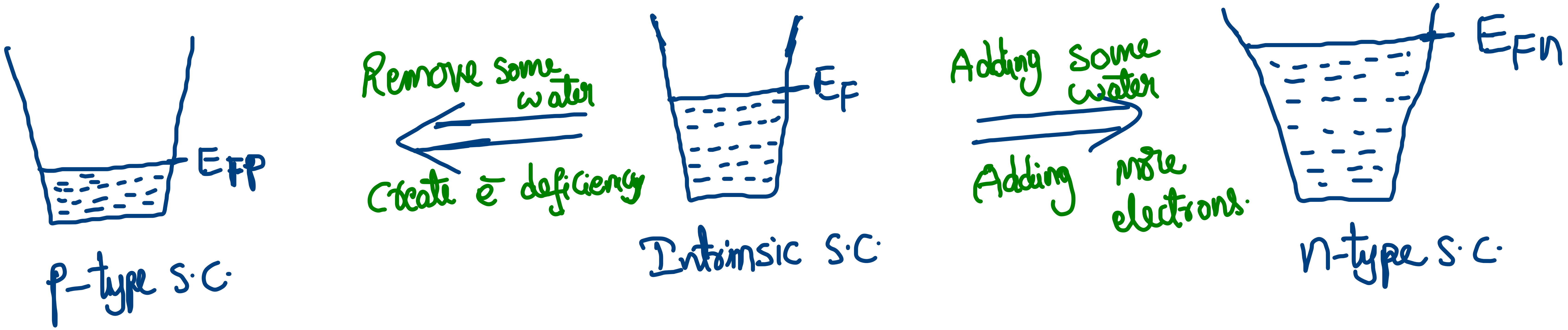


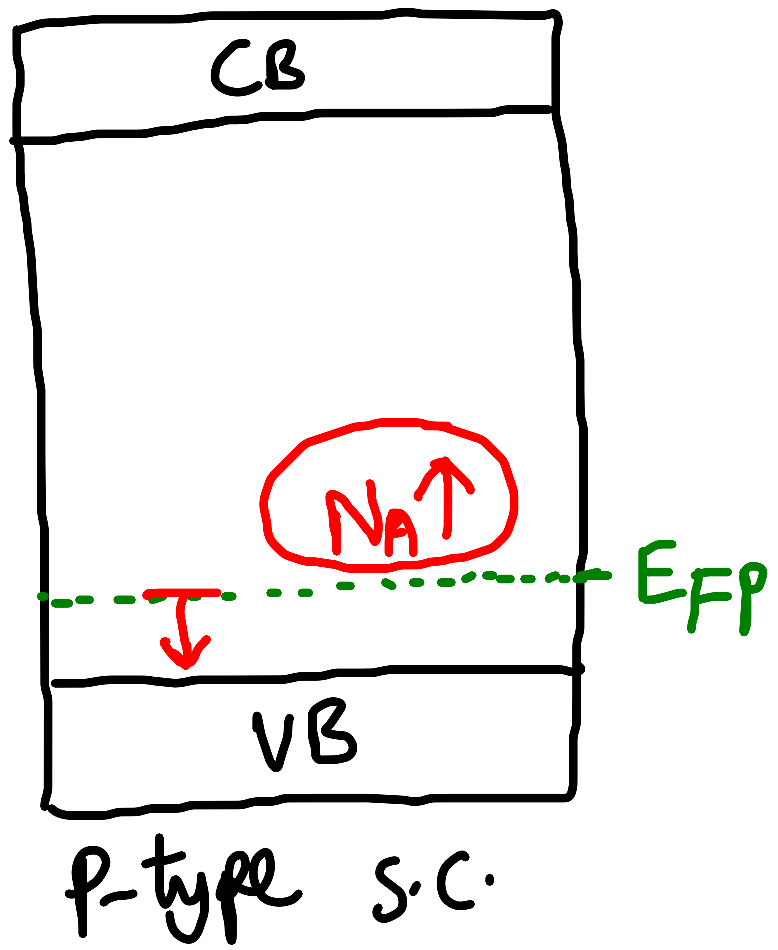



- Impurity Ionization (I.I) happens for small energy, but produces only majority carriers [holes in p-sc; ē in n-sc].
- I.I is the reason that holes are majority p-type sc, ē are majority in n-sc.
- B.B occurs for higher energy & produces both ēs & holes.

# Effect of Doping Concentration on Fermi-level :—

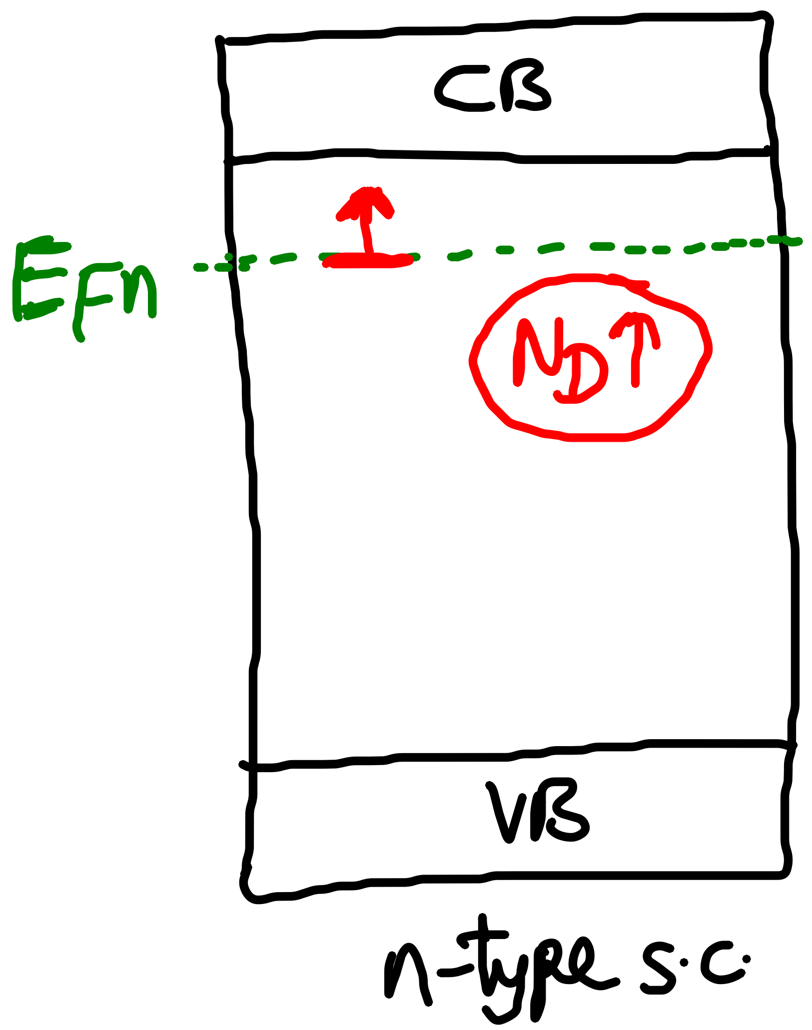



(water Glass Analogy)

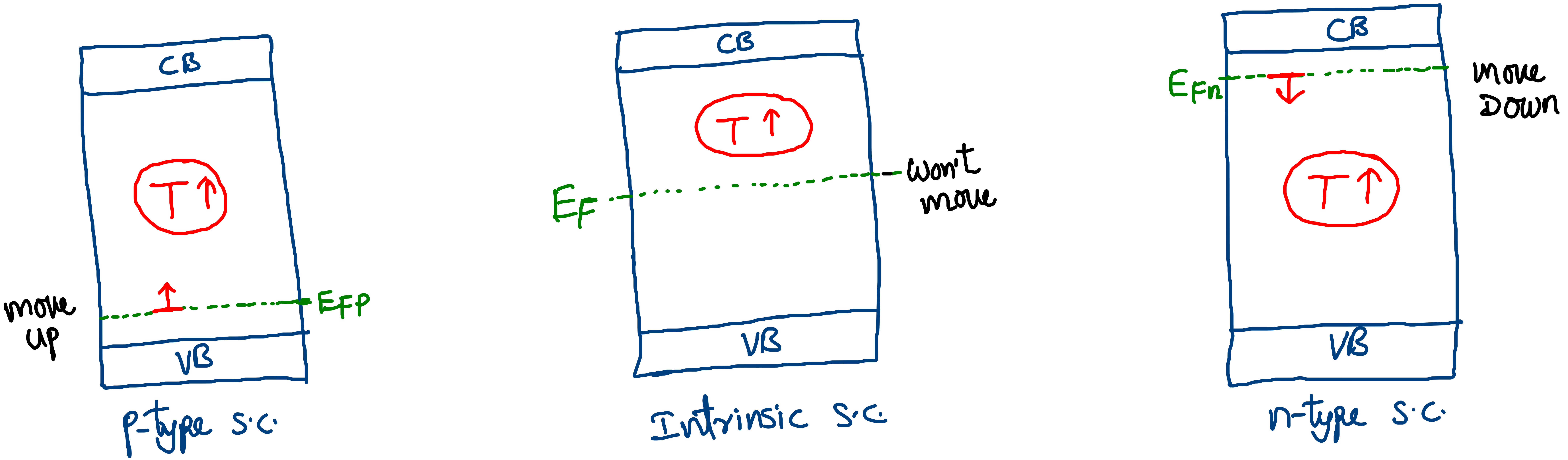



$N_A \rightarrow$ Acceptor (p-type) doping concentration.

$N_D \rightarrow$ Donor (n-type) doping concentration.



# Effect of Temperature on Fermi level :—




- As Temperature is increased to very high, extrinsic S.C (p-type & n-type) behave like intrinsic S.C.
- In p-type S.C., $E_{FP}$ can move up to the middle of Energy band gap.
  In n-type S.C, $E_{Fn}$ can move Down to " " ".

**Note:**

~~Intrinsic~~ s.c. :— No. of free Electrons = holes.
p-type s.c. :— No. of free Electrons < holes
n-type s.c. :— No. of free Electrons > holes.

| Temperature | Extrinsic s.c (Ex: n-type) | |
|---|---|---|
| T (small) $\longrightarrow$ | 100 $\bar{e}$ (I.I) | 0 holes |
| T ↑ $\longrightarrow$ | 100,000 $\bar{e}$ (B.B) + 100 $\bar{e}$ (I.I) = 100,100 $\bar{e}$ (Total) | 100,000 holes + 0 |
| T ↑↑ $\longrightarrow$ | 900,000 $\bar{e}$ (B.B) + 100,100 $\bar{e}$ (earlier) = 10,00,100 $\bar{e}$ (Total) ≈ | 900,000 holes + 100,000 holes = 10,00,000 holes |

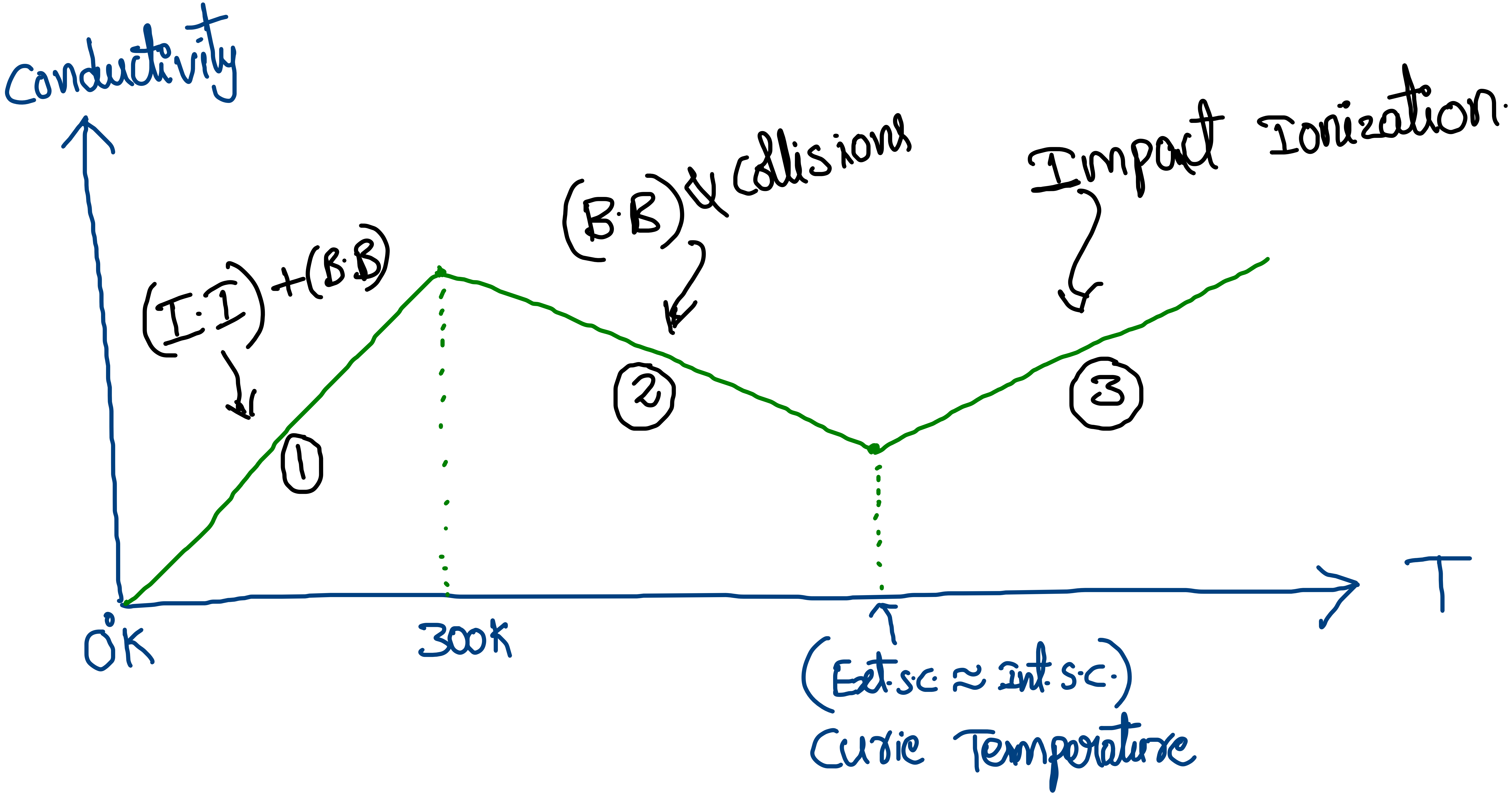
- As Temperature is increased, the Band to Band Tunneling (B-B) dominates, which produces produces both majority & minority carriers.

- At some Temperature (Curie point), the major carrier concentration is almost equal to minority carrier concentration.

  i.e Extrinsic S.C Turns to Intrinsic S.C.

- This is the reason, the Fermi level in Extrinsic S.C tries to reach the middle of Band gap as Temperature is increased.

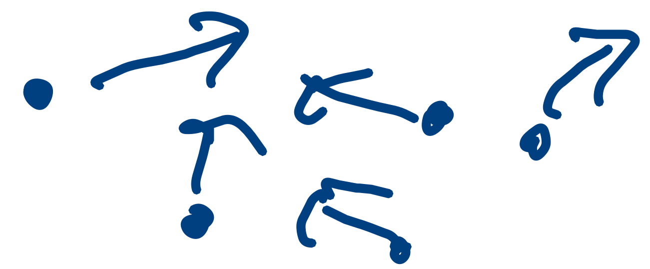
## Temperature impact on Conductivity of Extrinsic s.c :-



① Mainly Impurity Ionization (I.I) & some Band to Band (B.B) Tunneling.

Hence conductivity increases.

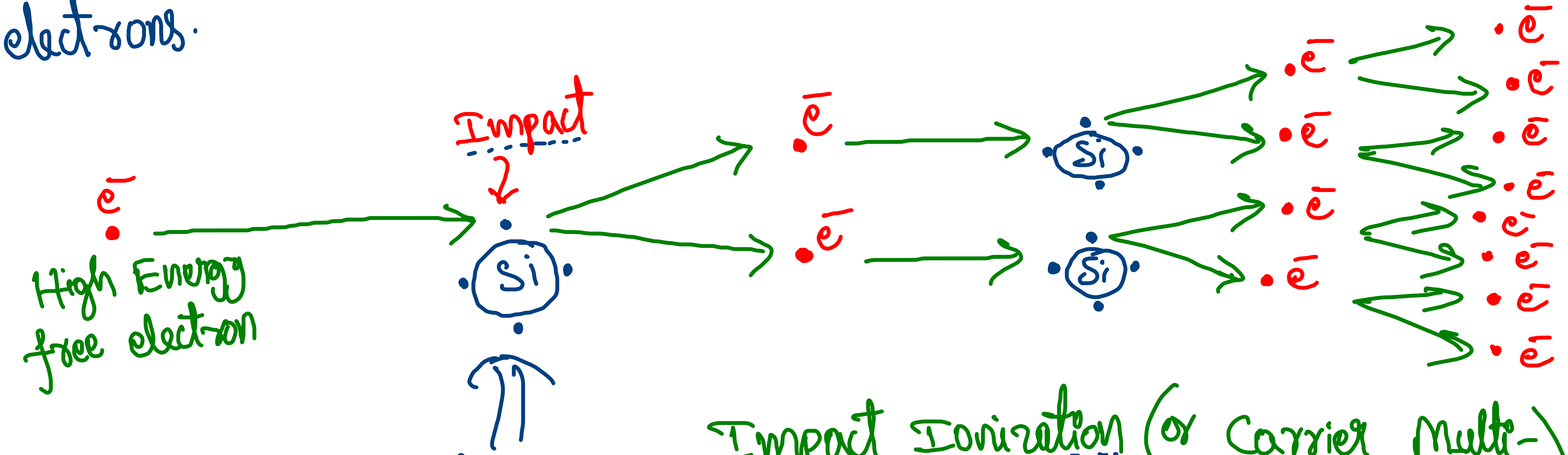
② After 300°K, B.B dominates & the collisions among the carriers will increase.



These collisions cause drop in conductivity.

③ After Curie Temperature, $\bar{e}$s gain too much of energy.

These high energy $\bar{e}$s are now capable of freeing the bonded electrons.




Impact Ionization (or Carrier Multiplication)

After losing $\bar{e}$, Si atom is positively Ionized.

Rest mass $\Longrightarrow$ Mass of Isolated electron (or) hole.

(Rest mass of $\bar{e}$, $m_e = 9.1 \times 10^{-31}$ Kg.)

Effective mass $\Longrightarrow$ mass experienced by $\bar{e}$ (or) hole when it is interacting with other $\bar{e}$s, atoms & surroundings.

$\left( m_e^* = 0.01 \text{ to } 10 \times m_e ;\ m_h^* = 0.01 \text{ to } 10 \times m_e \right)$

$m_e^*$ (or) $m_h^*$ $\uparrow$ $\Longrightarrow$ $\mu_n$ (or) $\mu_p$ $\downarrow$ $\quad \boxed{\mu_n > \mu_p}$

$\boxed{m_e^* < m_h^*}$

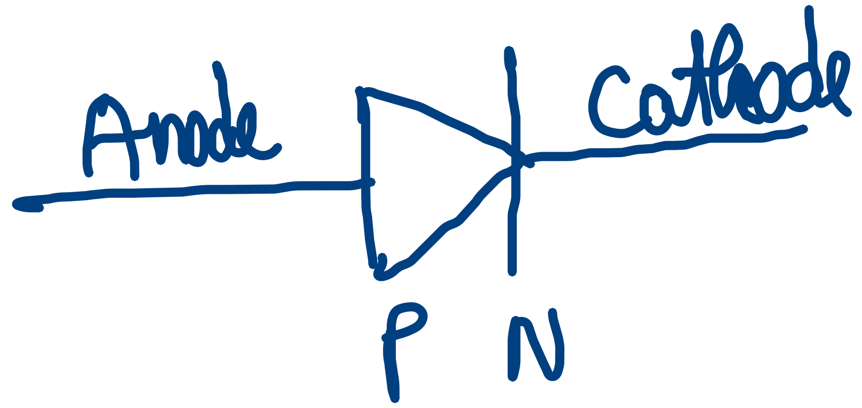
$\mu_n$ $\rightarrow$ Mobility of $\bar{e}$.

$\mu_p$ $\rightarrow$ Mobility of hole.

# PN - Junction Diode

If you are familiar with this, then you can easily understand, All other diodes (Zener, Schottky, Tunnel, LED, etc.) & Transistors (BJT, JFET, MOSFET, IGBT, SCR, power MOSFET, etc.)

Symbol:

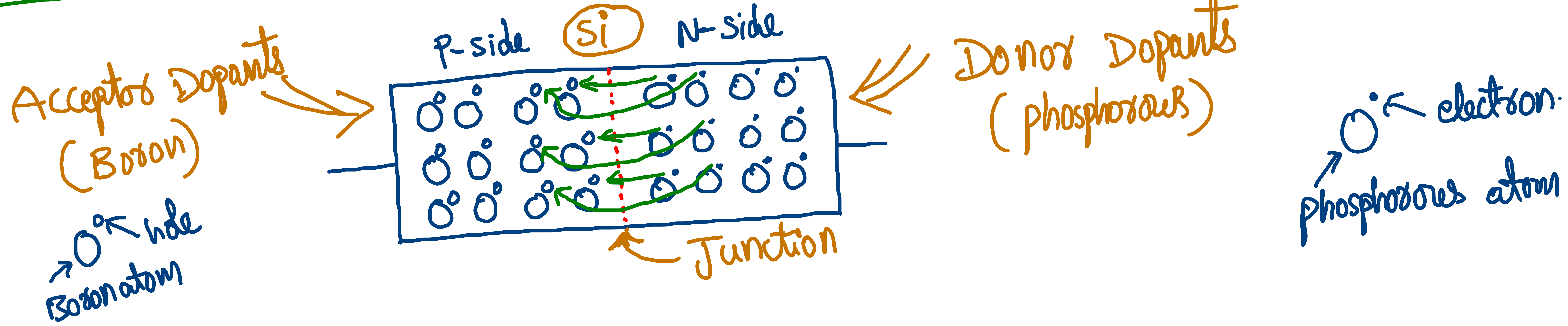


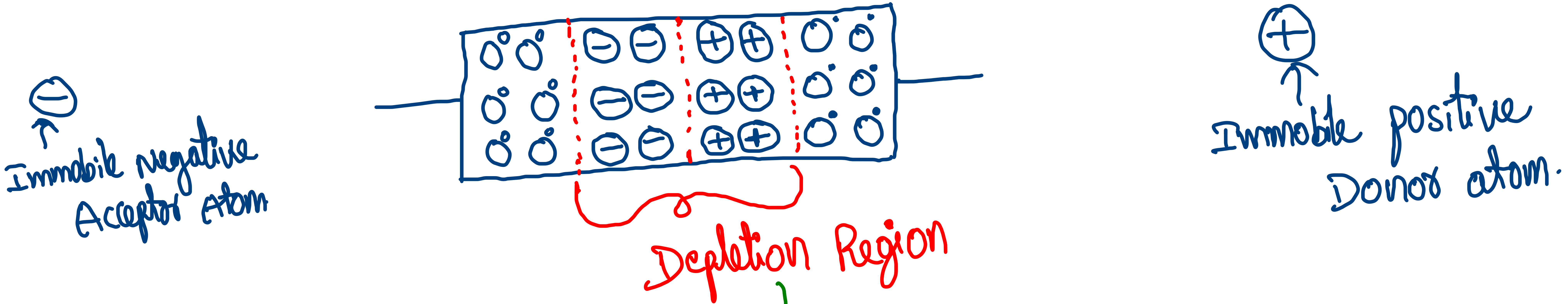

Diode

↓ e

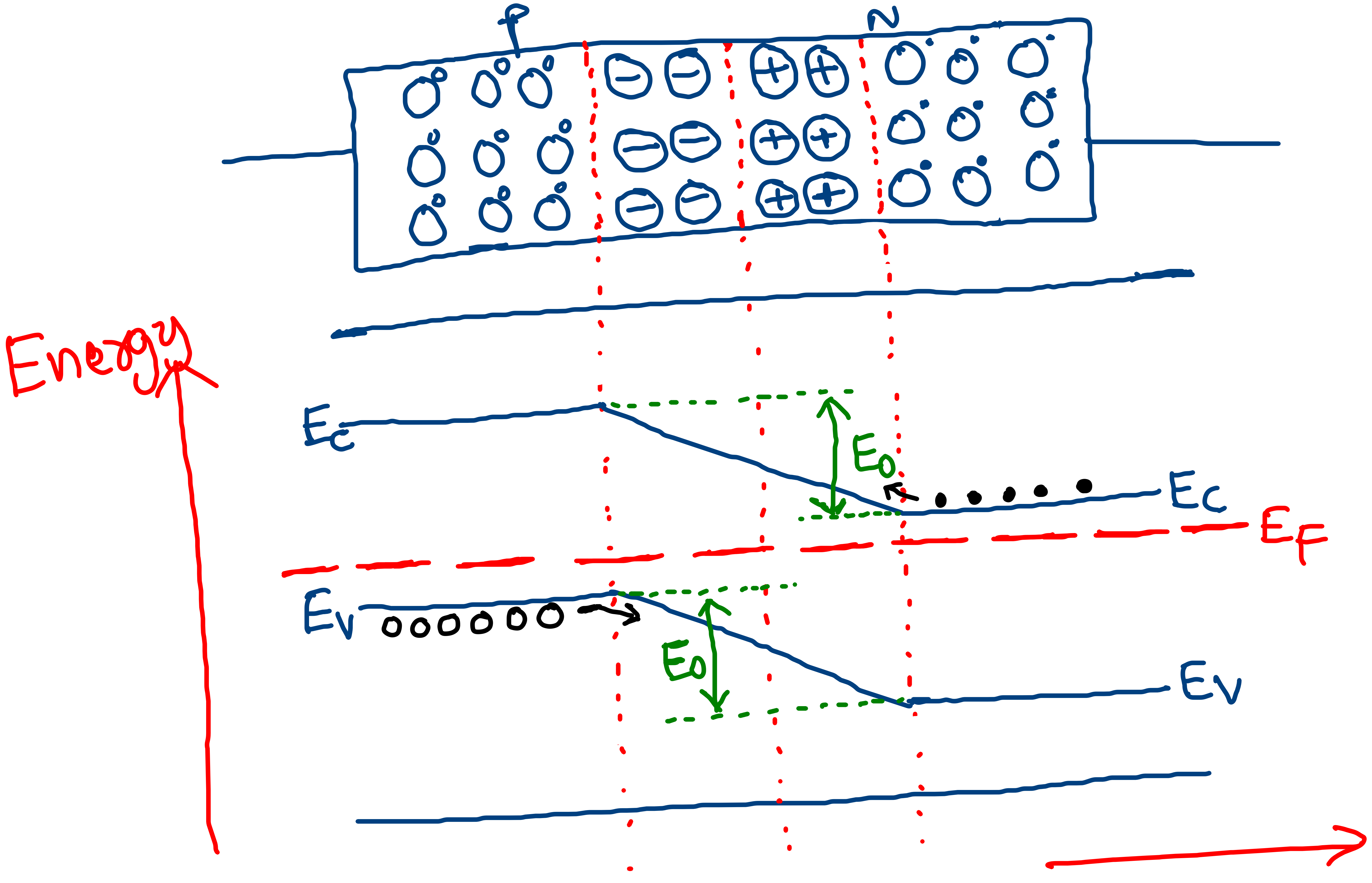
↓ Electrodes

# Operation & Energy Band Diagram of PN-diode :—




Forms due to Recombination of $\bar{e}$'s from N-side & holes from P-side at the Junction.




(At equilibrium)

Note :- In Any electronic Device, at equilibrium, its Fermi Level is always constant throughout the device.

shift between CB edges (or) VB edges,

$$E_0 = KT \ln\left(\frac{N_A N_D}{n_i^2}\right)$$

[Units: eV]

Built-in potential ($V_0$),

[$V_0$ is offered by the depletion Region]

$$V_0 = \frac{KT}{q} \ln\left(\frac{N_A N_D}{n_i^2}\right)$$

[Units: V]

$e$ (or) $q \rightarrow 1.6 \times 10^{-19}$ C (elementary charge)

$K \rightarrow$ Boltzmann's const.

$T \rightarrow$ Temperature

$N_A \rightarrow$ Acceptor doping Concentration

$N_D \rightarrow$ Donor doping Concentration

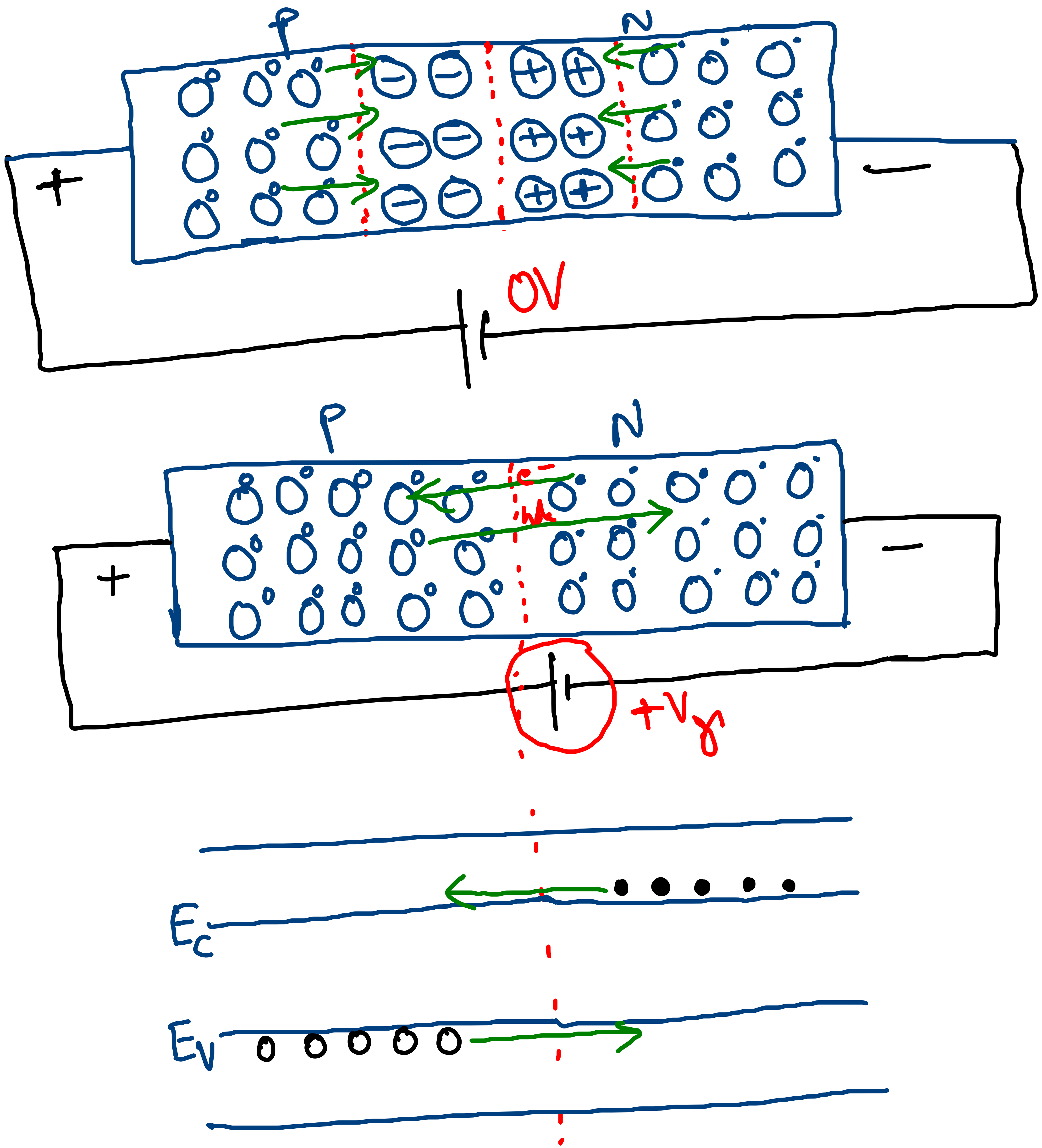
$n_i \rightarrow$ Intrinsic S.C. carrier conc.

At $300^\circ K$,

$KT = 26$ meV.

$\frac{KT}{q} = 26$ mV.

# Forward Bias :-




positive side of battery to P-side

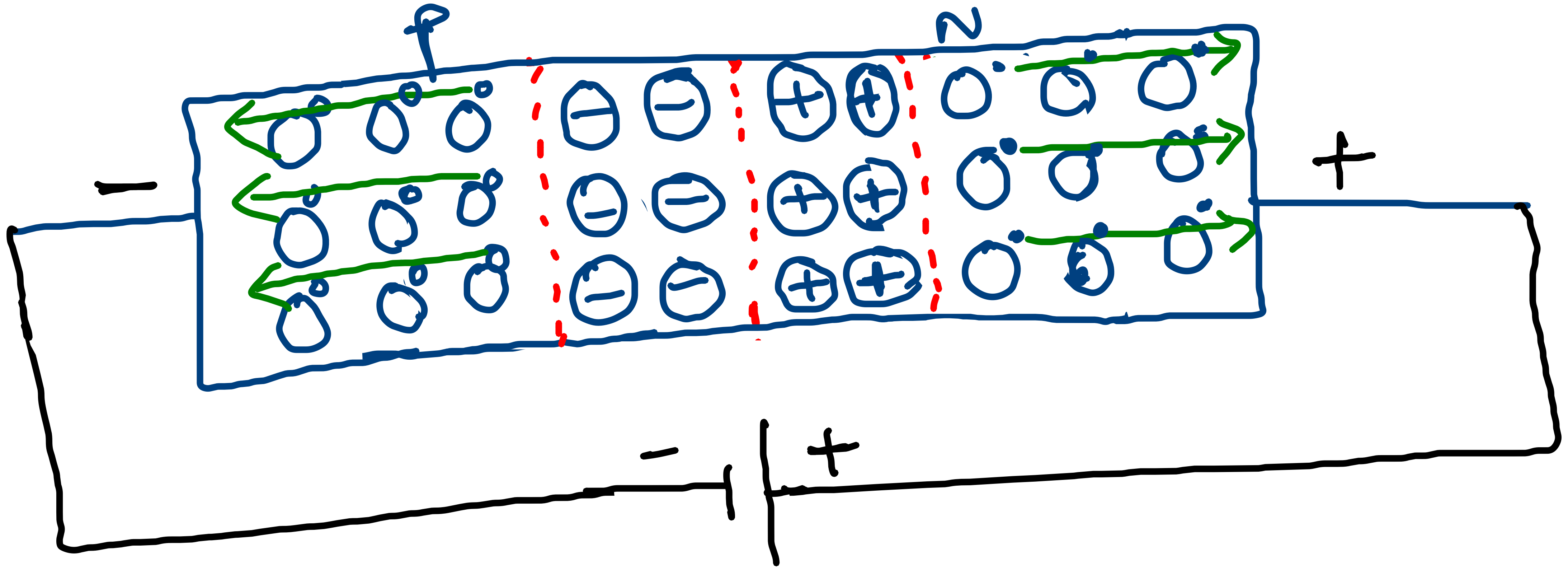
&

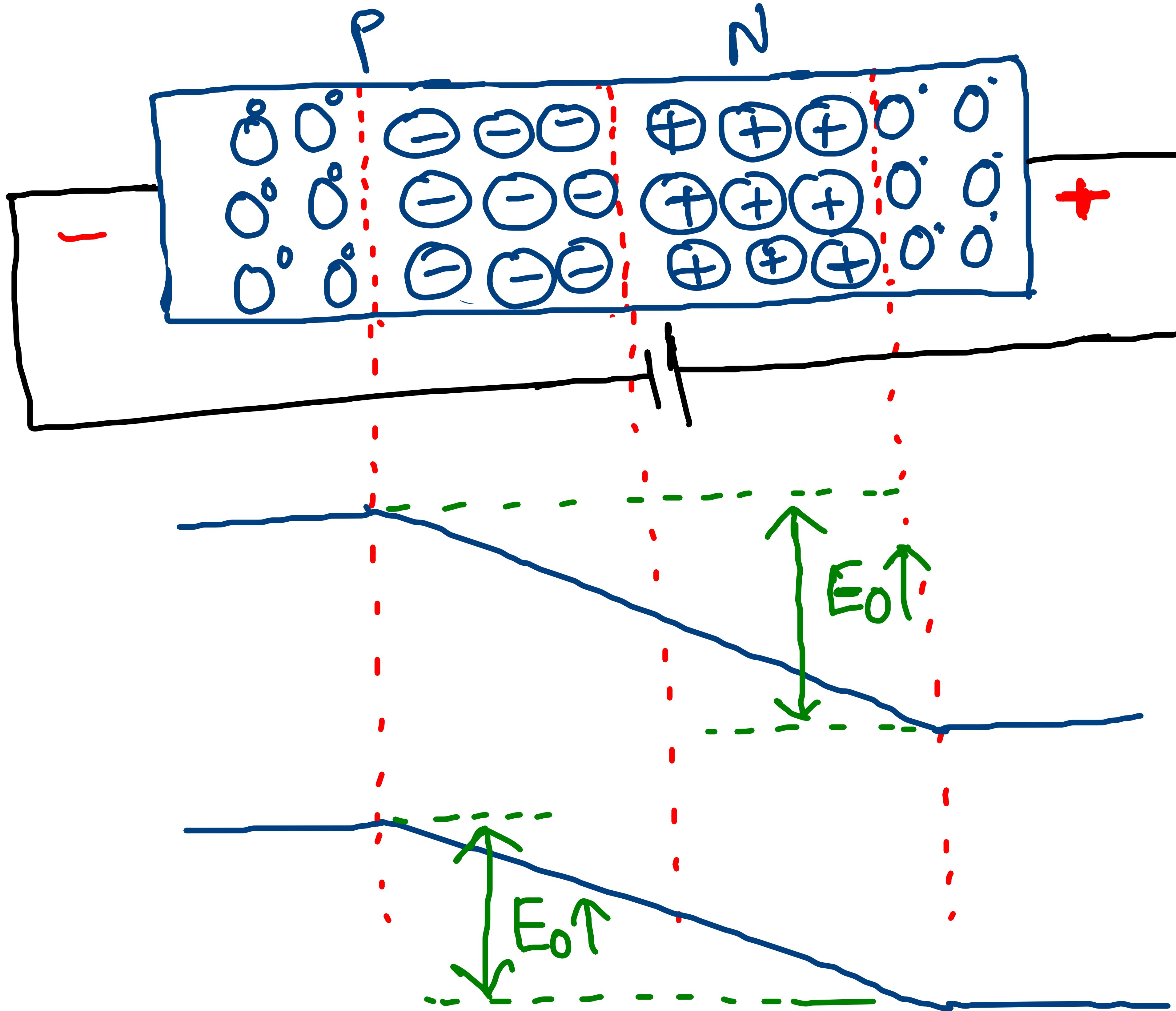
Negative side of battery to N-side

hole — positive charge carrier

$\bar{e}$ — Negative charge carrier.

## Reverse Bias:-



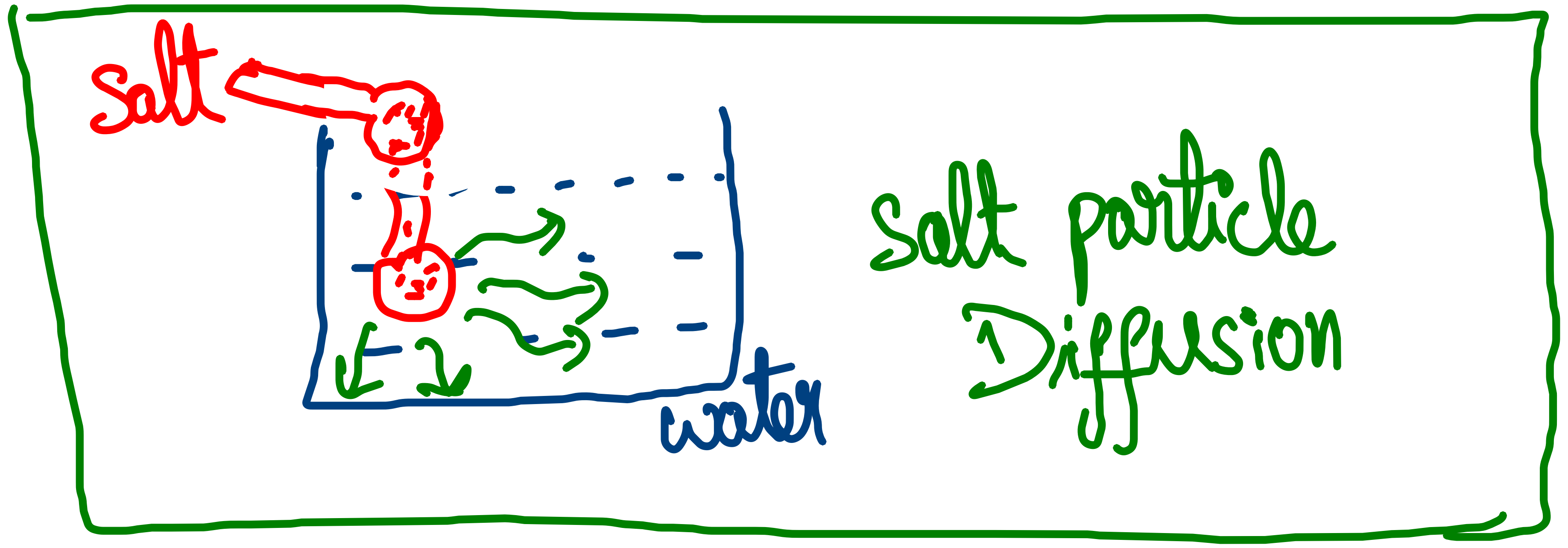



- In FB, $E_0$ decreases, because width of the Depletion region decreases.
- In RB, $E_0$ increases, because width of the Depletion region increases.
- $E_0$ represents the potential Energy barrier faced by the carriers.

## Drift & Diffusion

Drift → movement caused by the applied voltage.

Diffusion → movement of carriers by themselves due to difference in the Concentration Gradient.

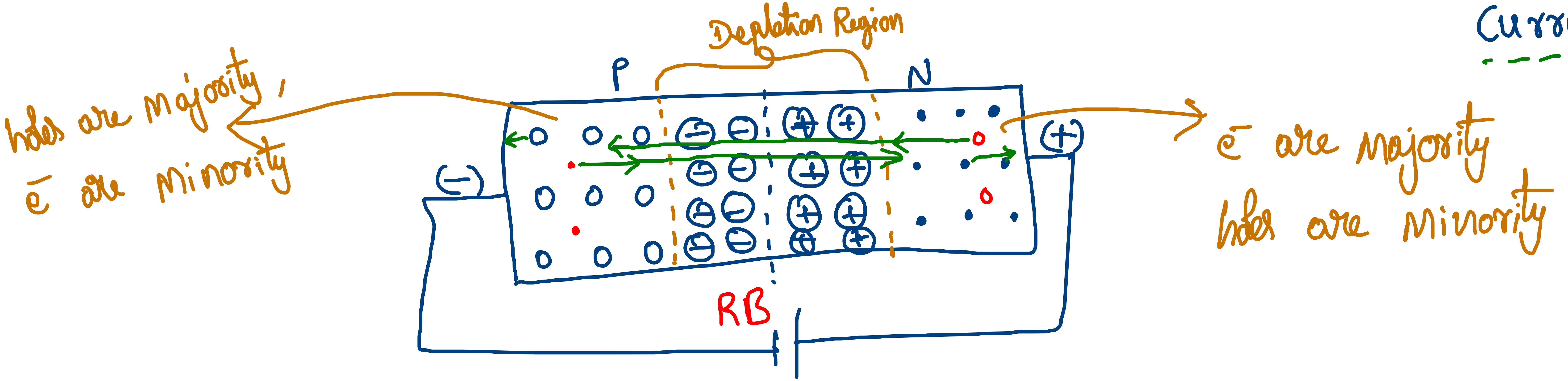


- In FB, majority carriers move because of both Diffusion & Drift.

  Dominant in FB.

- In RB, Minority carriers move because of Drift.

  current due to minority carriers in PN-diode is called leakage current.



- Drift current is proportional to concentration of charge carriers & the applied Electric field Intensity (E).

$$I_{drift} = (\underbrace{nq\mu_n}_{\text{Due to } e^-\text{s.}} + \underbrace{pq\mu_p}_{\text{Due to holes}})A \cdot E$$

n = free $\bar{e}$ concentration

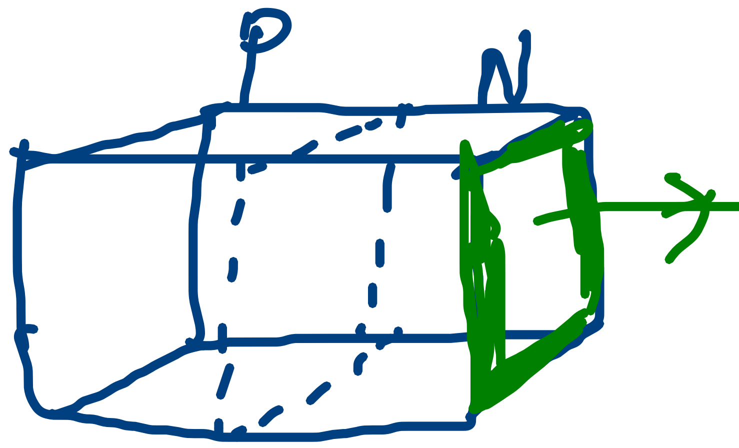
p = hole concentration

q = elementary charge.

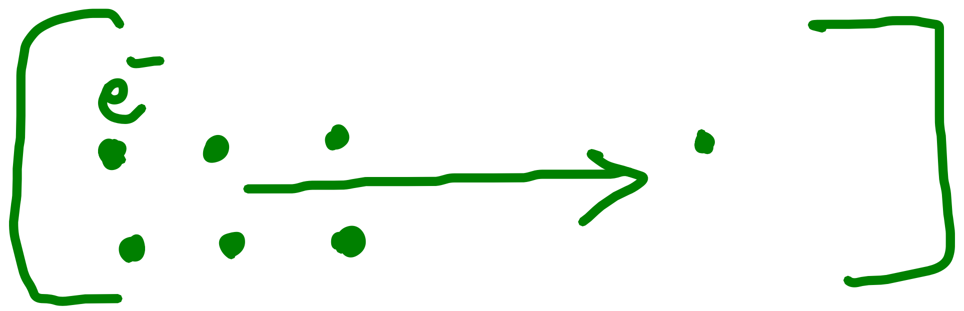
$\mu_n$ & $\mu_p$ = mobility of $\bar{e}$ & hole.

A = Area of cross-section

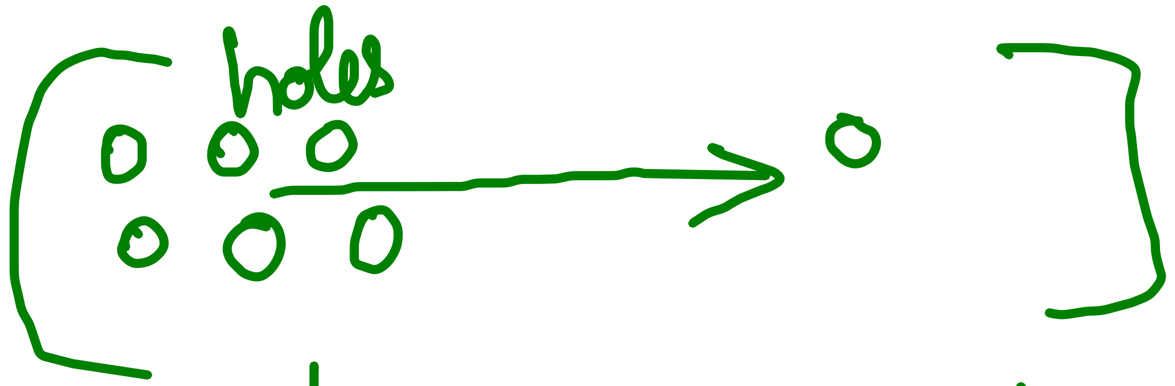
E = Electric field Intensity.



- Diffusion current proportional to Concentration Gradient of carrie




$\frac{dn}{dx}$ (concentration gradient of $\bar{e}$)




$\frac{dp}{dx}$ (concentration Gradient of hole)

$\frac{dn}{dx} \neq 0$ then $\bar{e}$ diffusion happens

$\frac{dn}{dx} = 0$ then $\bar{e}$ diffusion won't happen.

$\frac{dp}{dx} \neq 0$ then hole diffusion happens.

$\frac{dp}{dx} = 0$ then hole diffusion won't happen.

diffusion current,

$$I_{diff} = \underset{\text{Due to holes}}{I_p} + \underset{\text{Due to } \bar{e}\text{s.}}{I_n}$$

$$= \left( q D_p \frac{dp}{dx} + q D_n \frac{dn}{dx} \right) \cdot A$$

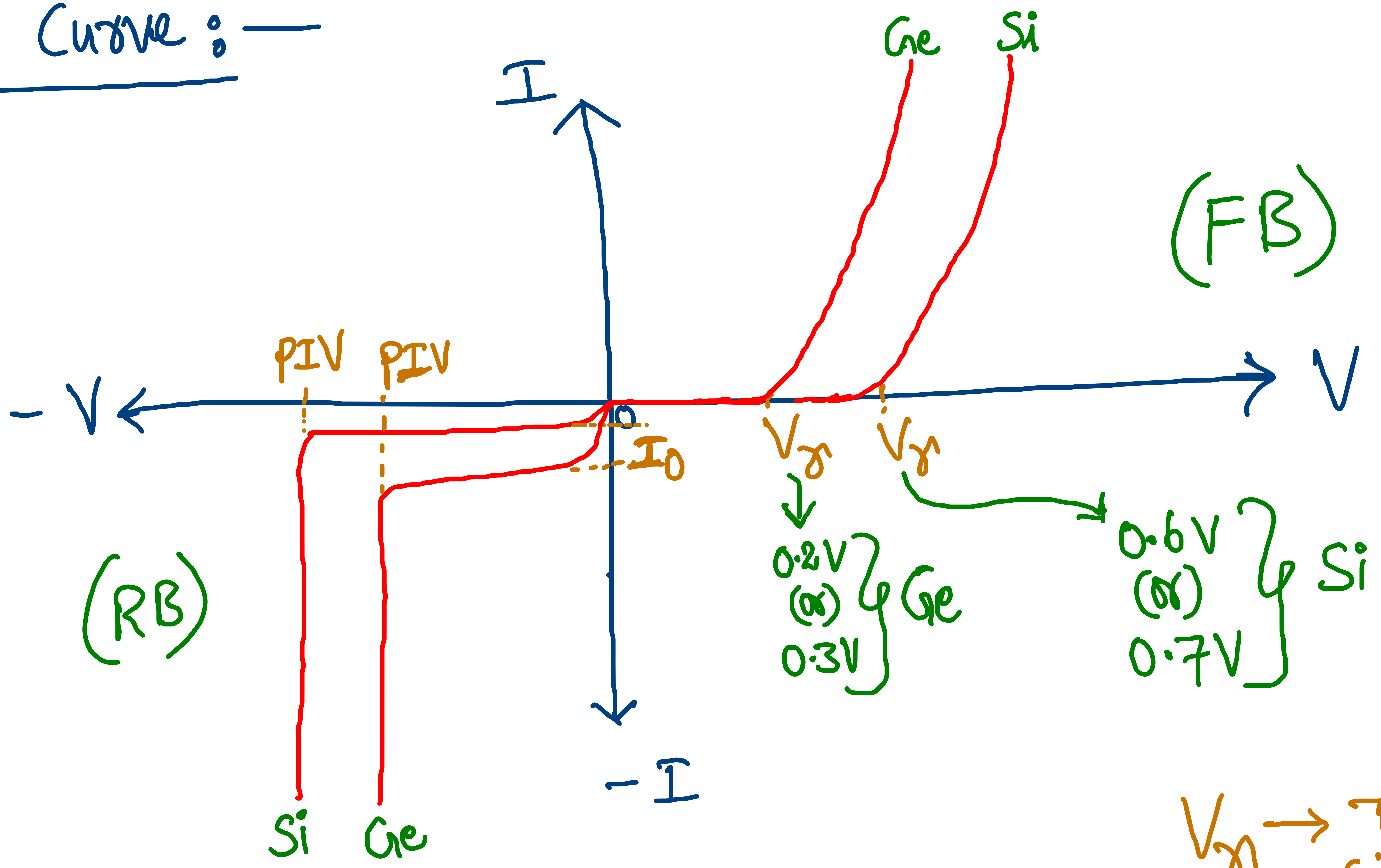
$D_p$ = Diffusion constant of hole
$D_n$ = Diffusion constant of $\bar{e}$

$D_p$ & $D_n$ can be extracted from,

$$\frac{D_p}{\mu_p} = \frac{D_n}{\mu_n} = \frac{KT}{q} = \frac{T(^\circ K)}{11{,}600} = V_T \leftarrow \text{Thermal voltage}$$

$$= 26 \text{ mV at } 300^\circ K.$$

## I - V Curve :—




$V_\gamma \rightarrow$ Threshold voltage (or) Cut-in voltage

$I_0 \rightarrow$ Reverse leakage current

PIV $\rightarrow$ peak Inverse voltage.

Current expression in PN- diode,

$$I = I_0\left(e^{V/\eta V_T} - 1\right)$$

$I_0 \rightarrow$ Reverse Leakage current

$V \rightarrow$ Applied voltage.

$\eta \rightarrow$ constant $= 1$ for Ge

$= 2$ for Si

$V_T \rightarrow$ Thermal voltage (26 mV at 300 K)

In FB, $I \approx I_0 \cdot e^{V/\eta V_T}$ [V is +ve so −1 is neglegible]

In RB, $I \approx -I_0$ [V is −ve, so $e^{-V/\eta V_T}$ is neglegible]

- In FB, Current flows because of both drift & diffusion of carriers.

  In RB, small leakage current flows only due to Drift.

- In both FB & RB, current is caused by both $\bar{e}$ & holes together.

- Current direction is opposite to $\bar{e}$ direction.

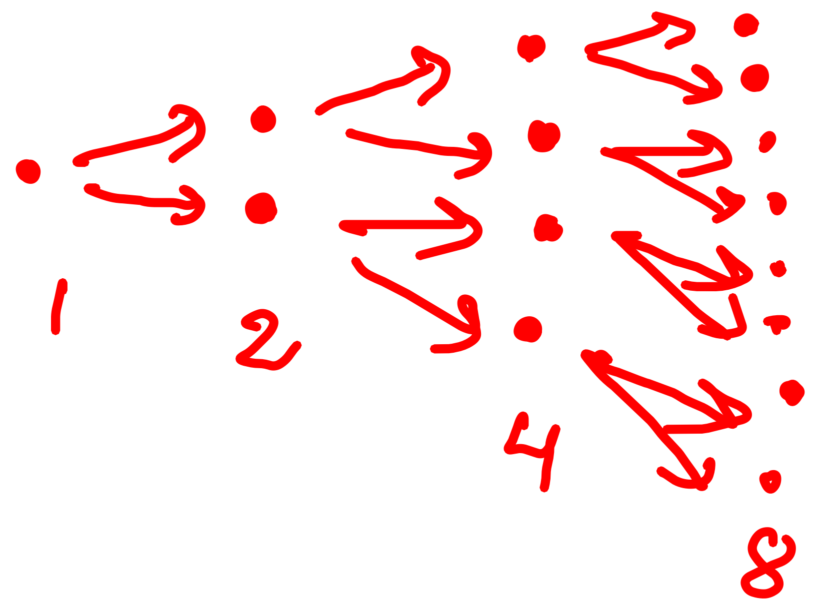
  Current direction is in same direction of hole.

- Threshold (or) Cut-in voltage is the minimum applied voltage for considerable current to flow in FB.

- PIV is the maximum voltage the diode can survive in RB. (Burns device)

- If Reverse voltage higher than peak Inverse voltage (PIV) is applied, then

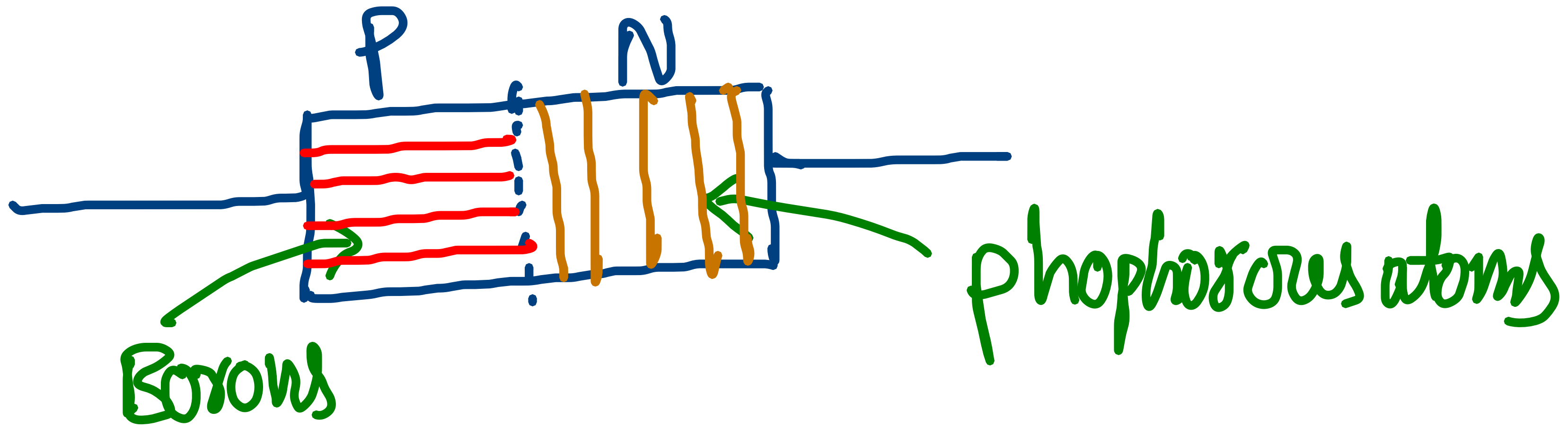
Avalanche Breakdown will takesplace due to Impact Ionization (or) carrier multiplication




It causes Large Current flow, due to which a higher heat inside the device. It may burn the device.

## ↳ Various Types of PN-Junctions :←

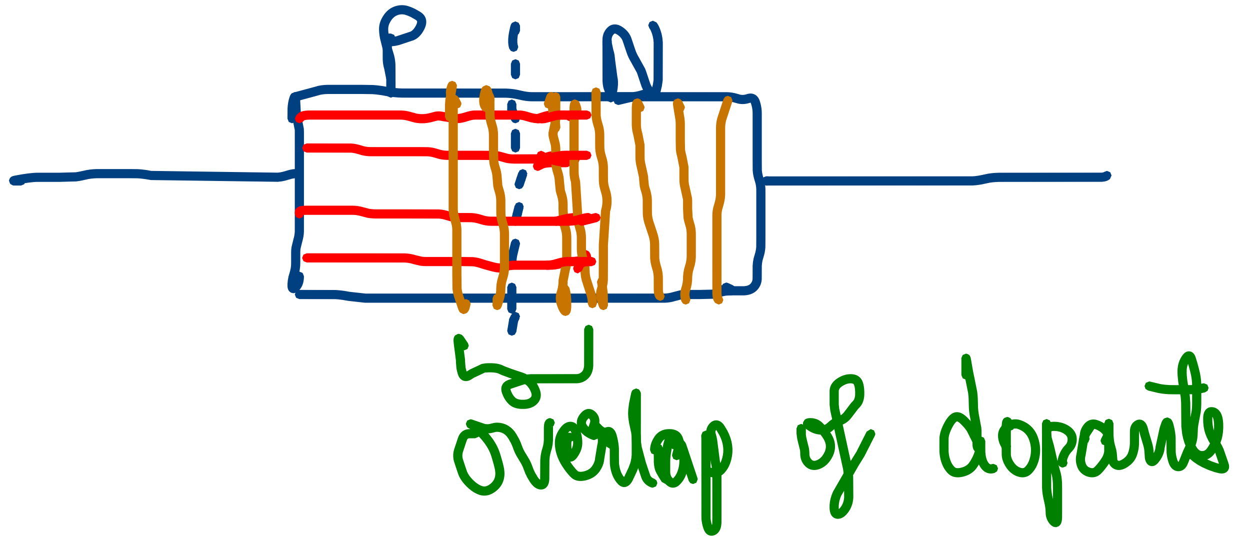
① **Step Junction :**




sudden or Abrupt change of doping type at the Junction.

[i.e. no overlap of dopants at Junction]

② **Graded Junction :**




A overlap between the dopants at the Junction

## ③ Step - Graded Junction :

A step Junction, with different doping Concentrations on p-side & n-side.

## ④ Linearly - Graded Junction :

A Graded Junction, with Linearly varying charge density profile in the depletion region.

↳ Charge Density ($\rho$), Electric Field Intensity (E) & Electrostatic potential (V) profiles in PN-diode depletion Region: